Lepton Non-Universality and Flavor in Rare Decays

(opportunities from R_K)

based on works with Martin Schmaltz and Ivo de Medeiros Varzielas
arXiv:1408.1627, arXiv:1411.4773, arXiv:1503.01084 [hep-ph].

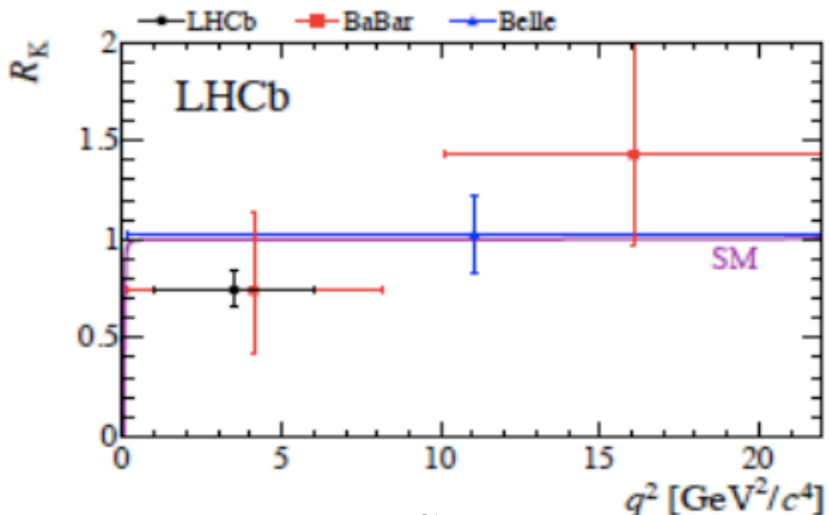
Gudrun Hiller, Dortmund

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

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 ....

$B^{\pm} \to K^{\pm}ee$ 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.

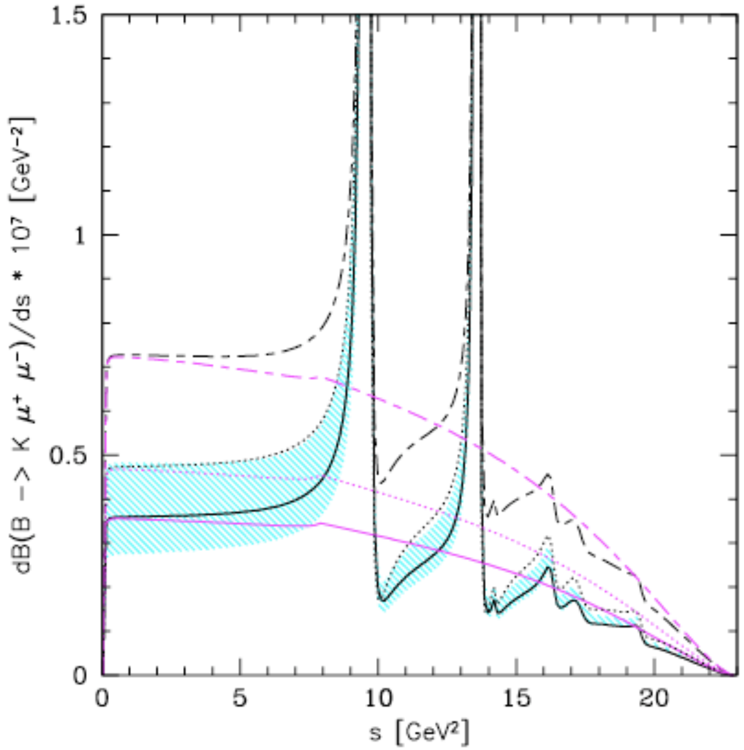


Fig from 9910221, solid: SM, dotted and dot-dashed: BSM scenario

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
$R_K\vert_{[1,6]}$	$0.745 \pm^{0.090}_{0.074} \pm 0.036$	$\simeq 1$

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

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.

1) About R_K ✓

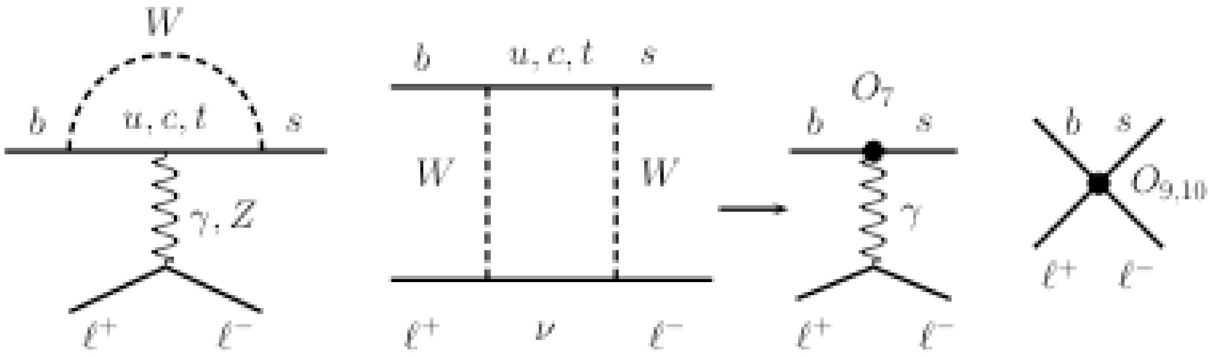
2) Model-independent interpretations (implications for Wilson coefficients)

3) Model-interpretations; Leptoquarks; mass scale for this?

4) Diagnosing with more ratios: R_K vs R_{K^*} vs R_φ vs R_{X_s} vs ..

5) Connecting to flavor; LFV and probing the origin

$b \to s\ell\ell$ FCNCs model-independently



Construct EFT $\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i(\mu)O_i(\mu)$ 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 $C_iO_i \to C_i^\ell O_i^\ell$, $\ell = e, \mu, \tau$

Barring the presence of several different types of operators, or species, 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.

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

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

– The required NP is large $C_9^{\mathrm{SM}} \simeq -C_{10}^{\mathrm{SM}} \simeq 4.2$.

– 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 is 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
$C_9^{\mathrm{NP}\ell} = -C_{10}^{\mathrm{NP}\ell}\,, \quad C_9^{\mathrm{NP}\prime\ell} = -C_{10}^{\mathrm{NP}\prime\ell}$.

R_K -interpretations – $SU(2)_L$

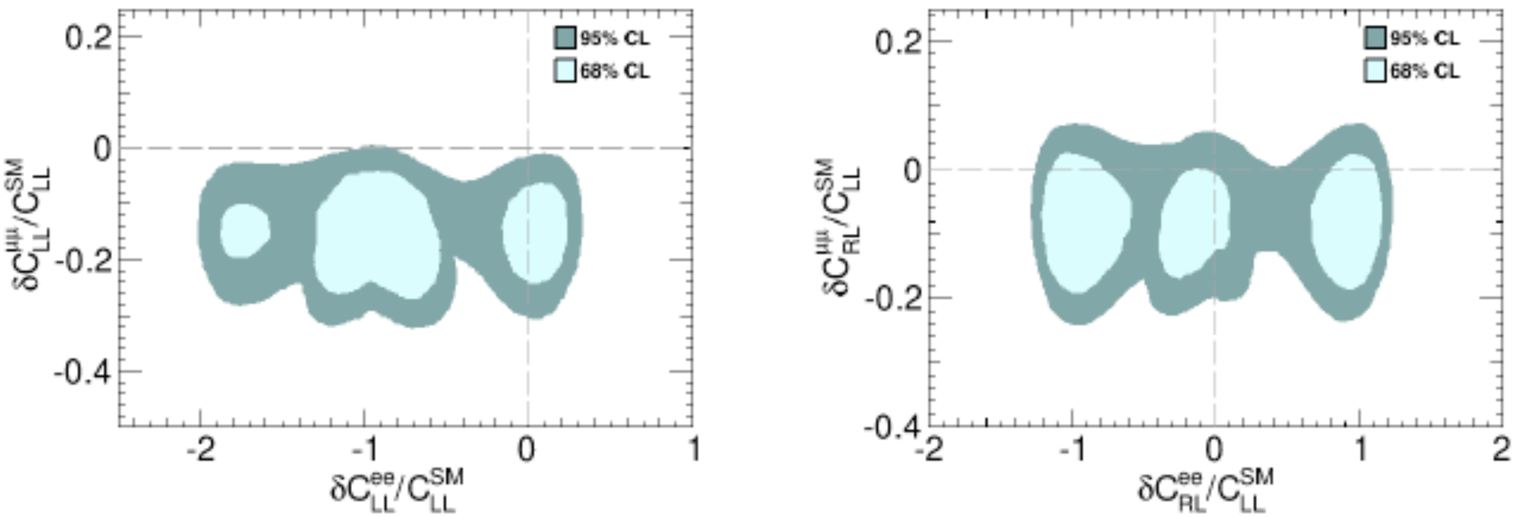


Fig from 1410.4545 – global fit including R_K

– 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 -$B_s \to \mu\mu$

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

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

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

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_{RL}^{e} (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:

$C_{10}^{\prime e} = -C_9^{\prime e} = \frac{\lambda_{se}\lambda_{be}^*}{V_{tb}V_{ts}^*} \frac{\pi}{\alpha_e} \frac{\sqrt{2}}{4M^2 G_F} = -\frac{\lambda_{se}\lambda_{be}^*}{2M^2} (24\mathrm{TeV})^2$
R_K-benchmark: $C_9^{\prime e} = -C_{10}^{\prime e} \simeq 1/2$ follows $M^2/\lambda_{se}\lambda_{be}^* \simeq (24\mathrm{TeV})^2$
ambiguity between M^2 and $\lambda\lambda^*$ can be resolved by $Bs-$mixing!

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

see also 1412.1791 (composite leptoquarks

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

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

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

Decay modes of φ-triplet:

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

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.)

lots of recent interest, papers by crivellin et al, vicente et al, Altmannshofer et al

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, ...

$$0.7 \lesssim -\mathrm{Re}[C^{\mu}_{LL} + C^{\mu}_{RL} - (C^{e}_{LL} + C^{e}_{RL})] \lesssim 1.5 \,. \qquad (R_K)$$

By parity and lorentz invariance, C, C' enter decay amplitudes $B \longrightarrow K\ell\ell$ etc as GH, Schmaltz 1411.4773

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

so different ratios R_K, R_{K^*} etc are complementary.

$$\begin{aligned} R_K &\simeq 1 + \Delta_+ \,, \\ R_{K_0(1430)} &\simeq 1 + \Delta_- \,, \\ R_{K^*} &\simeq 1 + p\,(\Delta_- - \Delta_+) + \Delta_+ \,, \\ R_{K_1} &\simeq 1 + p'\,(\Delta_+ - \Delta_-) + \Delta_- \,, \\ R_{X_s} &\simeq 1 + (\Delta_+ + \Delta_-)/2 \,, \\ \Delta_\pm &= \frac{2}{|C_9^{\rm SM}|^2 + |C_{10}^{\rm SM}|^2} \left[{\rm Re}\left(C_9^{\rm SM} (C_9^{{\rm NP}\mu} \pm C_9'^{\mu})^* \right) + {\rm Re}\left(C_{10}^{\rm SM} (C_{10}^{{\rm NP}\mu} \pm C_{10}'^{\mu})^* \right) - (\mu \to e) \right] . \end{aligned} \tag{1}$$

Double ratios $X_H = R_H/R_K$ are probing right-handed currents!

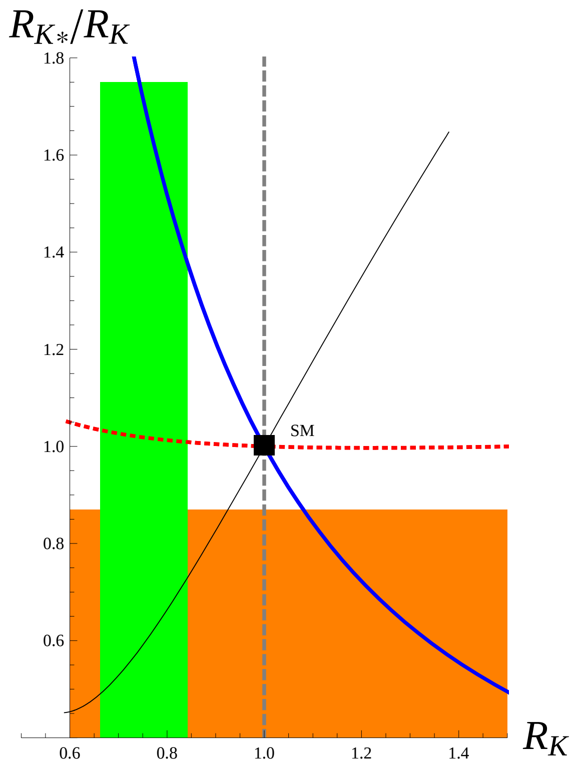
$$\begin{aligned} X_{K_0(1430)} &\simeq 1 + \Delta_- - \Delta_+ \,, \\ X_{K^*} &\simeq 1 + p\,(\Delta_- - \Delta_+)\,, \qquad (2) \\ X_{X_s} &\simeq 1 + \frac{1}{2}(\Delta_- - \Delta_+)\,. \\ X_{K_1} &\simeq 1 + (1-p')\,(\Delta_- - \Delta_+) \qquad (3) \\ \Delta_- - \Delta_+ &\simeq -0.48\,\mathrm{Re}\left(C_9'^{\mu} - C_{10}'^{\mu} - (\mu \to e)\right)\,. \qquad (4) \end{aligned}$$

Since K^* is dominated by $'0'$ and $'\parallel'$ polarization, the complementarity between R_K and R_{K^*} (similarly R_φ) is maximal , $p \simeq O(1)$

$p = \frac{g_0+g_\parallel}{g_0+g_\parallel+g_\perp}$ where $\mathcal{B}(\bar{B} \to \bar{K}^*\ell\ell) = \int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \frac{d\mathcal{B}}{dq^2} = (g_0 + g_\parallel)|C - C'|^2 + g_\perp|C + C'|^2$

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 $B \to X_s \ell\ell$: $R_{X_s}^{\mathrm{Belle}'09} = 0.42 \pm 0.25\,, \quad R_{X_s}^{\mathrm{BaBar}'13} = 0.58 \pm 0.19$.

Diagnosing quark and lepton flavor

Given the breakdown of lepton-universaltiy, chances are that generically there is lepton flavor violation, too arXiv:1411.0565.

Explaining R_K with muons and electrons requires theory of flavor. Thats an opportunity– given a signal– to access origin of flavor arXiv:1503.01084

Leptoquark coupling matrix: $\lambda \equiv \begin{pmatrix} \lambda_{de} & \lambda_{d\mu} & \lambda_{d\tau} \\ \lambda_{se} & \lambda_{s\mu} & \lambda_{s\tau} \\ \lambda_{be} & \lambda_{b\mu} & \lambda_{b\tau} \end{pmatrix}$, $\mathcal{L} = \bar{Q}_i \lambda_{ij} \varphi \ell_j$

Well-motivated ansatz: use $U(1)$-flavor-symmetry for quarks and non-abelian one e.g. A_4 for leptons and assume Higgs to be uncharged. Predicts generically hierarchies for quarks and ”zeros” and ”ones” for leptons. Explicit realizations include

Single lepton flavor $\lambda^{[e]} \equiv \begin{pmatrix} \lambda_{de} & 0 & 0 \\ \lambda_{se} & 0 & 0 \\ \lambda_{be} & 0 & 0 \end{pmatrix}\,, \quad \lambda^{[\mu]} \equiv \begin{pmatrix} 0 & \lambda_{d\mu} & 0 \\ 0 & \lambda_{s\mu} & 0 \\ 0 & \lambda_{b\mu} & 0 \end{pmatrix}$

hierarchy: $\lambda^{[\rho\kappa]} \sim \lambda_0 \begin{pmatrix} \rho_d\kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}$

constraints: $\rho_d \lesssim 0.02\,, \kappa \lesssim 0.5\,, 10^{-4} \lesssim \rho \lesssim 1\,, \kappa/\rho \lesssim 0.5\,, \rho_d/\rho \lesssim 1.6$

predictions:

$$\mathcal{B}(B \to K\mu^{\pm}e^{\mp}) \simeq 3 \cdot 10^{-8}\,\kappa^2 \left(\frac{1-R_K}{0.23}\right)^2 , \tag{5}$$

$$\mathcal{B}(B \to Ke^{\pm}\tau^{\mp}) \simeq 2 \cdot 10^{-8}\,\kappa^2 \left(\frac{1-R_K}{0.23}\right)^2 , \tag{6}$$

$$\mathcal{B}(B \to K\mu^{\pm}\tau^{\mp}) \simeq 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2 , \tag{7}$$

and

$$\mathcal{B}(\mu \to e\gamma) \simeq 2 \cdot 10^{-12}\, \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{8}$$

$$\mathcal{B}(\tau \to e\gamma) \simeq 4 \cdot 10^{-14}\, \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{9}$$

$$\mathcal{B}(\tau \to \mu\gamma) \simeq 3 \cdot 10^{-14}\, \frac{1}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{10}$$

$$\mathcal{B}(\tau \to \mu\eta) \simeq 4 \cdot 10^{-11}\, \rho^2 \left(\frac{1 - R_K}{0.23} \right)^2 . \tag{11}$$

asymmetric branching ratios:

$$\frac{\mathcal{B}(B_s \to \ell^+\ell'^-)}{\mathcal{B}(B_s \to \ell^-\ell'^+)} \simeq \frac{m_\ell^2}{m_{\ell'}^2} \, . \qquad \text{Left-handed leptons only} \tag{12}$$

$$\frac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \simeq 0.01\,\kappa^2 \cdot \left(\frac{1-R_K}{0.23}\right)^2 , \tag{13}$$

$$\frac{\mathcal{B}(B_s \to \tau^+ e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \simeq 4\,\kappa^2 \cdot \left(\frac{1-R_K}{0.23}\right)^2 , \tag{14}$$

$$\frac{\mathcal{B}(B_s \to \tau^+ \mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \simeq 4 \cdot \left(\frac{1-R_K}{0.23}\right)^2 , \tag{15}$$

- 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, with $M \lesssim 50$ TeV. There is no conflict with other measurements nor with model-building.

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

- $R_K \neq 1$ is a very important measurement.
- R_K, R_K^* et al
- $B \to Kee$ angular distribution
- LFV in $b \to s$
- More data for $B \to K^*\mu\mu$! Preliminary $3\mathrm{fb}^{-1}$ $B \to K^*(\to K\pi)\mu\mu$ out – ok – havent explored the full benefit for $b \to s$ fits yet; understanding of all kinds of systematic vital here and for future.

Points of interest/Comments

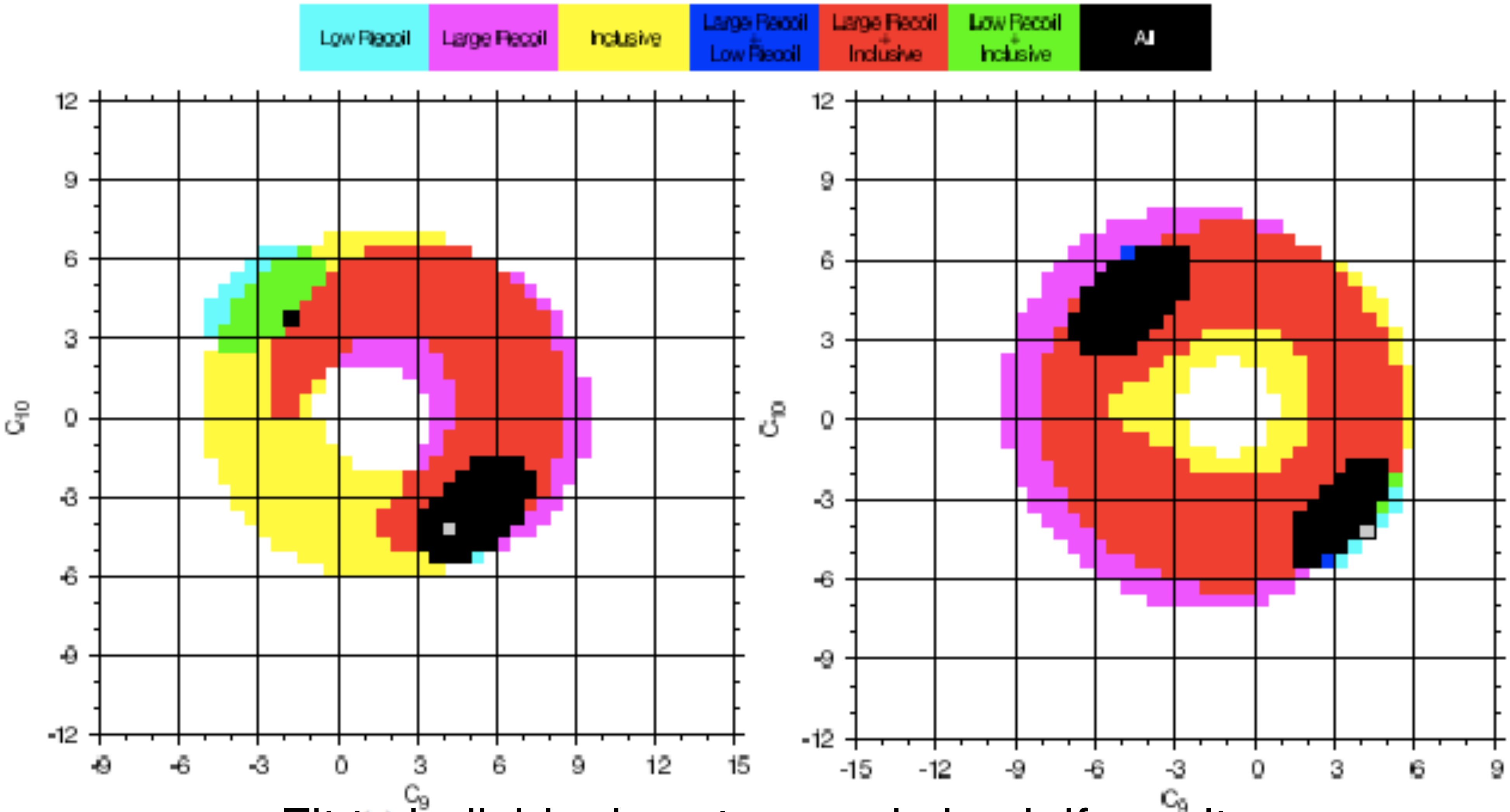


Fig from 1006.5013 Fit to individual sectors and check if results agree.