BSM Flavor Physics with Quarks and Leptons

based on works with Stefan de Boer, Martin Schmaltz and Ivo de Medeiros Varzielas arXiv:1408.1627, arXiv:1411.4773, arXiv:1503.01084, arXiv:1510.00311

see also talk by Dennis Loose

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DFG FOR 1873

Generational structure & mixing is a feature of the SM and many BSM particles. VIRTUES:

i) high sensitivity to BSM in flavor violation;
FCNCs $b \to s\ell\ell, \mu \to e\gamma, h \to \tau\mu, ...$
we may discover BSM in flavor physics (even first)

ii) flavorful processes are intrinsically linked to the ”flavor puzzle”:
masses, i.e., Yukawa matrices in $\mathcal{L}_{SM} = -\bar{Q} Y_u H^C U - \bar{Q} Y_d H D + ...$
do not appear to be random but rather structured - from where?
with a BSM-signal, we may be able to progress here

iii) plenty of modes $s \to d$, $c \to u$, $b \to s, d$, $t \to c, u$, $\mu \to e$, $\tau \to \mu, e$
plus charged ones and $h \to f\bar{f}'$; ongoing & future experiments, too.
we may identify $\mathcal{L}_{BSM}$; complementary to direct searches

Flavor Themes 2015/16 (simplified)

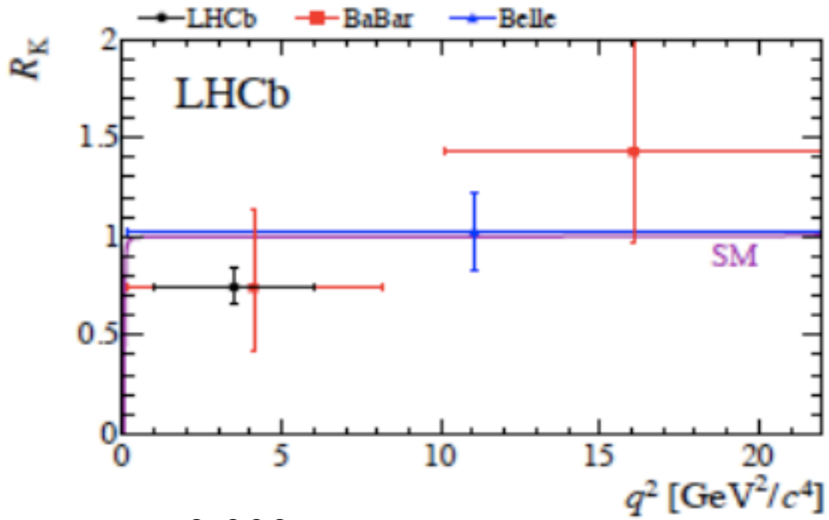
crosstalk theory(SM/BSM)/pheno/experiment

new bottom-up New Physics benchmark models

leptons $\leftrightarrow$ quarks

$$R_H = \frac{\mathcal{B}(\bar{B}\to\bar{H}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{H}ee)}, \quad H = K, K^*, X_s, ...$$

Lepton-universal models (SM): $R_H = 1+$tiny, GH, Krüger '03



LHCb 2014: $R_K = 0.745 \pm^{0.090}_{0.074} \pm 0.036 < 1$ at 2.6 σ

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

apriori too few muons, or too many electrons, or combination thereof.

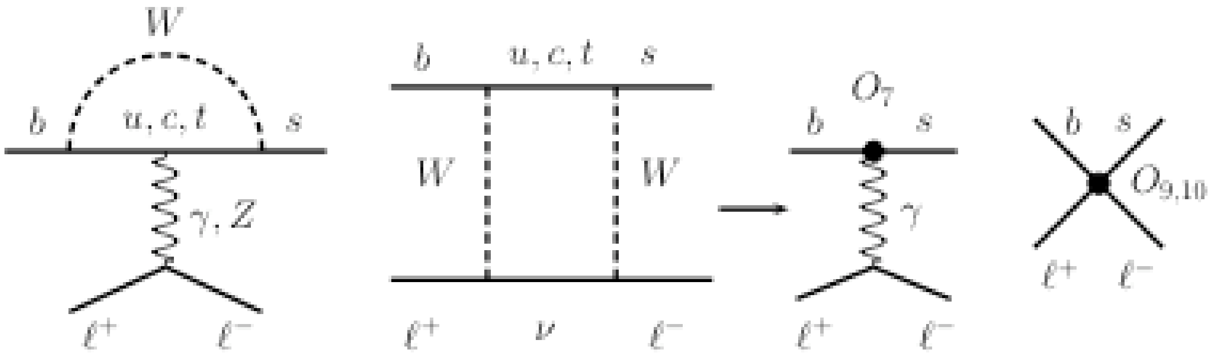
situation for numerator $\mu\mu$ and denominator ee of R_K separately:

	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.

PS: There is another anomaly pointing hat LNU: $R_{D^{(*)}}$, see talk by Dennis Loose.



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

Model-independent interpretations with V,A operators: Das et al 1406.

$$0.7 \lesssim \mathrm{Re}[X^e - X^\mu] \lesssim 1.5\,,$$

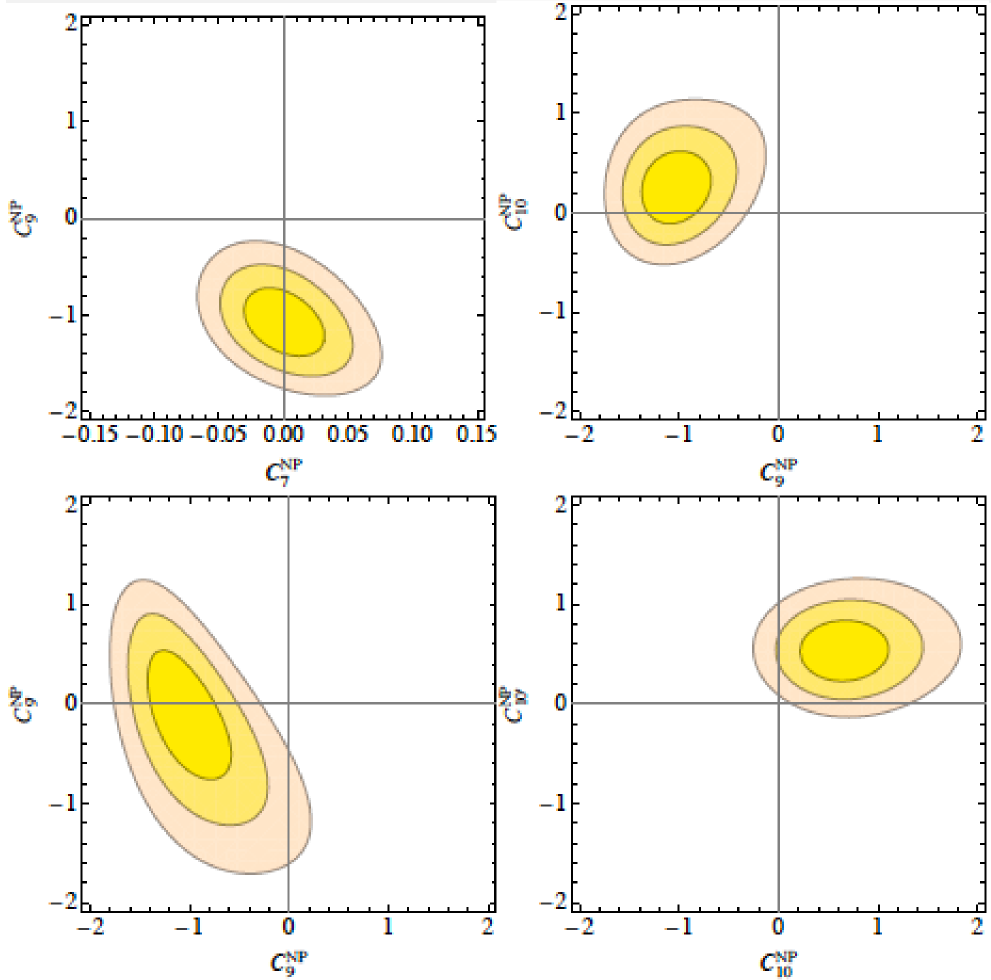
$$X^\ell = C_9^{\mathrm{NP}\ell} + C_9^{\prime\ell} - (C_{10}^{\mathrm{NP}\ell} + C_{10}^{\prime\ell})$$

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

$X^e \simeq 0$ and $X^\mu \simeq C_9^{\mu NP} \simeq -1$ is consistent with global fit to existing $b \to s$ data!

Descotes-Genon et al

Global fits: 2D hypotheses



Hyp.	Best-fit pt	Pull
(C_7^{NP}, C_9^{NP})	(0.0, -1.1)	4.2
(C_9^{NP}, C_{10}^{NP})	(-1.1, 0.2)	4.2
$(C_9^{NP}, C_{9'})$	(-1.0, -0.1)	4.2
$(C_{10}^{NP}, C_{10'})$	(0.5, 0.6)	3.4

$\to$ Main effect from C_9

Explanations ?

- Z' boson
- Leptoquarks
- Composite models
- Difficult with susy (?)

[Almannshoffer, Straub, Haisch, Gauld, Peczak, Buras, De Fazio, Girrbach, Hiller, Schmaltz, Varzielas, Crivellin. . .]

S. Descotes-Genon (LPT-Orsay) | $b \to s\ell\ell$ 2015 & NP | 12/06/15 | 18

Why are muons different from electrons?

Splitting electrons from muons:

Z'- $U(1)_{\tau-\mu}$ (BSM in $b \to s\mu\mu$, not in $b \to see$).

Altmannshofer, Crivellin, Fuentes, Vicente, .. et al

Links with $h \to \tau\mu$ with extras Higgses Crivellin et al, Heeck et al

new particle exchanged at tree level, including leptoquarks, MSSM with R-Parity violation amended with Froggatt-Nielsen flavor symmetry (both $\mu\mu$ and/or ee possible) Schmaltz, Gripaios, Varzielas, .. et al

This naturally provides a link for LFV decays Guadagnoli, Kane, Varzielas which however is not strict Alonso et al, Fuentes et al

pl see original refs for complete list of contributions to this effort

Leptoquark model $\mathcal{L} = -\lambda_{d\ell}\,\varphi\,(\bar{d}P_L\ell)$ with scalar leptoquark $\varphi(3,2)_{1/6}$ with mass M; includes R-parity violating MSSM)

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

In terms of the usual Wilson coefficients:

$$C_{10}'^{e} = -C_9'^{e} = \frac{\lambda_{se}\lambda_{be}^*}{V_{tb}V_{ts}^*}\frac{\pi}{\alpha_e}\frac{\sqrt{2}}{4M^2G_F} = -\frac{\lambda_{se}\lambda_{be}^*}{2M^2}(24\mathrm{TeV})^2$$

R_K-data implies $\lambda_{se}\lambda_{be}^*/M^2 \simeq 1/(24\mathrm{TeV})^2$

Viable parameters of the (scalar) leptoquarks read

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

The upper limit on M arises from correlation with B_s mixing, which constrains $(\lambda_{se}\lambda_{be}^*)^2/M^2$.

– $SU(2)$ 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 $b \to s\gamma$, and direct searches.

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

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

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

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:

$$\begin{aligned} \varphi^{2/3} &\rightarrow t\,\nu \\ \varphi^{-1/3} &\rightarrow b\,\nu\,,\ t\,\mu^- \\ \varphi^{-4/3} &\rightarrow b\,\mu^- \end{aligned}$$

Leptoquark triplet or doublet? That is, more generally,

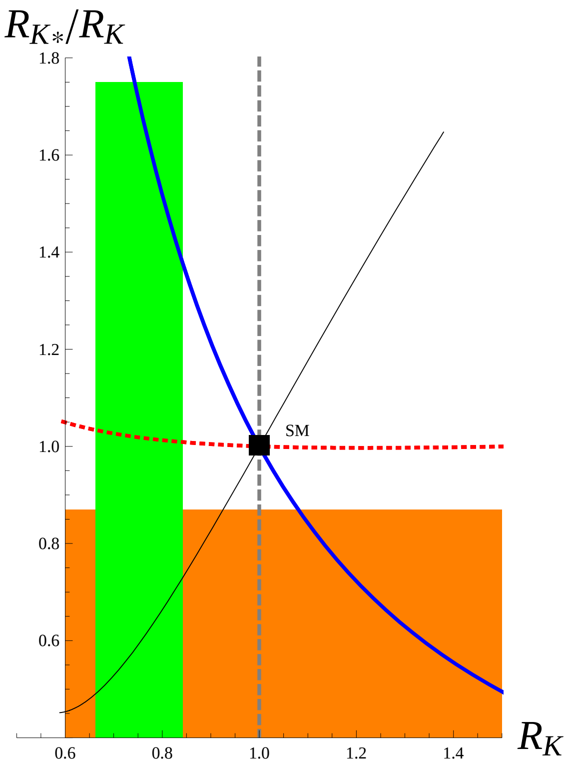
C (V-A-quark currents) versus
C' (V+A quark currents)?

By parity and lorentz invariance, C, C' enter decay amplitudes $B \to K\ell\ell$ etc as

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

so different ratios R_K, R_{K^*} etc are complementary, double ratios R_{K^*}/R_K are cleanly probing right-handed currents!

Distinguish R_K explanations



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

Flavor patterns of leptoquark coupling matrix λ (rows=quark flavor, columns=lepton flavor):

$$\lambda_{ql} \sim \begin{pmatrix} \rho_d \kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}, \quad \begin{pmatrix} 0 & * & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \quad \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \ldots$$

LQs make interesting link between quark (hierarchy) and lepton (anarchy? non-abelian discrete?) flavor 1503.01084.

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

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

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

$$\mathcal{B}(\mu \to e\gamma) \simeq 2 \cdot 10^{-12} \, \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{4}$$

$$\mathcal{B}(\tau \to e\gamma) \simeq 4 \cdot 10^{-14} \, \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{5}$$

$$\mathcal{B}(\tau \to \mu\gamma) \simeq 3 \cdot 10^{-14} \, \frac{1}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{6}$$

$$\mathcal{B}(\tau \to \mu\eta) \simeq 4 \cdot 10^{-11} \, \rho^2 \left(\frac{1 - R_K}{0.23} \right)^2 . \tag{7}$$

$$\frac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\text{SM}}} \simeq 0.01\,\kappa^2 \cdot \left(\frac{1 - R_K}{0.23}\right)^2 , \tag{8}$$

$$\frac{\mathcal{B}(B_s \to \tau^+ e^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\text{SM}}} \simeq 4\,\kappa^2 \cdot \left(\frac{1 - R_K}{0.23}\right)^2 , \tag{9}$$

$$\frac{\mathcal{B}(B_s \to \tau^+ \mu^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\text{SM}}} \simeq 4 \cdot \left(\frac{1 - R_K}{0.23}\right)^2 , \tag{10}$$

Predictions for charm decays

	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$	$\mathcal{B}(D^0 \to \mu^+\mu^-)$	$\mathcal{B}(D^+ \to \pi^+ e^\pm \mu^\mp)$	$\mathcal{B}(D^0 \to \mu^\pm e^\mp)$	$\mathcal{B}(D^+ \to \pi^+ \nu\bar{\nu})$
i)	SM-like	SM-like	$\lesssim 2 \cdot 10^{-13}$	$\lesssim 7 \cdot 10^{-15}$	$\lesssim 3 \cdot 10^{-13}$
ii.1)	$\lesssim 7 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$\lesssim 3 \cdot 10^{-9}$	0	0	$\lesssim 8 \cdot 10^{-8}$
ii.2)	SM-like	$\lesssim 4 \cdot 10^{-13}$	0	0	$\lesssim 4 \cdot 10^{-12}$
iii.1)	SM-like	SM-like	$\lesssim 2 \cdot 10^{-6}$	$\lesssim 4 \cdot 10^{-8}$	$\lesssim 2 \cdot 10^{-6}$
iii.2)	SM-like	SM-like	$\lesssim 8 \cdot 10^{-15}$	$\lesssim 2 \cdot 10^{-16}$	$\lesssim 9 \cdot 10^{-15}$

Table 1: Branching fractions for the full q^2-region (high q^2-region) for different classes of leptoquark couplings. Summation of neutrino flavors is understood. "SM-like" denotes a branching ratio which is dominated by resonances or is of similar size as the resonance-induced one. All $c \to ue^+e^-$ branching ratios are "SM-like" in the models considered. Note that in the SM $\mathcal{B}(D^0 \to \mu\mu) \sim 10^{-13}$.

LHCb: arXiv:1512.00322 [hep-ex] $\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3 \cdot 10^{-8}$ at 90 % CL

i): hierarchy, ii) muons only iii) skewed, 1) no kaon bounds 2) kaon bounds apply for $SU(2)_L$-dublets $Q = (c, s)$

– Great prospects to test the SM and look for BSM physics in semileptonic rare decays.

– Whether new Physics can be seen depends on flavor, and vice versa; links between K, D, B-physics and LFV can provide new insights into flavor.

– Current anomalies in the flavor sector have triggered new types of bottom-up model-building (Z', leptoquarks, ..), that deserves attention in direct searches.