LNU and LFV in B and D decays

based on works with Stefan de Boer, Dennis Loose, Martin Schmaltz, Kay Schönwald and Ivo de Medeiros Varzielas

arXiv:1408.1627, arXiv:1411.4773, arXiv:1503.01084, arXiv:1510.00311 and work in progress

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

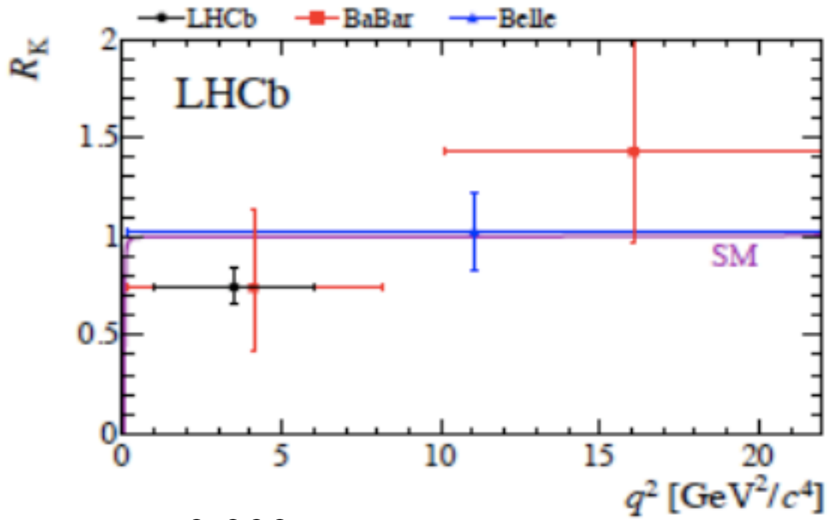
i) high sensitivity to BSM in flavor violation, notably FCNCs $b \to s\ell\ell, \mu \to e\gamma, ..$ we may discover BSM in flavor physics (even first)

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

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

Lepton-universal models (incl. 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.

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

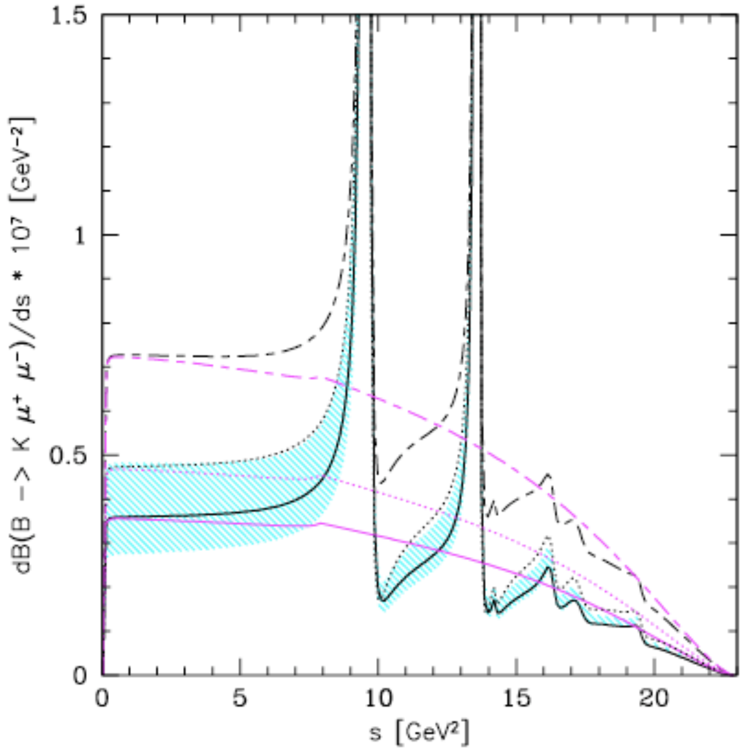


Fig from 9910221, solid: SM, dotted and dot-dashed: BSM scenario

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

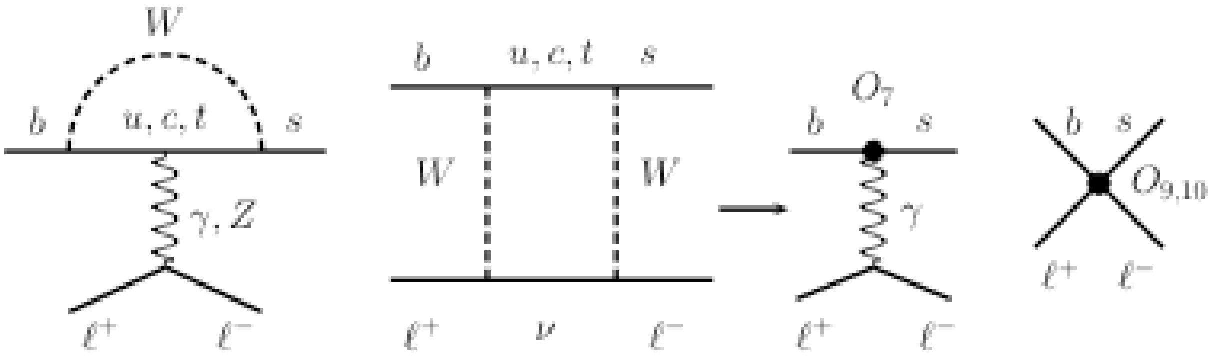
situation for numerator $\mu\mu$ and denominator ee of R_K separately:

	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. Primary reason for considering R_H in first place.

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

Model-independent R_K-interpretations with V,A operators: Das et al 1406.6681

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

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

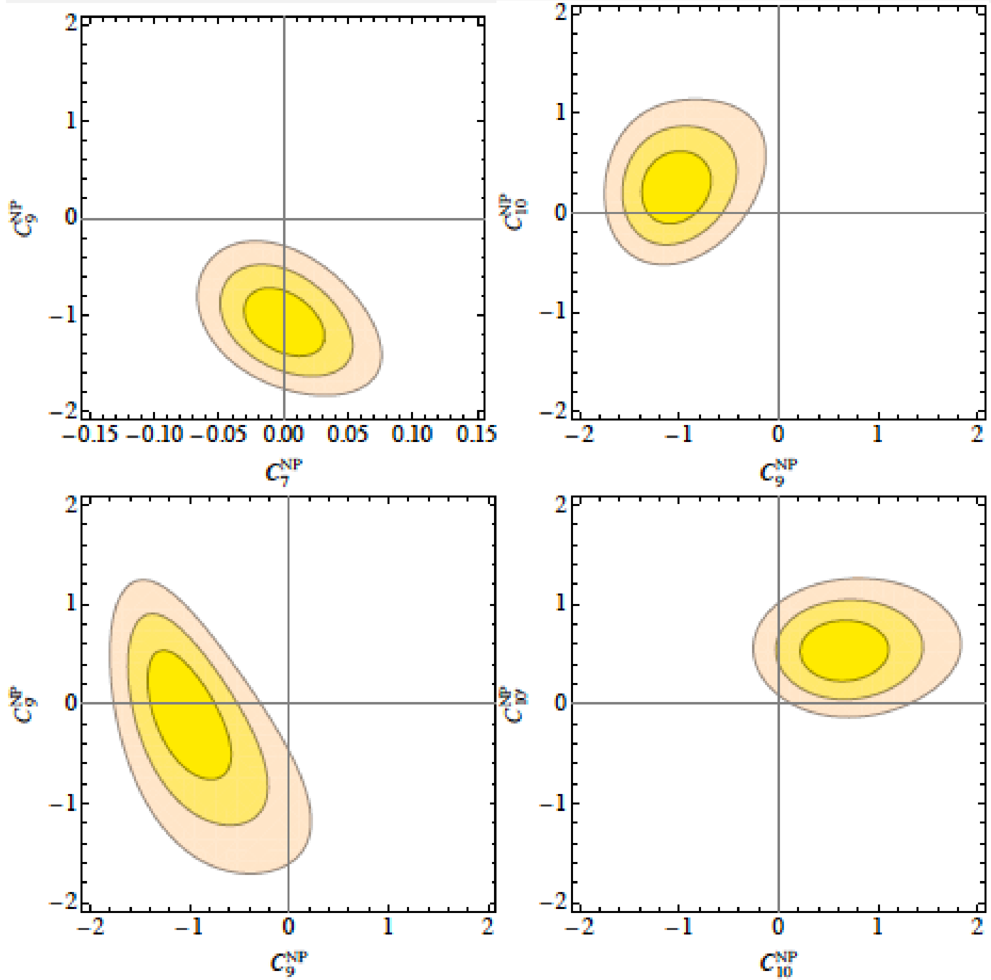
Tensors and S,P muon operators are excluded as sole sources of R_K; S,P electronic operators allowed at 2 σ and require cancellations, testable with $\bar{B} \to \bar{K} ee$ angular distributions.

$\mathcal{B}(B_s \to \mu\mu)$ gives $0 \lesssim \mathrm{Re}[C_{10}^{\mathrm{NP}\mu} - C_{10}^{\prime\mu}] \lesssim 1$.

$X^e \simeq 0$ and $X^\mu \simeq C_9^{\mathrm{NP}\mu} \simeq -1$ is consistent with global fit to $b \to s$ data (without R_K).

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

$\rightarrow$ Main effect from C_9

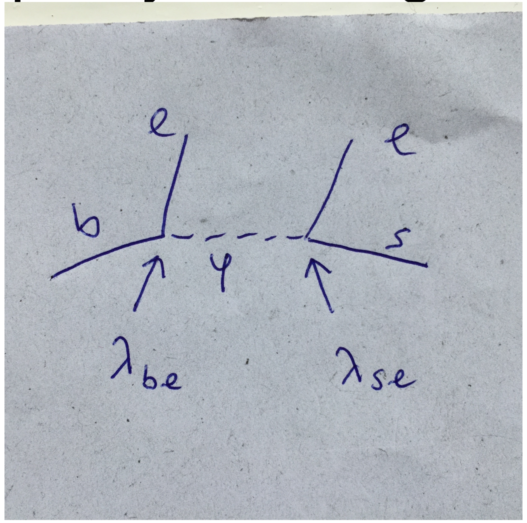
Explanations ?

- 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

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



$$\mathcal{H}_{\text{eff}} = -\frac{|\lambda_{d\ell}|^2}{M^2}(\bar{d}P_L\ell)\,(\bar{\ell}P_Rd) = \frac{|\lambda_{d\ell}|^2}{2M^2}[\bar{d}\gamma^\mu P_Rd]\,[\bar{\ell}\gamma_\mu P_L\ell]$$

In terms of the usual Wilson coefficients:

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

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

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: $\varphi^{2/3} \to b\, e^+ \,, \quad \varphi^{-1/3} \to b\, \nu$

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

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

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

Decay modes of φ-triplet:

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

more leptoquarks and R_K Fajfer, Kosnikm Nisandzic, Gripaios, Nardeccia, Renner, et al ..

Distinguish R_K explanations

Leptoquark triplet or doublet? That is, more generally,

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

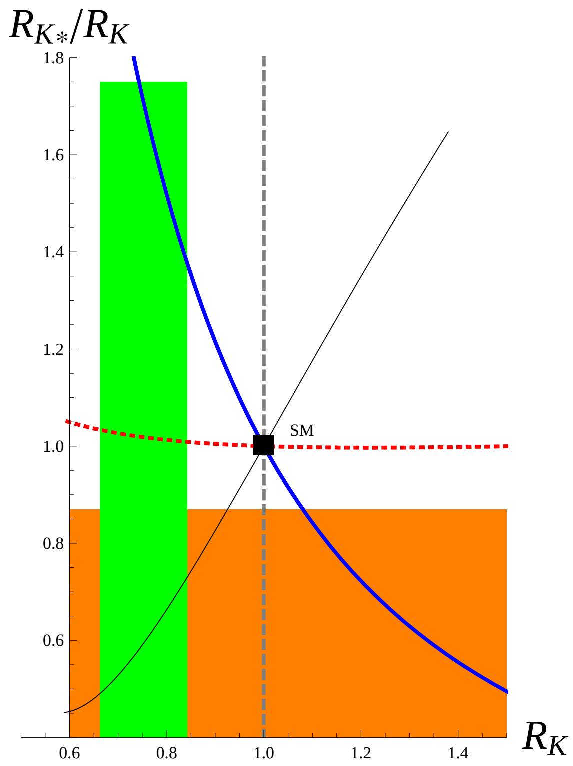
By parity and lorentz invariance, C, C' enter decay amplitudes $B \to K\ell\ell$ etc as

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

and at both high and low q^2 windows $K^*_\perp$ subleading, so different ratios R_K, R_{K^*} etc are complementary, double ratios R_{K^*}/R_K are cleanly probing right-handed currents!

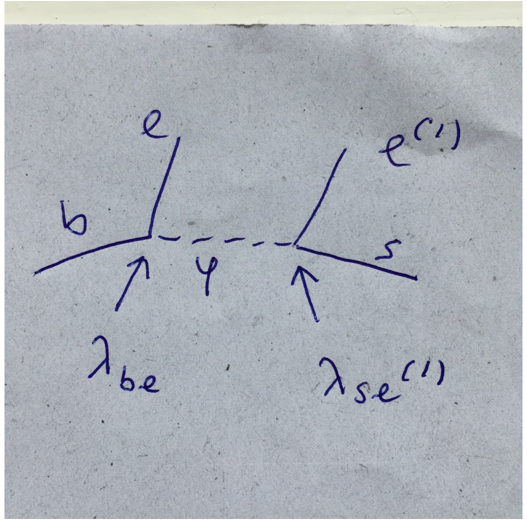
predictions: $R_K = R_\eta$, $R_{K^*} = R_\Phi$ plus correlations among R_H.

Distinguish R_K explanations



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

Why are muons different from electrons? $\rightarrow$ flavor physics



Leptoquark coupling matrix: $\lambda_{ql} \equiv \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix}$

$\rightarrow$ 1. Size of BSM effects depends on flavor and 2. Links of LNU with LFV Guadagnoli, Varzielas,Päs, etal which however is not strict Alonso et al, Fuentes, Jung et al

Explaining R_K with muons and electrons requires theory of flavor.
Thats an opportunity to access origin of flavor 1503.01084

LQ coupling matrix: $\lambda_{ql} \equiv \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix} \sim \begin{pmatrix} \rho_d \kappa & \rho_d & \rho_d \\ \rho \kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}$

rows $=$quarks, columns$=$ leptons

data:

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

Froggatt-Nielsen:
$\rho \sim \epsilon^2$, $\rho_d \sim \epsilon^3$ or ϵ^4 , (Q_L) $\qquad$ $\rho \sim \epsilon$, $\rho_d \sim \epsilon$ or ϵ^2 , (D_R) with $\epsilon \sim 0.2$.

observable	current 90 % CL limit	constraint	future sens.
$\mathcal{B}(\mu \to e\gamma)$	$5.7 \cdot 10^{-13}$ MEG	$\lvert\lambda_{qe}\lambda^*_{q\mu}\rvert \lesssim \frac{M^2}{(34\mathrm{TeV})^2}$	$6 \cdot 10^{-14}$ MEG
$\mathcal{B}(\tau \to e\gamma)$	$1.2 \cdot 10^{-8}$ Belle	$\lvert\lambda_{qe}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(1\mathrm{TeV})^2}$	
$\mathcal{B}(\tau \to \mu\gamma)$	$4.4 \cdot 10^{-8}$ Babar	$\lvert\lambda_{q\mu}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(0.7\,\mathrm{TeV})^2}$	$5 \cdot 10^{-9}$ $[B2]$
$\mathcal{B}(\tau \to \mu\eta)$	$6.5 \cdot 10^{-8}$ Belle	$\lvert\lambda_{s\mu}\lambda^*_{s\tau}\rvert \lesssim \frac{M^2}{(3.7\,\mathrm{TeV})^2}$	$2 \cdot 10^{-9}$ $[B2]$
$\mathcal{B}(B \to K\mu^\pm e^\mp)$	$3.8 \cdot 10^{-8}$ BaBar	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(19.4\,\mathrm{TeV})^2}$	
$\mathcal{B}(B \to K\tau^\pm e^\mp)$	$3.0 \cdot 10^{-5}$ PDG	$\sqrt{\lvert\lambda_{s\tau}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\tau}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(3.3\,\mathrm{TeV})^2}$	
$\mathcal{B}(B \to K\mu^\pm \tau^\mp)$	$4.8 \cdot 10^{-5}$ PDG	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{b\tau}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{s\tau}\rvert^2} \lesssim \frac{M^2}{(2.9\,\mathrm{TeV})^2}$	$\lesssim 10^{-6}$ K.Petridis
$\mathcal{B}(B \to \pi\mu^\pm e^\mp)$	$9.2 \cdot 10^{-8}$ BaBar	$\sqrt{\lvert\lambda_{d\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{de}\rvert^2} \lesssim \frac{M^2}{(15.6\,\mathrm{TeV})^2}$	

Table 1: Selected LFV data, constraints and future sensitivities. Here, $q = d, s, b$. The Belle II projections $[B2]$ are for $50\,ab^{-1}$. For the constraint from $\mathcal{B}(\tau \to \mu\eta)$ we ignored the possibility of cancellations with $\lambda_{d\mu}\lambda^*_{d\tau}$, see *e.g.*, [**?**]. We ignore tuning between leading order diagrams in the $\ell \to \ell'\gamma$ amplitudes. R_K: $0.7 \lesssim \mathrm{Re}[\lambda_{se}\lambda^*_{be} - \lambda_{s\mu}\lambda^*_{b\mu}]\frac{(24\mathrm{TeV})^2}{M^2} \lesssim 1.5$, K-decays $\lvert\lambda_{d\mu}\lambda^*_{s\mu}\rvert \lesssim \frac{M^2}{(183\mathrm{TeV})^2}$

predictions:

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

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

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

and

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

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

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

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

asymmetric branching ratios:

$$\frac{\mathcal{B}(B_s \to \ell^+ \ell'^-)}{\mathcal{B}(B_s \to \ell^- \ell'^+)} \simeq \frac{m_\ell^2}{m_{\ell'}^2} \, . \quad \text{Left-handed leptons only} \tag{8}$$

$$\frac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\rm SM}} \simeq 0.01 \, \kappa^2 \cdot \left(\frac{1 - R_K}{0.23} \right)^2 \, , \tag{9}$$

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

$$\frac{\mathcal{B}(B_s \to \tau^+ \mu^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\rm SM}} \simeq 4 \cdot \left(\frac{1 - R_K}{0.23} \right)^2 \, , \tag{11}$$

Quark and Lepton Flavor Patterns

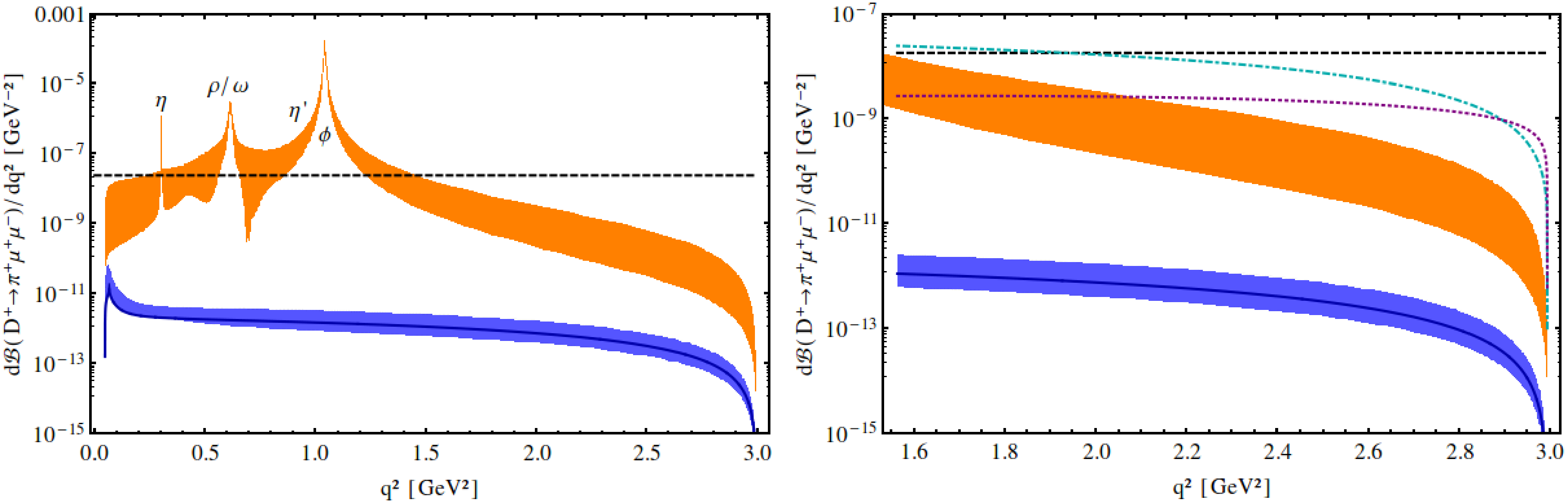
Use $U(1)$-flavor-symmetry for quarks (rows) and non-abelian one e.g. A_4 for leptons (columns) and assume Higgs to be uncharged. Predicts generically hierarchies for quarks and ”zeros” and ”ones” for leptons. Explicit realizations include

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

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

Impact on $c \to u\ell\ell$?

Resonance contributions vs BSM



BSM windows in $D \to \pi l^+ l^-$ branching ratios at high and very low q^2 only; BSM Wilson coefficients need to be very large, ~ 1.

$|C_9^R(q^2 = 1.5\,\text{GeV}^2)| \simeq 0.8$ versus $|C_9^{nr\,\text{SM}}(q^2 \gtrsim 1\,\text{GeV}^2)| \lesssim 5 \cdot 10^{-4}$.

To observe BSM in rare charm either i) BSM is very large (plot to the right) or ii) contributes to SM null tests (LFV, LNU, CP, angular distr.)

Sample flavor patterns of leptoquark coupling matrix λ (rows=quark flavor, columns=lepton flavor) that follow from $U(1) \times A_4$

$$\lambda_{i)} \sim \begin{pmatrix} \rho_d \kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}, \quad \lambda_{ii)} \sim \begin{pmatrix} 0 & * & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \quad \lambda_{iii)} \sim \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix},$$

	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$	$\mathcal{B}(D^0 \to \mu^+\mu^-)$	$\mathcal{B}(D^+ \to \pi^+e^\pm\mu^\mp)$	$\mathcal{B}(D^0 \to \mu^\pm e^\mp)$	$\mathcal{B}(D^+ \to \pi^+\nu\bar{\nu})$
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 2: 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.

BACK-UP

$c \to u$ amplitudes are strongly GIM-suppressed:

$\mathcal{A}_{c\to u} \simeq \sin\Theta_C[f(m_s^2/m_W^2) - f(m_d^2/m_W^2)] + O(\sin^5\Theta_C)$

Resulting (non-resonant) SM branching ratios are $10^{-12} - 10^{-13}$:

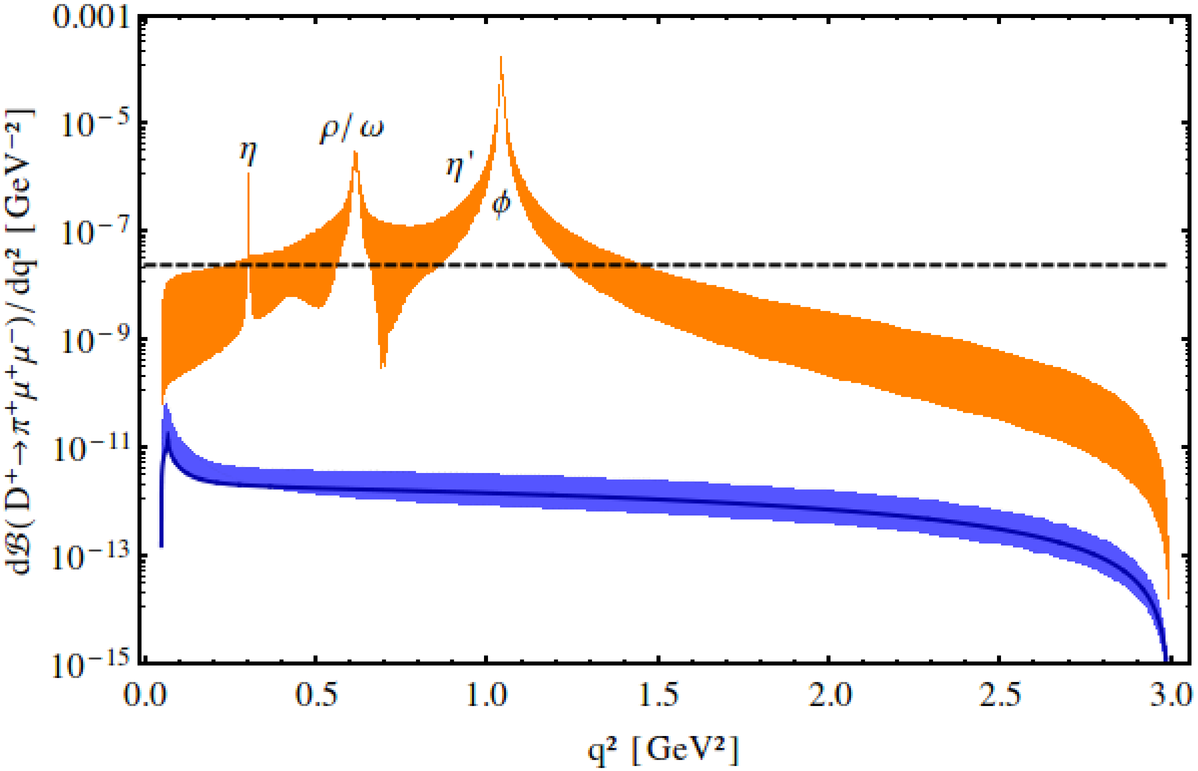
q^2-bin	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)^{\rm SM}_{\rm nr}$	90% CL limit LHCb'13
full q^2:	$3.7 \cdot 10^{-12}\,(\pm 1, \pm 3, ^{+16}_{-15}, \pm 1, ^{+4}_{-1}, ^{+158}_{-1}, ^{+16}_{-12})$	$7.3 \cdot 10^{-8}$
low q^2:	$7.4 \cdot 10^{-13}\,(\pm 1, \pm 4, ^{+23}_{-21}, ^{+10}_{-11}, ^{+11}_{-1}, ^{+238}_{-23}, ^{+6}_{-5})$	$2.0 \cdot 10^{-8}$
high q^2:	$7.5 \cdot 10^{-13}\,(\pm 1, \pm 6, ^{+15}_{-14}, \pm 6, ^{+2}_{-1}, ^{+136}_{-45}, ^{+27}_{-20})$	$2.6 \cdot 10^{-8}$

Table 3: Non-negligible uncertainties correspond to (normalization, m_c, m_s, μ_W, μ_b, μ_c, f_+), respectively, given in percent arXiv:1510.00311

Largest uncertainty: μ_c-scale dependence $m_c/\sqrt{2} < \mu_c \leq \sqrt{2}m_c$.

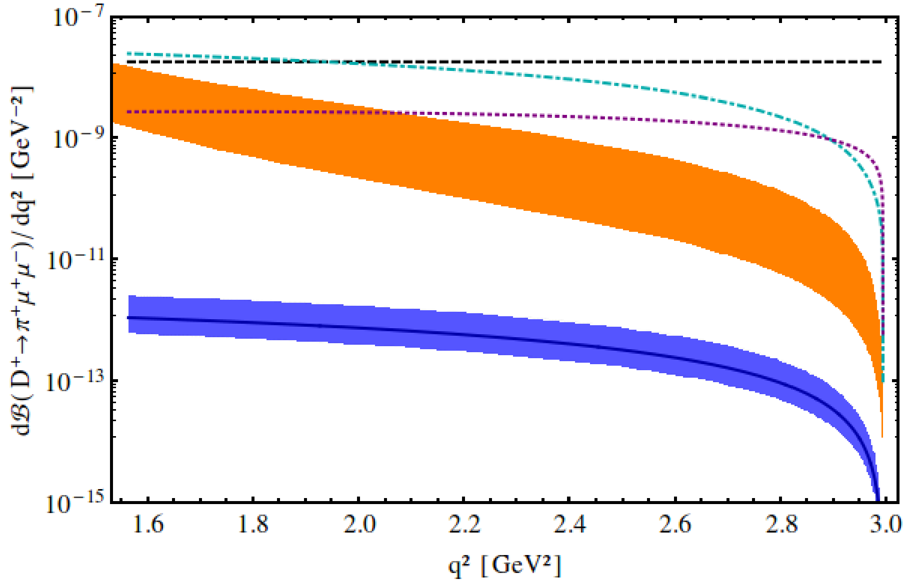
$D \to \pi M \to \pi l^+ l^-$, with $M = \eta^{(\prime)}, \rho, \omega, \Phi$

Model with Breit-Wigners, branching ratio data and relative phases:



solid blue: SM with μ_c-uncertainty, dashed 90% CL upper limit, gray: resonance contribution

Model-independent constraints on BSM



$c \to u\mu\mu$: $|C^{(\prime)}_{V,A}| \lesssim 1$ (illustrated above), $|C_{T,T5}| \lesssim 1$, $|C^{(\prime)}_{S,P}| \lesssim 0.1$.

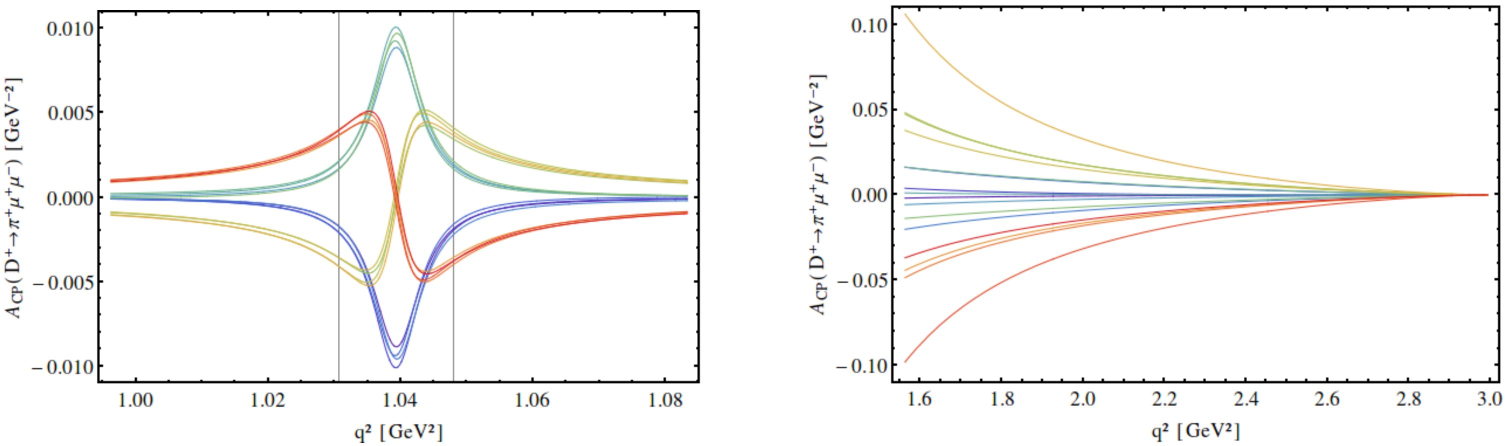
BSM weak loop $\Lambda_{NP} \gtrsim O(5)$ TeV, BSM tree level $\Lambda_{NP} \gtrsim$ weak scale.

$c \to uee$: constraints are weaker (data) by a (2-4) $\times$ muon bounds.

$c \to ue\mu$: weaker by (6-7) $\times$ muon bounds.

Probing even small couplings: A_{CP}

GIM-suppression can be eased by the resonances, which are less $SU(3)_F$-symmetric than the nr- contributions. also "resonance-catalyzed CP", Fajfer et al '13



Large uncertainties, however, large BSM signals possible ($|A_{CP}^{\rm SM}| \lesssim few 10^{-3}$) even independent of strong phases around Φ.

Opportunity to probe SM-like lorentz-structure $C_{V,A}$ even in presence of $SU(2)$-link to K-physics – links between charm and b-physics

Θ: angle between negatively charged lepton and D in dilepton cms

$$\frac{d\Gamma(D \to \pi l^+ l^-)}{d\cos\Theta} = \frac{3}{4}(1 - F_H)(1 - \cos^2\Theta) + A_{FB}\cos\Theta + F_H/2$$ Bobeth et al '07

SM: $A_{FB}, F_H \simeq 0$ by lorentz-structure and small lepton masses. Both require S,P- and or tensor operators.

Model-independently, striking BSM signals possible (high q^2):

$|A_{\rm FB}(D^+ \to \pi^+\mu^+\mu^-)| \lesssim 0.6$, $|A_{\rm FB}(D^+ \to \pi^+ e^+ e^-)| \lesssim 0.8$ and $F_H(D^+ \to \pi^+ l^+ l^-) \lesssim 2$ for $l = e, \mu$.

LFV-rates and dineutrino modes which vanish in SM can be just around the corner (model-independently).

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 $C^{\mathrm{NP}\ell}_{9} = -C^{\mathrm{NP}\ell}_{10}\,, \quad C^{\mathrm{NP}\prime\ell}_{9} = -C^{\mathrm{NP}\prime\ell}_{10}$.

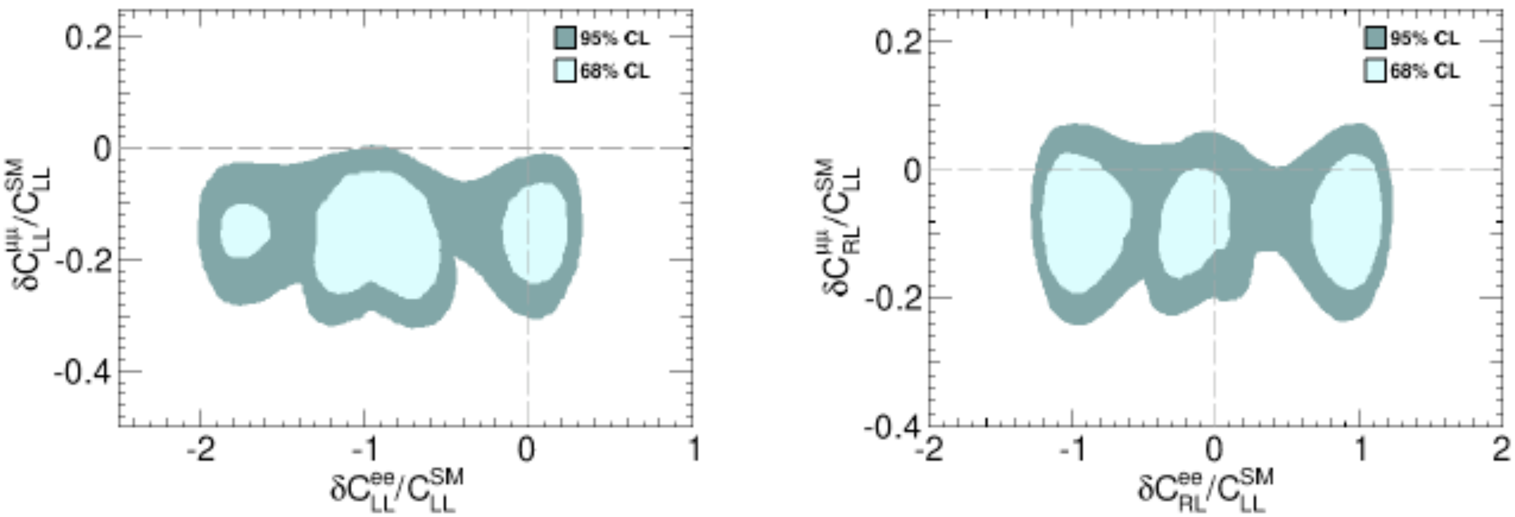


Fig from 1410.4545 – global fit including R_K

– 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 -$B_s \to \mu\mu$

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

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

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

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.

Of course charm FCNCs are of interest by themselves, however, the recent anomalies in semileptonic B-decays add to the physics case of charm decays into leptons.

Improved (N)NLO calculation in SM: S de Boer et al, to appear, DO-TH 15-11

2-step matching:

$$\mathcal{L}_{\text{eff}}^{\text{weak}}|_{m_W \geq \mu > m_b} = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s,b} V_{cq}^* V_{uq} \left(\tilde{C}_1(\mu) P_1^{(q)}(\mu) + \tilde{C}_2(\mu) P_2^{(q)}(\mu) \right) , \tag{12}$$

$$\mathcal{L}_{\text{eff}}^{\text{weak}}|_{m_b > \mu \geq m_c} = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s} V_{cq}^* V_{uq} \left(\tilde{C}_1(\mu) P_1^{(q)}(\mu) + \tilde{C}_2(\mu) P_2^{(q)}(\mu) - \sum_{i=3}^{10} \tilde{C}_i(\mu) P_i(\mu) \right) . \tag{13}$$

$P_{1,2}^{(q)}$: tree-level W-induced. $P_{3..10}$: penguins

	$j=1$	$j=2$	$j=7$	$j=8$	$j=9$	$j=10$
$\tilde{C}_j^{(0)}$	-1.0275	1.0925	0	0	-0.0030	0
$(\alpha_s/(4\pi))\,\tilde{C}_j^{(1)}$	0.3214	-0.0549	0.0035	-0.0020	0.0004	0
$(\alpha_s/(4\pi))^2\,\tilde{C}_j^{(2)}$	0.0787	-0.0035	0.0002	-0.0001	-0.0048	0
$\tilde{C}_j$	-0.6274	1.0341	0.0037	-0.0021	-0.0074	0

Table 4: The ith order contributions $(\alpha_s/(4\pi))^i\,\tilde{C}_j^{(i)}$, $i = 0, 1, 2$ to the SM Wilson coefficients, at $\mu = m_c$. The last row gives their sum, $\tilde{C}_j(m_c)$. For $j = 3, 4, 5, 6$ see 1510.00311.