Implications of lepton non-universality for BSM models and colliders

with input from arXiv:1408.1627, arXiv:1411.4773 , arXiv:1503.01084, arXiv:1609.08895, arXiv:1704.05444, arXiv:1801.09399 with Martin Schmaltz, Ivo de Medeiros Varzielas, Dennis Loose, Kay Schönwald, Ivan Nisandzic

Gudrun Hiller, TU Dortmund

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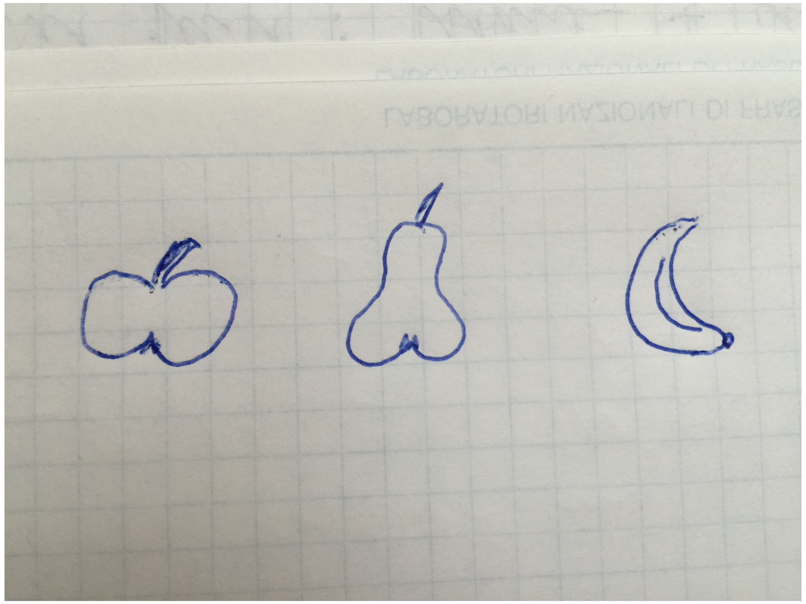


symmetry, and symmetry-breaking (the same yet not the same)

Matter comes in 3 generations $\psi \to \psi_i$, $i = 1, 2, 3$.

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$$

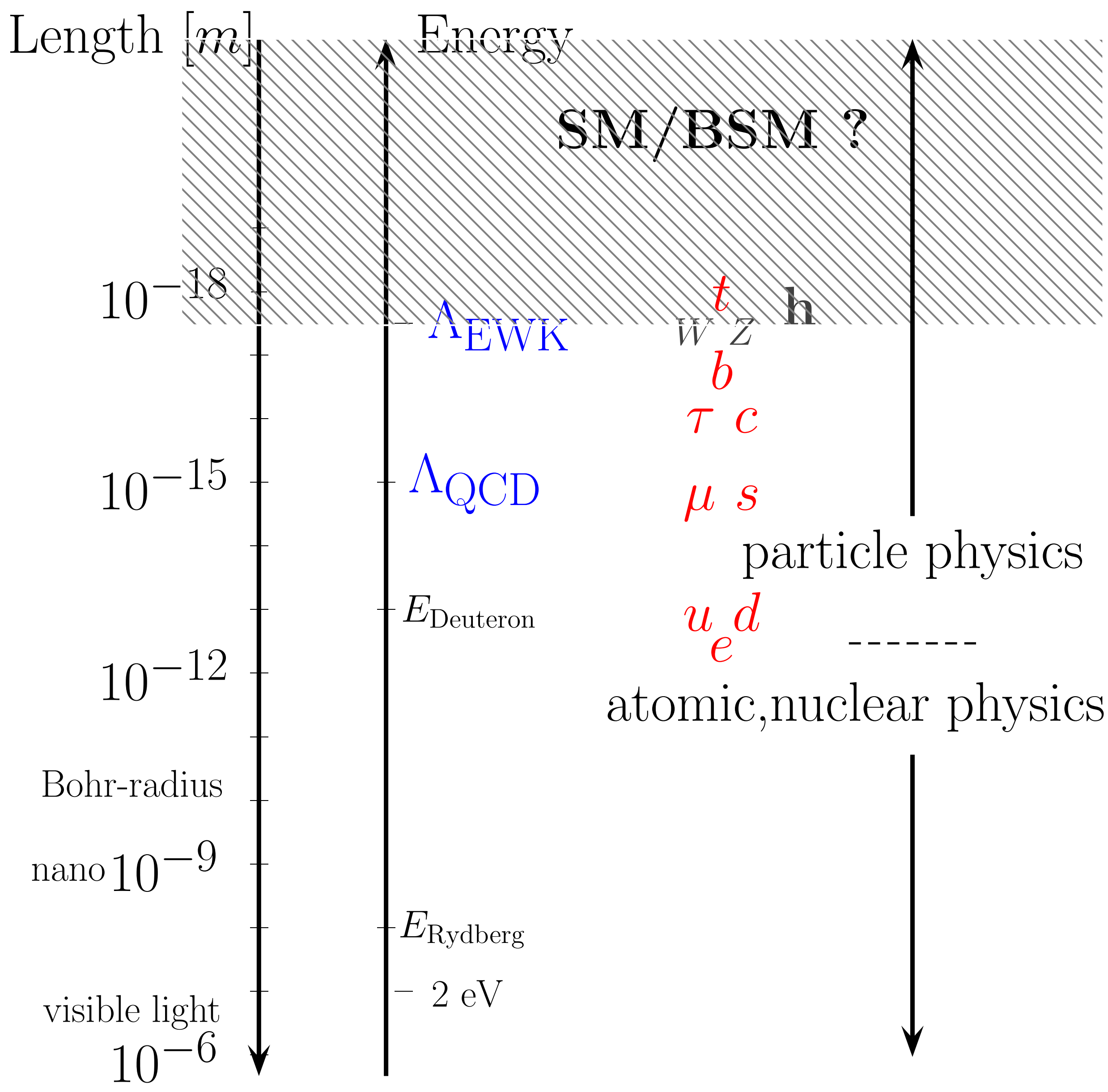
Fermions mix, change ”flavor” in weak processes and violate CP!

$$\mathcal{L}_{SM} = -\frac{1}{4}F^2 + \bar{\psi} i \not{D} \psi + \frac{1}{2}(D\Phi)^2 - \bar{\psi} Y \psi \Phi + \mu^2 \Phi^2 - \lambda \Phi^4$$

Strength of couplings, forces: $\alpha_s, \alpha_w, \alpha_e$:	3
Electroweak scale, e.g., m_Z:	1
Scalar potential. e.g., m_h:	1
Fermions:	13

18 parameters (minimal, without neutrino masses and strong phase)

flavor most uneconomical part of SM, masses and mixing puzzling


Length [m]
Energy
SM/BSM ?
10^{-18}
Λ_{EWK}
t
W Z
h
b
τ c
10^{-15}
Λ_{QCD}
μ s
particle physics
E_{Deuteron}
u d
e

10^{-12}
atomic,nuclear physics
Bohr-radius
nano 10^{-9}
E_{Rydberg}
2 eV
visible light
10^{-6}

The Yukawa coupling Y in $\mathcal{L}_{SM} = -\bar{\psi} Y \psi \Phi + ...$ is a 3×3 matrix.

Experimentally:

$$
\begin{aligned}
Y_u &\sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix} \\
Y_d &\sim \mathrm{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \\
Y_e &\sim \mathrm{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right)
\end{aligned}
$$

very peculiar structure **not understood**

quark mixing is hierarchal, lepton mixing anarchical $O(1)$ entries

Why flavor tests of the SM

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

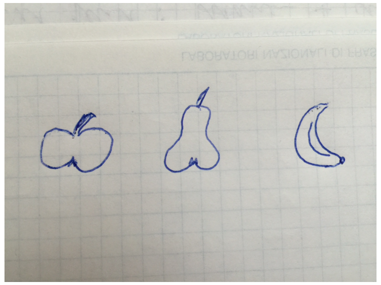
i) high sensitivity to BSM in flavor violation; predictive, and suppressed in SM therefore ideal to look for New Physics in,e.g., $b \to s\ell\ell, \mu \to e\gamma, ..$

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

Lepton Non-universality?

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$



Anomalies in semileptonic B-meson decays:

$R_K = \frac{\mathcal{B}(B\to K\mu\mu)}{\mathcal{B}(B\to Kee)}$ 2.6σ (LHCb'14)

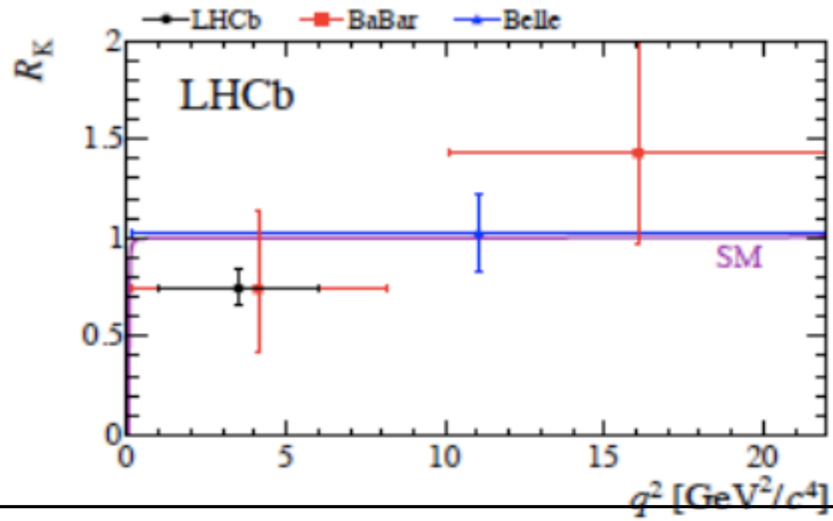
$R_{K^*} = \frac{\mathcal{B}(B\to K^*\mu\mu)}{\mathcal{B}(B\to K^*ee)}$ 2.6σ (LHCb'17)

$R_{D^{(*)}} = \frac{\mathcal{B}(B\to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B\to D^{(*)}\ell\nu_\ell)}$ $\sim 2.7\sigma$ (D^*), $\sim 2\sigma$ (D)
(LHCb'15,B-factories)

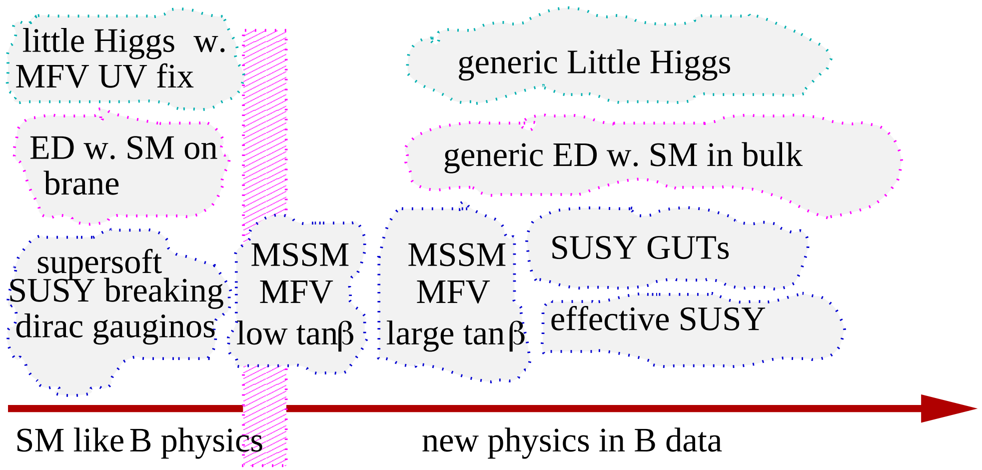
$$R_H = \frac{\mathcal{B}(B \to H\mu\mu)}{\mathcal{B}(B \to Hee)}, \quad H = K, K^*, X_s, \Phi, \dots$$

In models with lepton universality (incl. SM): $R_H = 1+$tiny GH, Krüger '03

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



ψ_i may be more different than we thought



model space 2002

2002: top-down models plot from hep-ph/0207121

2018: $U(1)$-extensions, leptoquarks,...

theory activities how to get these from UV-models 1708.06450, 1708.06350, 1706.05033, 1808.00942 ..

The situation

We are seeing $\sim 2.6\sigma$ hints of new physics in $b \to sll$, LNU between e's and μ's in both observables R_K and R_{K^*} LHCb '14, '17,

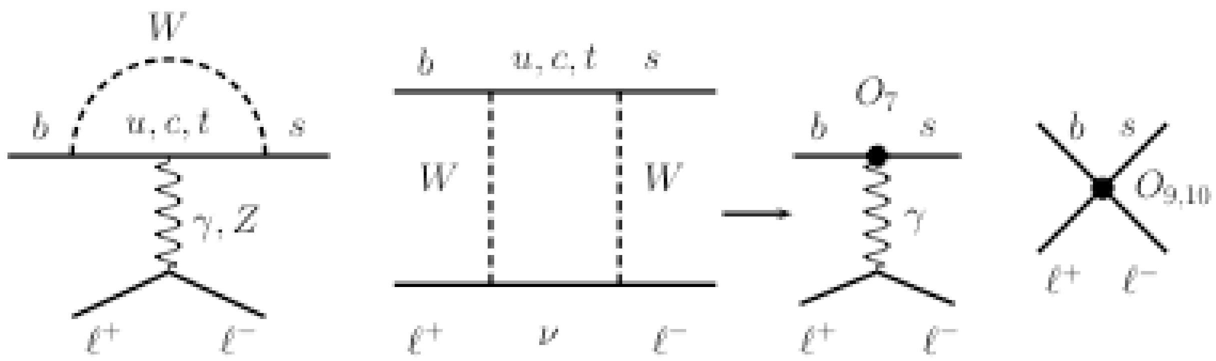
$$R_H = \frac{\mathcal{B}(\bar{B} \to \bar{H}\mu\mu)}{\mathcal{B}(\bar{B} \to \bar{H}ee)}, \text{ same cuts e and mu, } \quad H = K, K^*, X_s, ...$$

Lepton-universal models (incl. SM): $R_H = 1+$tiny GH, Krüger, hep-ph/0310219

How can we go on, consolidate and decipher this effect?

1. Which operators are responsible for the deviation? 1411.4773
2. BSM in electrons, or muons, or in both?
3. Side effects from flavor: LFV, τ's, or $SU(2)$: ν's 1411.0565 , 1412.7164, 1503.01084 Charm and Kaons
4. BSM CP violation 1411.4773
5. Collider implications (leptoquarks!)

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



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

$R_K^{(*)}$ fit:

$\mathrm{Re}[C_9^{\mathrm{NP}\mu} - C_{10}^{\mathrm{NP}\mu} - (\mu \to e)] \sim -1.1 \pm 0.3, \quad \mathrm{Re}[C_9'^{\mu} - C_{10}'^{\mu} - (\mu \to e)] \sim 0.1 \pm 0.4$

At linear approximation it suffices to measure 2 different (by spin parity of final hadron) R_H ratios and then all others serve as consistency checks 1411.4773

Wilson coefficients C: V-A, C': V+A currents

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

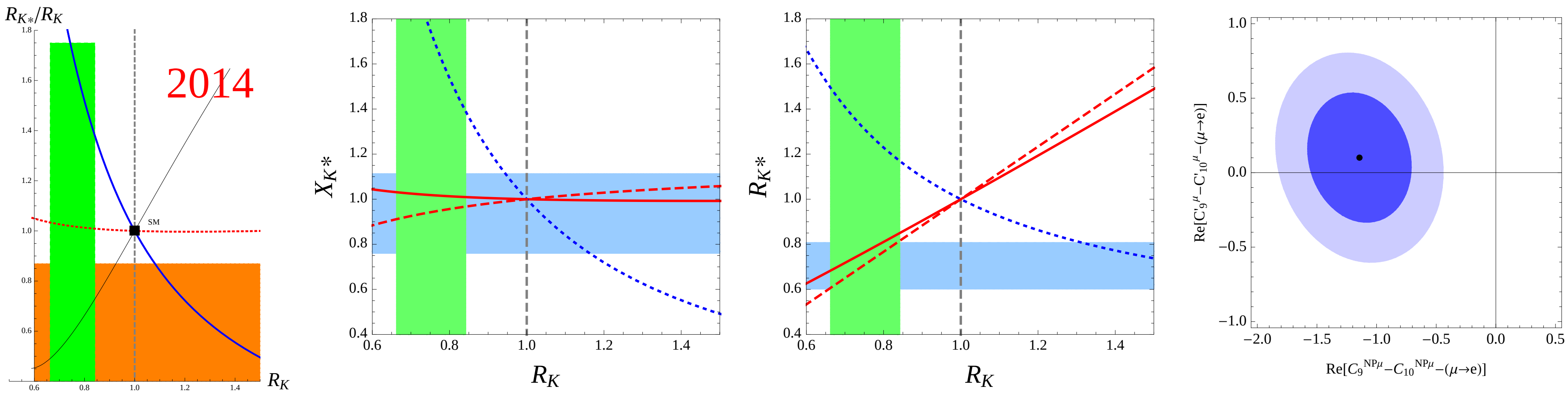
and $K^*_\perp$ subleading at both high and low q^2 windows. Predictions:

$$R_K \simeq R_\eta \simeq R_{K_1(1270,1400)}, \qquad R_{K^*} \simeq R_\Phi \simeq R_{K_0(1430)}$$

All R_H equal if no V+A currents present.

The measurement of R_K and R_{K^*} does this diagnozing job. SM-like chirality operators are the dominant source behind the anomalies.

Prediction: $R_{X_s} \simeq 0.73 \pm 0.07$ inclusive decays 1704.05444 Belle II talk by Komarov



Green band: R_K 1σ LHCb, blue band R_{K^*} 1σ LHCb. Different BSM scenarios are red dashed: pure C_{LL} (LQ triplet). Black solid: $C_{LL} = -2C_{RL}$. Blue: C_{RL} (LQ doublet)/disfavored as dominant source of LNU. Orange: data from $B \to X_s \ell\ell$. $R_{X_s}^{\mathrm{Belle}'09} = 0.42 \pm 0.25\,, \quad R_{X_s}^{\mathrm{BaBar}'13} = 0.58 \pm 0.19\,.$

$R_H < 1$:

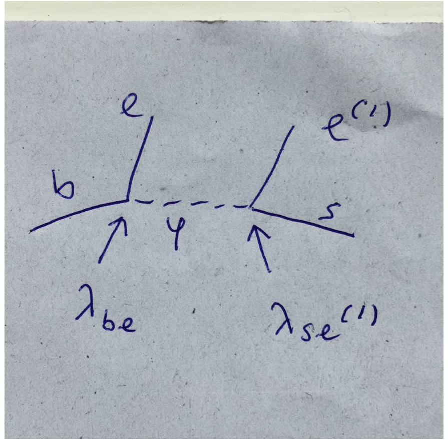
too few muons, or too many electrons, or combination thereof. To disentangle this lepton specific measurements are required. Belle 1612.05014

$B \to Hee$ and $B \to H\mu\mu$ studies; global fits Bobeth, van Dyk, Mahmoudi, Matias,Virto,Straub,Camalich,Altmannshofer, Hurth, Hofer,Jäger

It is interesting that also $B \to K, K^*\mu\mu$ has presently an anomaly, that even can point to the same direction as R_{K,K^*}. As NP in electrons is presently not NEEDED to explain data, one may work with BSM in muons only (occurs's razor, model-dependent argument, not a proof). **e vs mu: don't know for sure yet**

From a flavor perspective, LNU quite generically implies LFV

Guadagnoli, Lane, ...



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

rows=quarks, columns =leptons

(different from SM-Yukawas)

quark-lepton couplings: red: K and D physics

general:

$$\begin{pmatrix} \color{red}{\lambda_{q_1 e}} & \color{red}{\lambda_{q_1 \mu}} & \lambda_{q_1 \tau} \\ \color{red}{\lambda_{q_2 e}} & \color{red}{\lambda_{q_2 \mu}} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix} R_{K,K^*}: \begin{pmatrix} * & * & * \\ \lambda_{q2e} & \lambda_{q2\mu} & * \\ \lambda_{q3e} & \lambda_{q3\mu} & * \end{pmatrix} \text{+occam's razor}: \begin{pmatrix} * & * & * \\ * & \lambda_{q2\mu} & * \\ * & \lambda_{q3\mu} & * \end{pmatrix}$$

flavor models (quark,lepton masses,CKM,PMNS): 1503.01084, 1609.08895

$$\begin{pmatrix} \rho_d \kappa_e & \rho_d & \rho_d \kappa_\tau \\ \rho \kappa_e & \rho & \rho \kappa_\tau \\ \kappa_e & 1 & \kappa_\tau \end{pmatrix} \text{explicitly} c_\ell \begin{pmatrix} \delta\epsilon^4 & \epsilon^4 & \delta\epsilon^4 \\ \delta\epsilon^2 & \epsilon^2 & \delta\epsilon^2 \\ \delta & 1 & \delta \end{pmatrix} \text{or} \begin{pmatrix} c_\nu \kappa \epsilon^2 & c_\ell \epsilon^4 + c_\nu \kappa \epsilon^2 & c_\nu \kappa \epsilon^2 \\ c_\nu \kappa & c_\ell \epsilon^2 + c_\nu \kappa & c_\nu \kappa \\ c_\ell \delta + c_\nu \kappa \epsilon^2 & c_\ell & c_\ell \delta + c_\nu \kappa \epsilon^2 \end{pmatrix}$$

Search for LFV (B-decays, in charm decays, and with charged leptons (μ -e conversion, rare decays) $SU(2)$: $b \to s\nu\nu$

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 $\lambda_{d\mu}\lambda^*_{d\tau}$. 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 $\lvert\lambda_{d\mu}\lambda^*_{s\mu}\rvert \lesssim \frac{M^2}{(183\mathrm{TeV})^2}$.

Next round of μ-e conversion experiments reaching 10^{-16} sensitive to the R_{K,K^*} parameter space!

predictions semileptonic B-decays:

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

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

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

predictions μ and τ decays:

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

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

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

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

predictions purely leptonic decays (asymmetric branching ratios):

$$\frac{\mathcal{B}(B_s \to \ell^+\ell'^-)}{\mathcal{B}(B_s \to \ell^-\ell'^+)} \simeq \frac{m_\ell^2}{m_{\ell'}^2} \qquad \text{assuming left-handed leptons only} \tag{8}$$

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

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

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

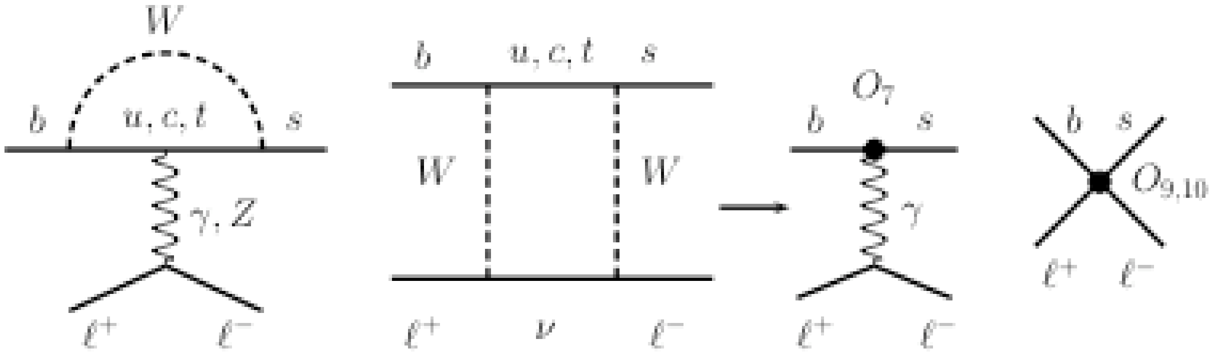
	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$	$\mathcal{B}(D^0 \to \mu^+\mu^-)$	$\mathcal{B}(D^+ \to \pi^+e^\pm\mu^\mp)$	$\mathcal{B}(D^0 \to \mu^\pm e^\mp)$	$\mathcal{B}(D^+ \to \pi^+\nu\bar{\nu})$
i)	SM-like	SM-like	$\lesssim 2 \cdot 10^{-13}$	$\lesssim 7 \cdot 10^{-15}$	$\lesssim 3 \cdot 10^{-13}$
ii.1)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

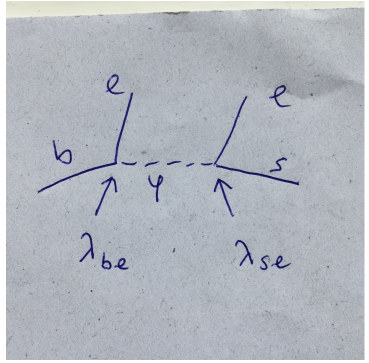
Table 2: Branching fractions for the full q^2-region (high q^2-region) for different classes of leptoquark couplings. Summation of neutrino flavors is understood. "SM-like" denotes a branching ratio which is dominated by resonances or is of similar size as the resonance-induced one. All $c \to ue^+e^-$ 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 $Q = (c, s)$ 1510.00311

Explanations II, Scales





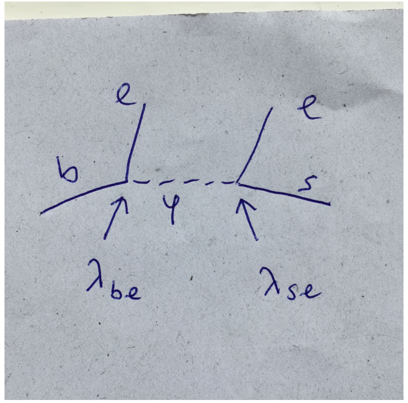
R_K, R_{K^*} tells us at face value $C_9^\mu = -C_{10}^\mu \simeq -0.6$ vs $C_9^{\rm SM} \simeq -C_{10}^{\rm SM} \simeq 4$

about 20 % BSM contribution to $O_{LL} = \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L$.

This actually is "according to plan": FCNCs are suppressed (GIM,CKM,loop) in SM and BSM physics can show up without big competition.

$R_{K^{(*)}} \neq 1$ would not only be a (loud) breakdown of the SM, it tells us something about flavor $\to$ possibly learn something about flavor

Tree level explanations:



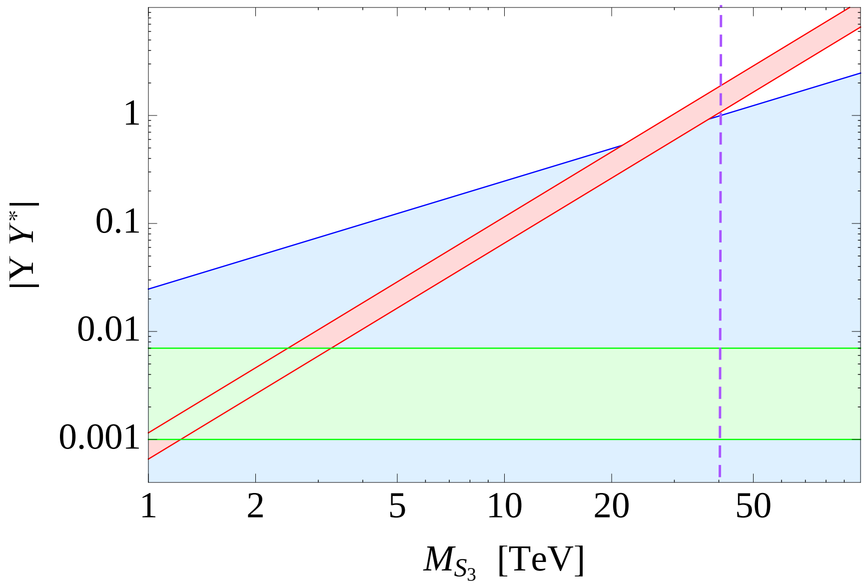
$$\frac{\lambda^2}{M^2} \sim \frac{1}{5}\frac{g^4}{m_W^2}\frac{1}{16\pi^2}V_{tb}V_{ts}^* \sim \frac{1}{(30\mathrm{TeV})^2}$$

for order one couplings this points to a collider-mass scale.

With (minimal) flavor violating BSM $\frac{\lambda^2}{M^2} \sim \frac{1}{5}\frac{g^4}{m_W^2}\frac{1}{16\pi^2} \sim \frac{1}{(6\mathrm{TeV})^2}$ this is within reach of the LHC.

In flavor models that explain quark, lepton masses, CKM, PMNS the BSM couplings can be further suppressed $\rightarrow$ TeV-ish BSM mass.

R_{K,K^*}: $\frac{Y_{b\mu}Y^*_{s\mu} - Y_{be}Y^*_{se}}{M^2} \simeq \frac{1.1}{(35\,\text{TeV})^2}$, (S_3) LQ scalar triplet GH, Nisandzic, 1704.05444



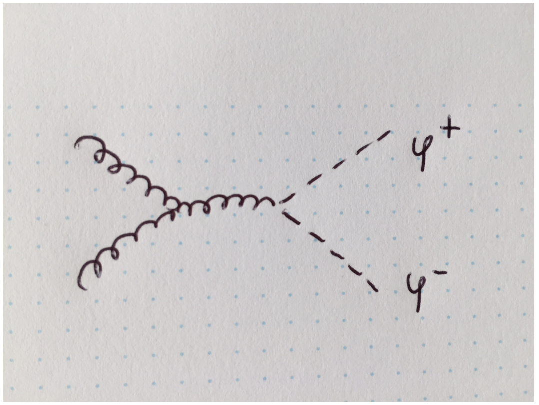
red: explains R_K, R_{K^*}, blue: allowed by $B_s - \bar{B}_s$-mixing, green: flavor model prediction

$Y_{q_3\ell} \sim c_l\,, \quad Y_{q_2\ell} \sim c_l\lambda^2\,, \quad q_3 = b, t, \;\; q_2 = s, c, \;\; \lambda, c_l \lesssim 0.2$ points to TeV-ish mass M!

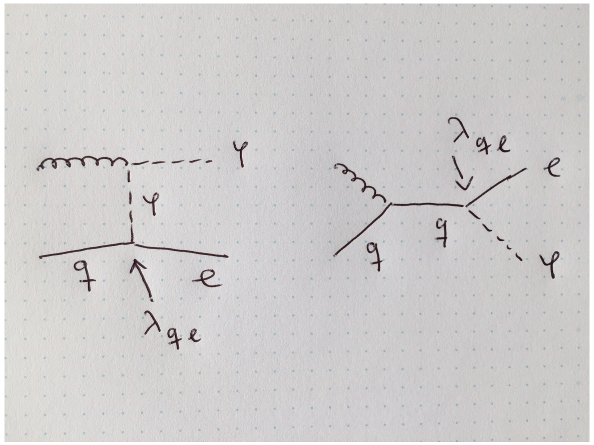
Model-independent upper limit by B_s-mixing $\propto \lambda^4/M^2$ at 40 TeV.

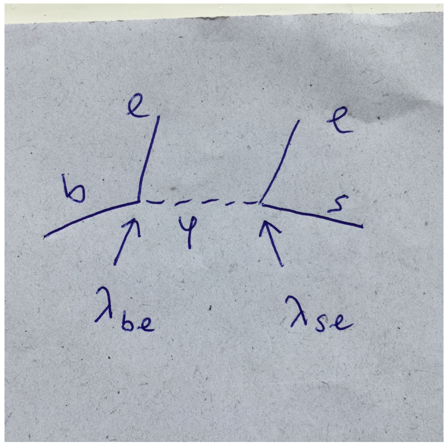
Pair production, e.g. recent works 1706.05033, 1710.06363 1801.07641

$\sigma(pp \to \varphi^+\varphi^-) \propto \alpha_s^2$



Single LQ production from b-anomalies 1801.09399 in association with a lepton $\sigma(pp \to \varphi\ell) \propto |\lambda_{q\ell}|^2\alpha_s$ depends on flavor





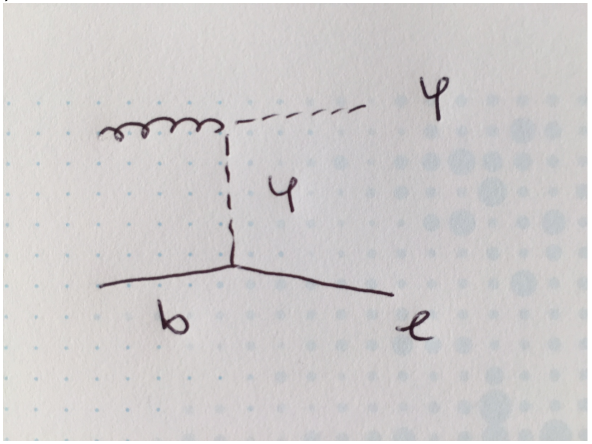
Links with b-physics and flavor

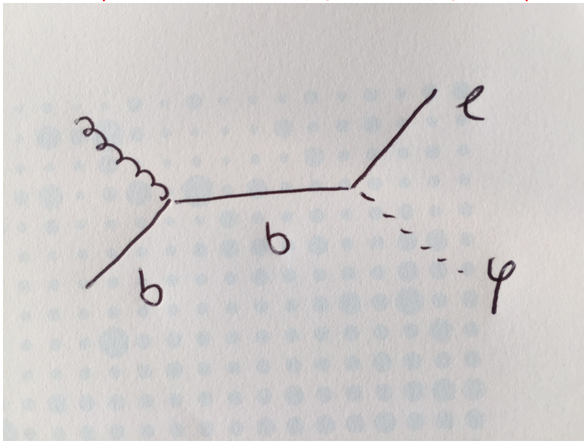
LHCb-data: $(\lambda_{b\mu}\lambda^*_{s\mu} - \lambda_{be}\lambda^*_{se})/M^2 \simeq 1/(35\,\text{TeV})^2$

$$R_K, R_{K^*} : \lambda_{ql} = \begin{pmatrix} * & * & * \\ * & \lambda_{q2\ell 2} & * \\ * & \lambda_{q3\ell 2} & * \end{pmatrix} \text{ or } \begin{pmatrix} * & * & * \\ \lambda_{q2\ell 1} & * & * \\ \lambda_{q3\ell 1} & * & * \end{pmatrix}, \begin{pmatrix} * & * & * \\ \lambda_{q2\ell 1} & \lambda_{q2\ell 2} & * \\ \lambda_{q3\ell 1} & \lambda_{q3\ell 2} & * \end{pmatrix}$$

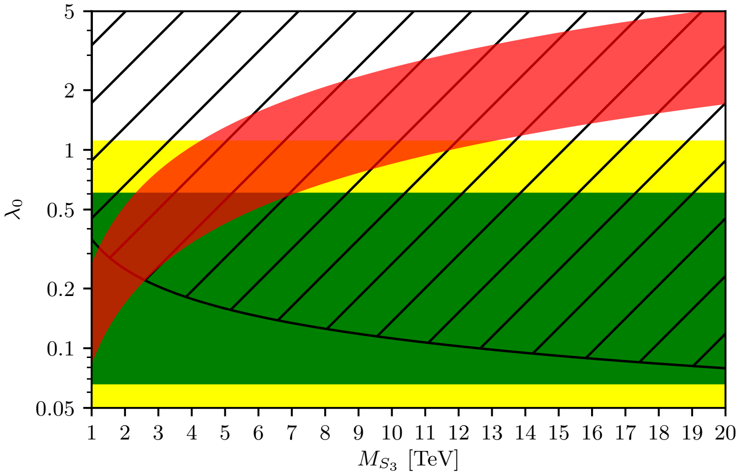
Hierarchies present in SM $m_b \gg m_s$, explain with symmetry, assume same mechanism for LQs:

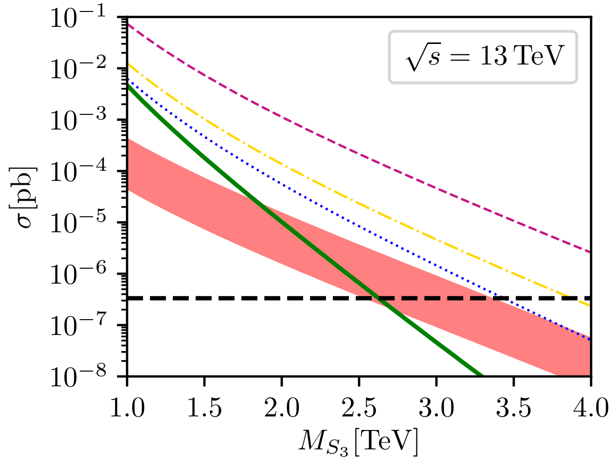
$\lambda_{s\ell i} \sim (m_s/m_b)\,\lambda_{b\ell i} \to$ third generation quarks dominant, $M/11.6\,\text{TeV} \lesssim \lambda_{b\ell} \lesssim M/3.9\,\text{TeV}$

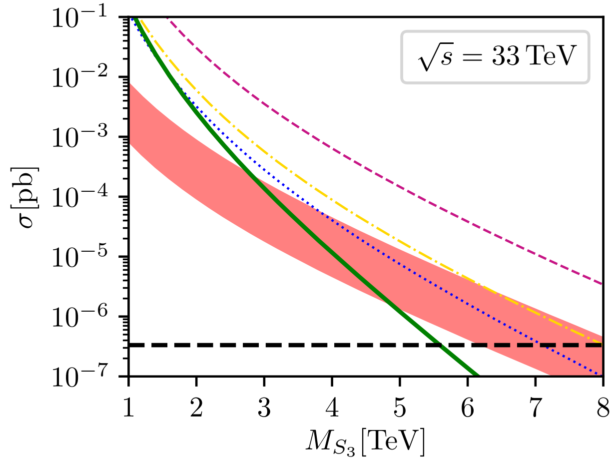




Producing LQs at the LHC







red: R_{K,K^*} with flavor $M/11.6$ TeV $\lesssim \lambda_{b\ell} \lesssim M/3.9$ TeV

left plot: green: flavor model prediciton points to multi-TeV mass; yellow: narrow width

other plots: magenta, yellow, blue: $\lambda_{d\mu} = 1, \lambda_{s\mu} = 1, \lambda_{b\mu} = 1$, black: no-loss reach with 3 ab^{-1}

green curve: pair production (LO Madgraph) 1801.09399

– Beauty wins over PDF if λ_{ql} follow quark mass hierarchies. Inverted hierarchies $\lambda_{sl} > \lambda_{bl}$ would be surprising from a symmetry-based flavor model perspective and suggests means beyond.

R_K, R_{K^*} anomaly points to $(V-A)\times(V-A)$ -type BSM:

$\lambda_{ql} = \begin{pmatrix} * & * & * \\ * & \lambda_{q2\ell 2} & * \\ * & \lambda_{q3\ell 2} & * \end{pmatrix}$ affects doublets: $\ell 2 = \mu, \nu_\mu$, $q2 = s, c$, $q3 = b, t$

S_3- dominant decay modes 1408.1627 [hep-ph]

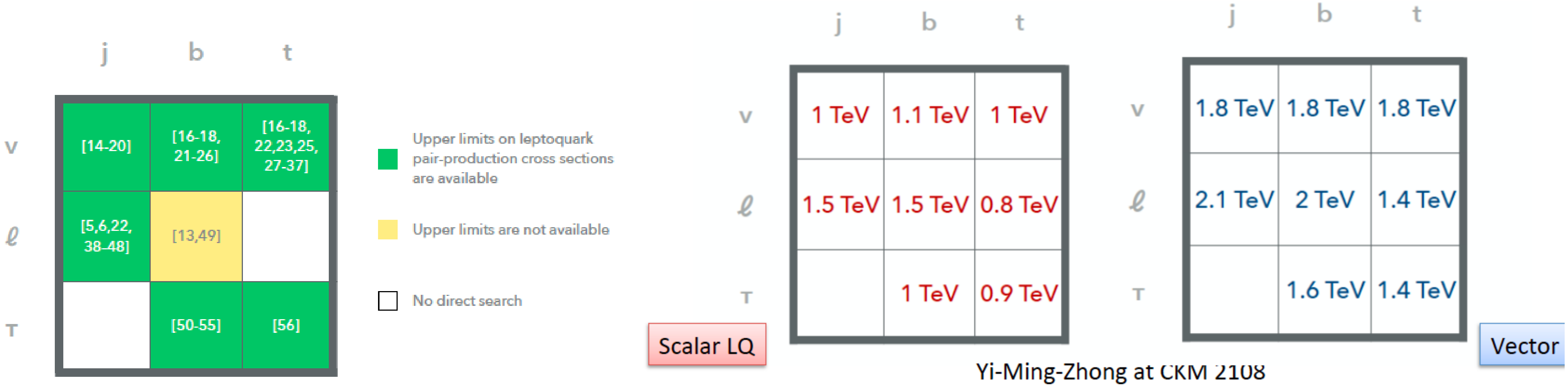
$$\begin{array}{lcl} S_3^{+2/3} & \to & t\,\nu \\ S_3^{-1/3} & \to & b\,\nu\ ,\ t\,\mu^- \qquad (SU(2)\text{-triplet}, scalar) \\ S_3^{-4/3} & \to & b\,\mu^- \end{array}$$

V_1- dominant decay modes

$$V_1^{+2/3} \;\to\; b\,\mu^+\ ,\ t\,\nu \qquad (SU(2)\text{-singlet}, vector)$$

tagging useful to identify LQ-type (electric charge), e.g.,
$V_1^{-2/3} \to \bar{b}\,\mu^-$ vs $S_3^{-4/3} \to b\,\mu^-$

Leptoquarks related to R_{K,K^*} can be in reach of direct searches at the LHC – but no guarantees 1710.06363, 1801.07641, 1801.09399



	j	b	t
ν	[14-20]	[16-18, 21-26]	[16-18, 22,23,25, 27-37]
ℓ	[5,6,22, 38-48]	[13,49]	
τ		[50-55]	[56]

Scalar LQ:

	j	b	t
ν	1 TeV	1.1 TeV	1 TeV
ℓ	1.5 TeV	1.5 TeV	0.8 TeV
τ		1 TeV	0.9 TeV

Vector:

	j	b	t
ν	1.8 TeV	1.8 TeV	1.8 TeV
ℓ	2.1 TeV	2 TeV	1.4 TeV
τ		1.6 TeV	1.4 TeV

Yi-Ming-Zhong at CKM 2108

matrix and lower limits from arXiv:1706.05033, Zhong, Schmaltz '18

From R_{K,K^*} perspective: $b\mu$ final states "vanilla", dopping a) the global $b \to s\mu\mu$ fit suggests also be, or b) flavor hierarchies: $j\mu$; additional modes $b\nu, t\mu, t\nu$ by $SU(2)$; more flavor: τ's $\to$ whole matrix

Summary

- Current anomalies in semileptonic B-decays hint at violation of lepton-universality – and therefore breakdown of standard model. The April 2017 release of R_{K^*} by LHCb has strengthened the hints and allowed to pin down the Dirac structure: predominantly $V-A$-type.

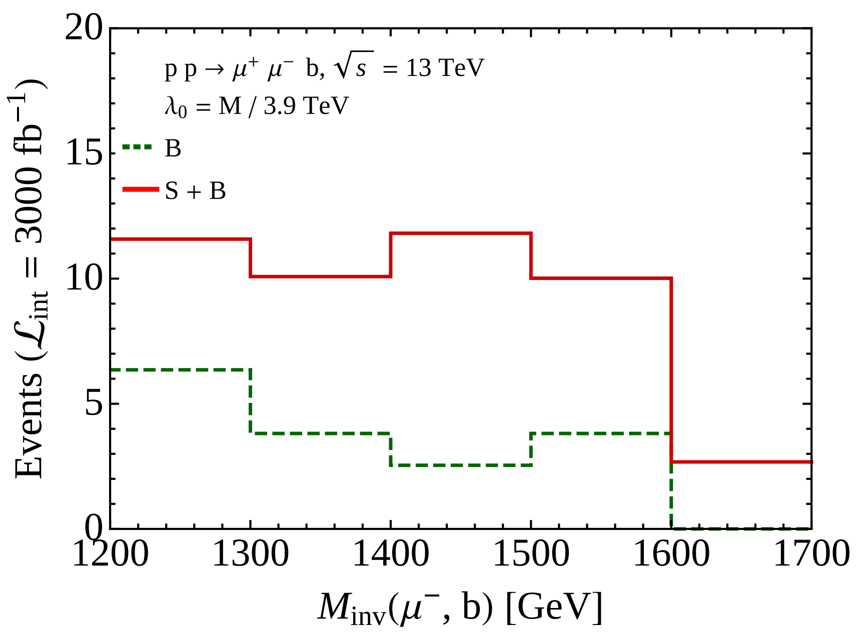
- Future data – LNU updates and other observables $R_\Phi, R_{X\,s}..., B \to K^* ee$ – from LHCb and in the nearer future from Belle II are eagerly awaited.

- No single measurement $> 5\sigma$ presently, but its intriguing that R_{K,K^*} and the $B \to K^{(*)}\mu\mu$ anomalies (”global fits”) go in the same direction!

- What makes these LNU-anomalies – iff true– so important? Because they are theoretically clean (enough) and intimately linked to ”flavor”: Look for imprints in other sectors: D, K physics, LFV.

- In addition, new BSM model-buildung has been triggered that deserves attention in direct searches at ATLAS and CMS and future colliders.
  Leptoquarks are flavorful and can be in reach of the LHC, where they can provide complementary information to rare decays: $\lambda_{s\ell}, \lambda_{b\ell}, M$ versus $\lambda_{b\ell}\lambda^*_{s\ell}/M^2 \simeq 1/(35\,\text{TeV})^2$
  Data-driven upper limit from B_s-mixing $\propto (\lambda_{b\ell}\lambda_{s\ell})^2/M^2$ at ~ 40 TeV.
  Bulk of parameter space outside of LHC.
  1710.06363, 1801.07641, 1801.09399

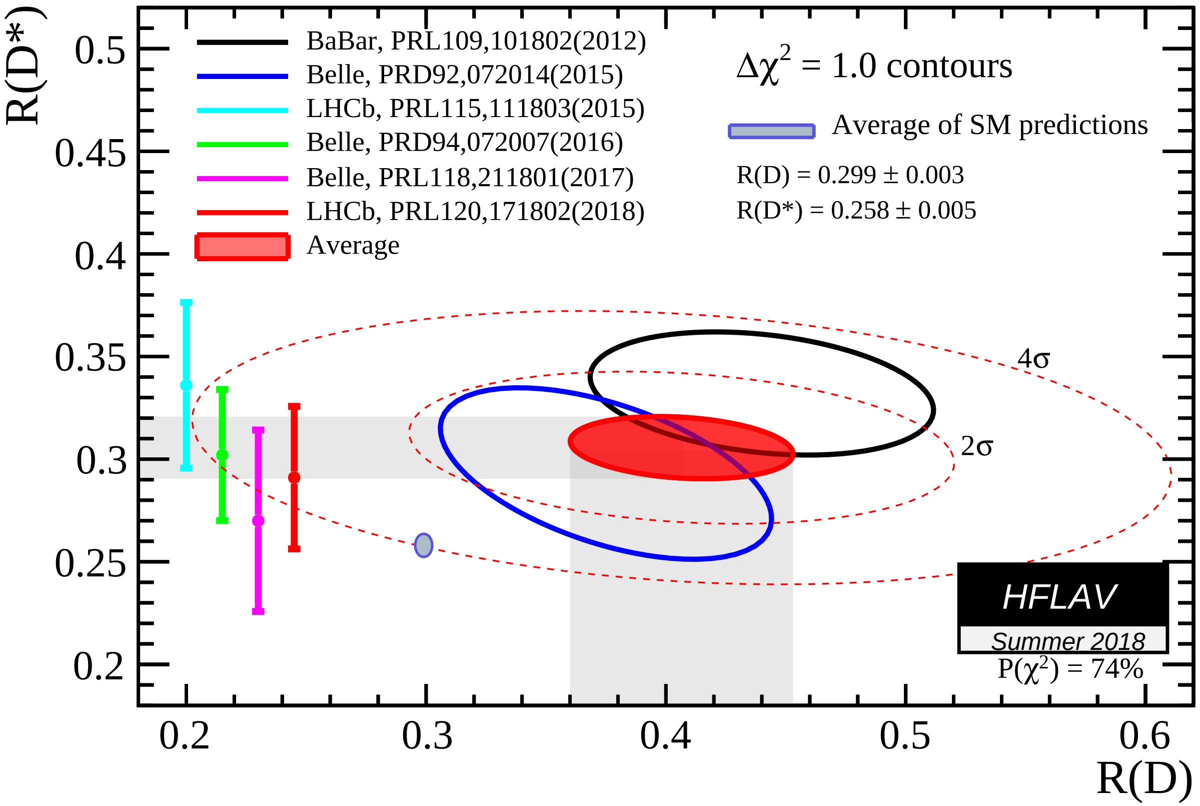
1801.09399, in PRD



$M = 1.5$ TeV; around 5 σ discovery significance for $3\,\text{ab}^{-1}$

Table 3: Experimental results and SM predictions for $R_D^{(*)}$, ' NEW' labels updates since 2016. *Error weighted average; †statistical and systematical uncertainties added in quadrature. from 1804.02011

	R_D	R_{D^*}
BaBar'12	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle'15	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
Belle '16	-	$0.302 \pm 0.030 \pm 0.011$
Belle '16	-	$0.270 \pm 0.035^{+0.028}_{-0.025}$
LHCb'15	-	$0.336 \pm 0.027 \pm 0.030$
LHCb '17 NEW	-	$0.286 \pm 0.019 \pm 0.025 \pm 0.021$
average NEW*†	0.406 ± 0.050	0.307 ± 0.015
HFLAV average NEW†	0.407 ± 0.046	0.306 ± 0.015
SM	0.300 ± 0.008 Na '15	0.252 ± 0.003 Fajfer '12
SM NEW	$(0.300 \pm 0.008)(1 + \%)$ deBoer '18	0.260 ± 0.008 Bigi '17
$\hat{R} = R^{exp}/R_{\rm SM}$ NEW*†	1.354 ± 0.170 (without QED)	1.180 ± 0.068
	1.33 ± 0.19 (with QED, inflated errors)	


R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, PRL120,171802(2018)
Average
Δχ^2 = 1.0 contours
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
4σ
2σ
HFLAV
Summer 2018
P(χ^2) = 74%

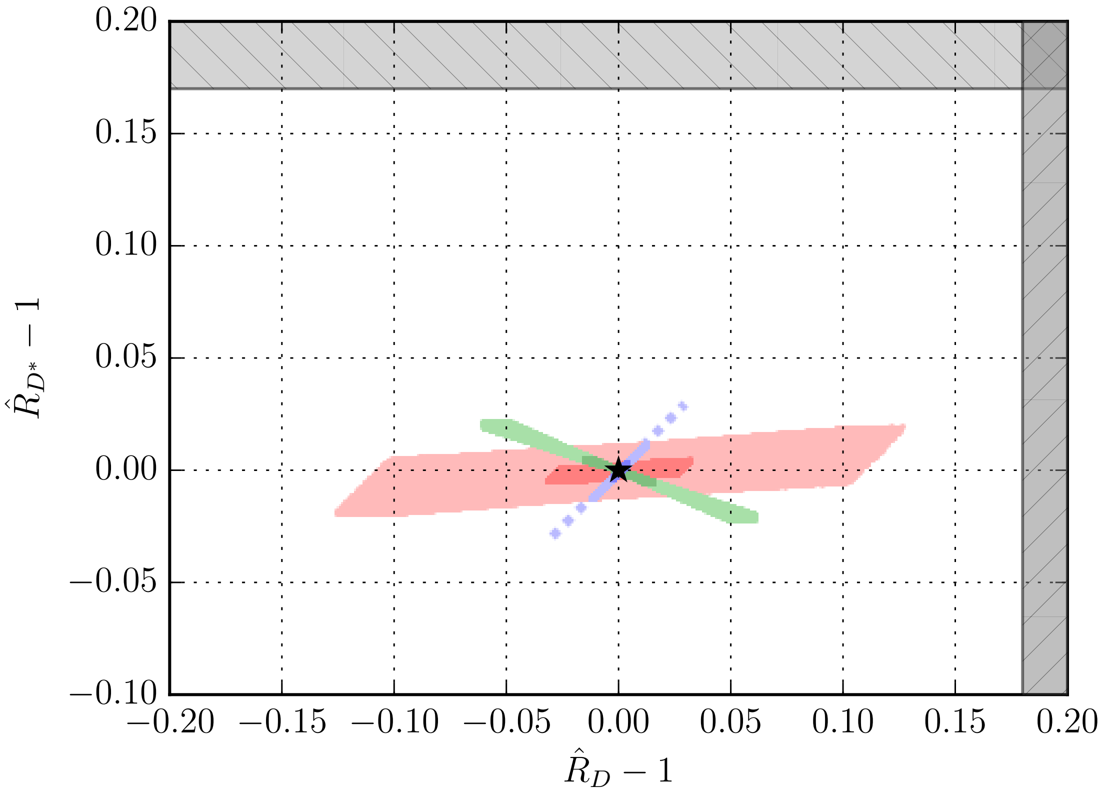
The expected mass scale depends on flavor.

The size of the effect – current hints for SM deviation – in $R_{K^{(*)}}$ is ”natural”, in the core of parameter space. How about $R_{D^{(*)}}$? Tree-level in SM, similar order of anomalous data as $R_{K^{(*)}}$ implies large couplings and very low BSM:

flavor	generic	minimal	PMNS/CKM
$R_{K^{(*)}}$ tree	30 TeV	6 TeV	few TeV
$R_{K^{(*)}}$ loop	few TeV	0.5 TeV	expected similar to $R_{D^{(*)}}$
$R_{D^{(*)}}$ tree	$\sim$ a TeV	0.3 TeV	not viable 1609.08895

Linking the anomalies is intriuging however not straightforward, lower deviation in $R_{D^{(*)}}$, in particular R_{D*} more ”natural”.

$R_{D^{(*)}}$ from leptoquarks with flavor?



$\hat{R}_{D^{(*)}} = R_{D^{(*)}}/R^{\text{SM}}_{D^{(*)}}$; star: SM, grey: exp 1σ band (too far away from SM to fit the plot); red:V_1, blue V_3, green S_2. LQs with flavor patterns, constraints: rare K decays, $\mu - e$ conversion, $B \to K\nu\nu$, perturbativity 1609.08895 — Ignoring the flavor model ones, only model V_1 can avoid exp constraints. All models S_3, V_1, V_3 can explain $R_{K^{(*)}}$.

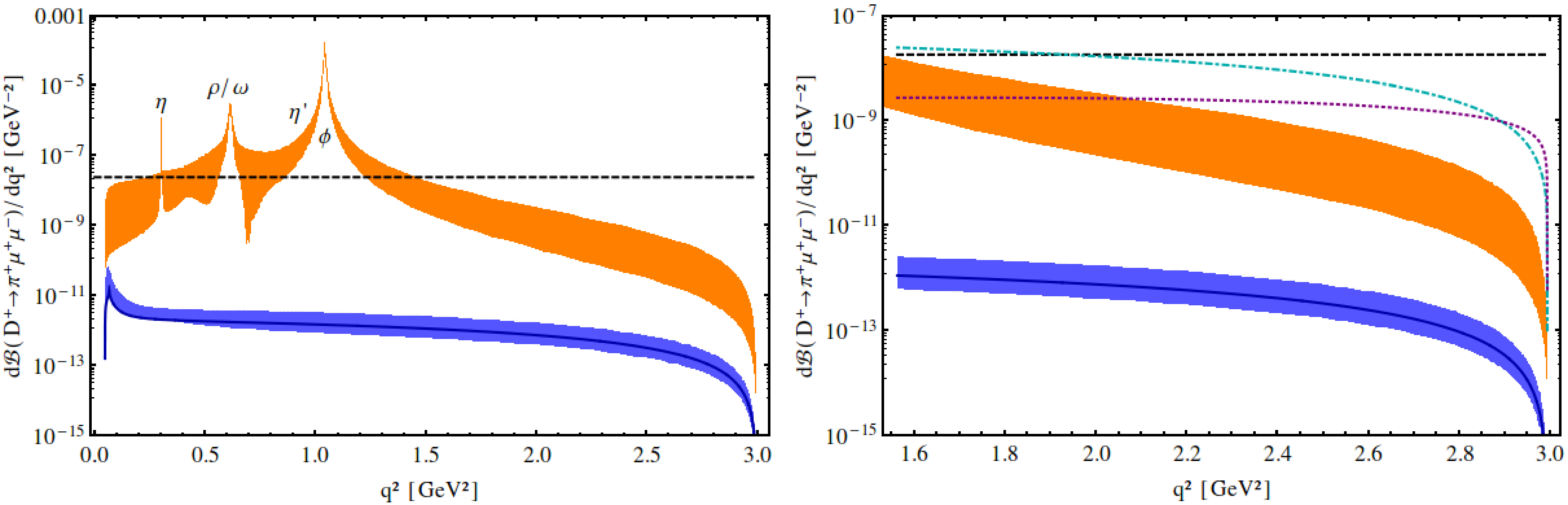
$R_{K^{(*)}}$

- triggered new type of BSM model-building: Z', leptoquarks
- its plausible (OK order of magnitude)
- its an opportunity (highly informative clash with SM)
- how to consolidate? rule out?
- if this really stays, decipher

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

see also Fajfer,Kosnik

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.)

$$\mathcal{B} = |A_{\rm SM}|^2 + 2Re(A_{\rm SM}A^*_{\rm NP}) + |A_{\rm NP}|^2$$

- Close to maximal BSM-CP violation switches off SM-BSM interference. Together with $R_X < 1$ this requires large NP couplings to electrons (muons would enhance R_X)

  Look for CP violation in $b \to see$, such as in the angular distribution in $B \to K^*ee$. (e.g. $J_{7,8,9}$) 1411.4773

- Explanation of R_K possible at 2σ with pseudo/scalar operators: cross check with $B \to Kee$ angular distribution 0709.4174, 1408.1627

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

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