Connections between $R(K)$, $R(K^*)$ and $\mu \to e$ processes

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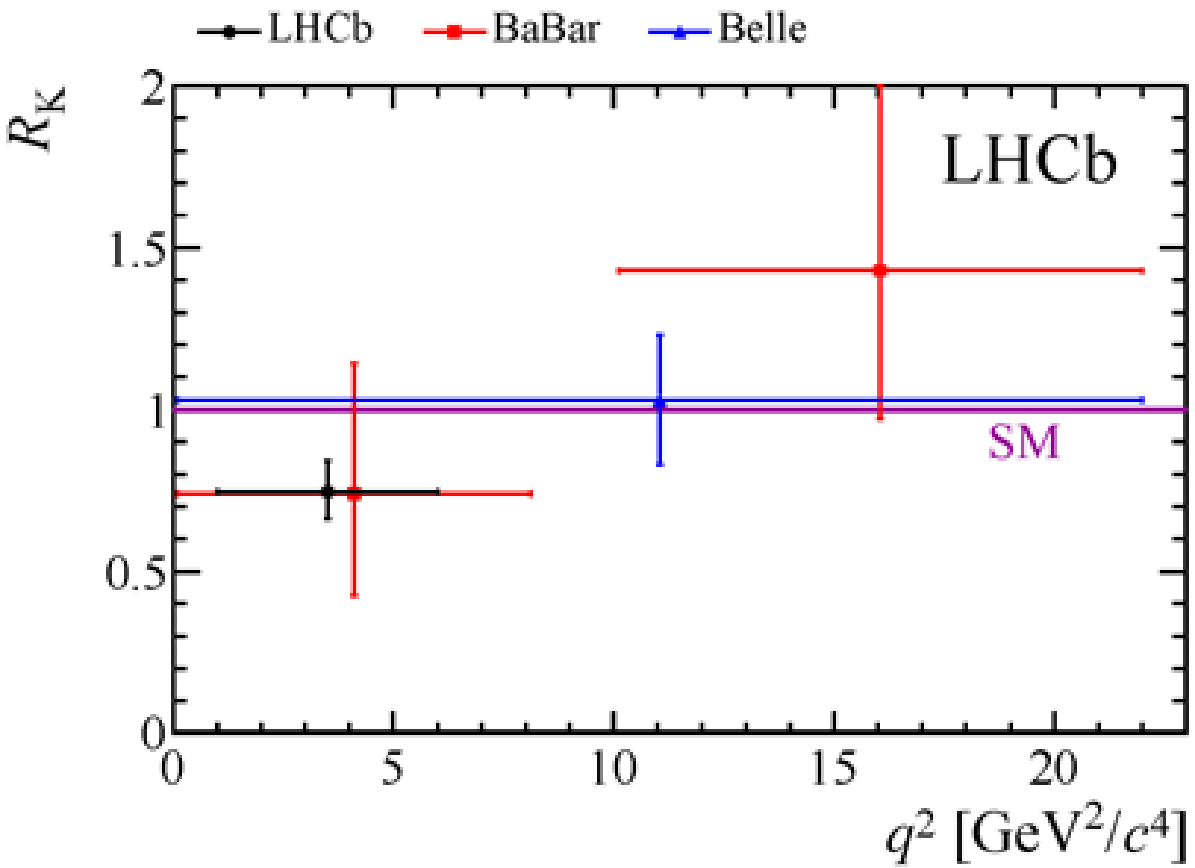
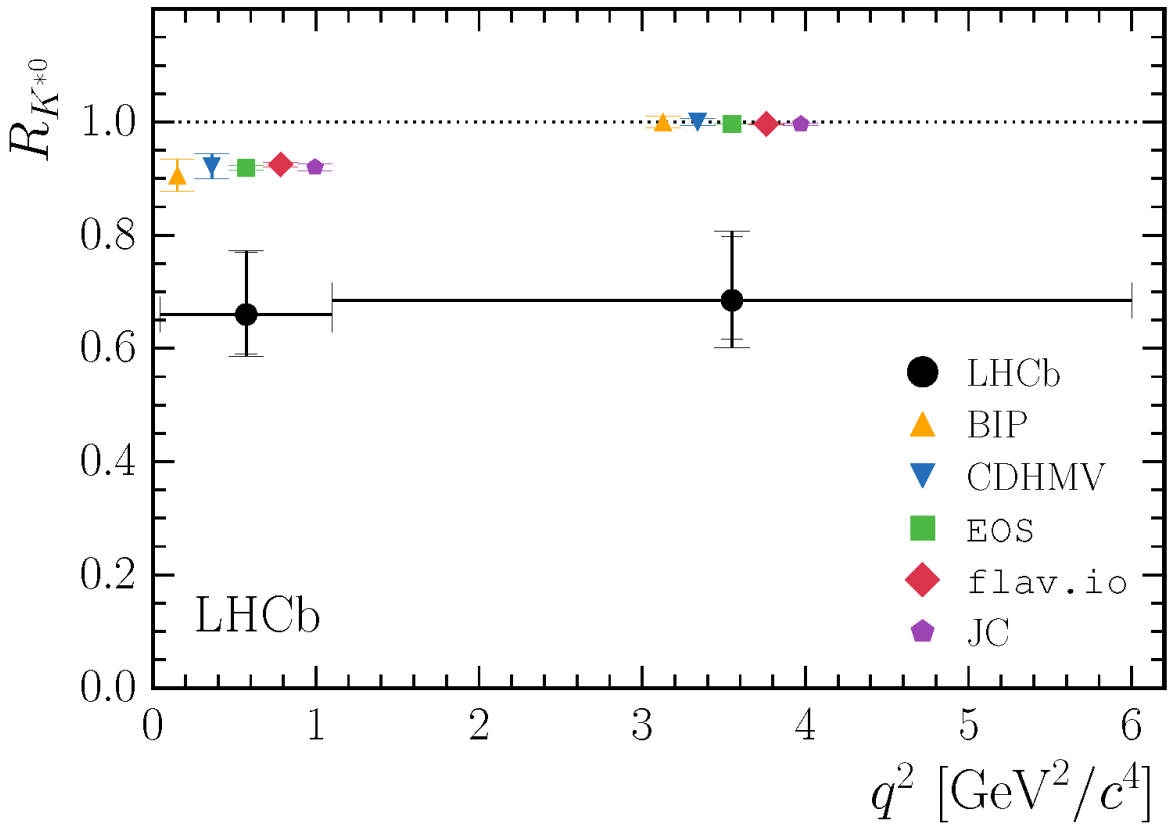
Clues...

$$R_K \equiv \mathcal{B}(B \to K\mu\mu) / \mathcal{B}(B \to Kee)$$



More clues...

$$R_{K^*} \equiv \mathcal{B}(B \to K^* \mu\mu) / \mathcal{B}(B \to K^* ee)$$



Interesting $> 2\sigma$ hints

$$R_K^{\text{LHCb}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036 \tag{1}$$

$$1\,\text{GeV}^2 \leq q^2 < 6\,\text{GeV}^2$$

2.6 σ from universality (SM)
Ratio cancels out theoretical uncertainties

If verified, BSM in quark FCNC linked with lepton sector

New physics BSM interpretation

Hiller, Schmaltz (PRD)
http://arxiv.org/abs/1408.1627
Model independent analysis: constrains Wilson coeffs.
Can be realized by Leptoquark models

Update post R_{K^*} from LHCb...
Hiller, Nisandzic
https://arxiv.org/abs/1704.05444

Many other possibilities:
Z' boson, compositeness, SUSY RPV...

Based on

IdMV, Hiller (JHEP) http://arxiv.org/abs/1503.01084

New physics and flavour

In SM, flavour only in Yukawa couplings:

$$\mathcal{L}_H = -Y_u H(Qu_R) - Y_d H(Qd_R) - Y_e H(Le_R) + h.c. \quad (2)$$

Probe only masses and CKM: $Y_u Y_u^\dagger$ and $Y_d Y_d^\dagger$
(u_R, d_R are $SU(2)$ singlets)

New physics can help us learn about flavour
Leptoquarks are great examples of this:

$$\mathcal{L}_\Delta = -\lambda \Delta(QL) + h.c. \quad (3)$$

Different processes probe columns and rows of λ matrix

LL and RL (scalar) leptoquarks

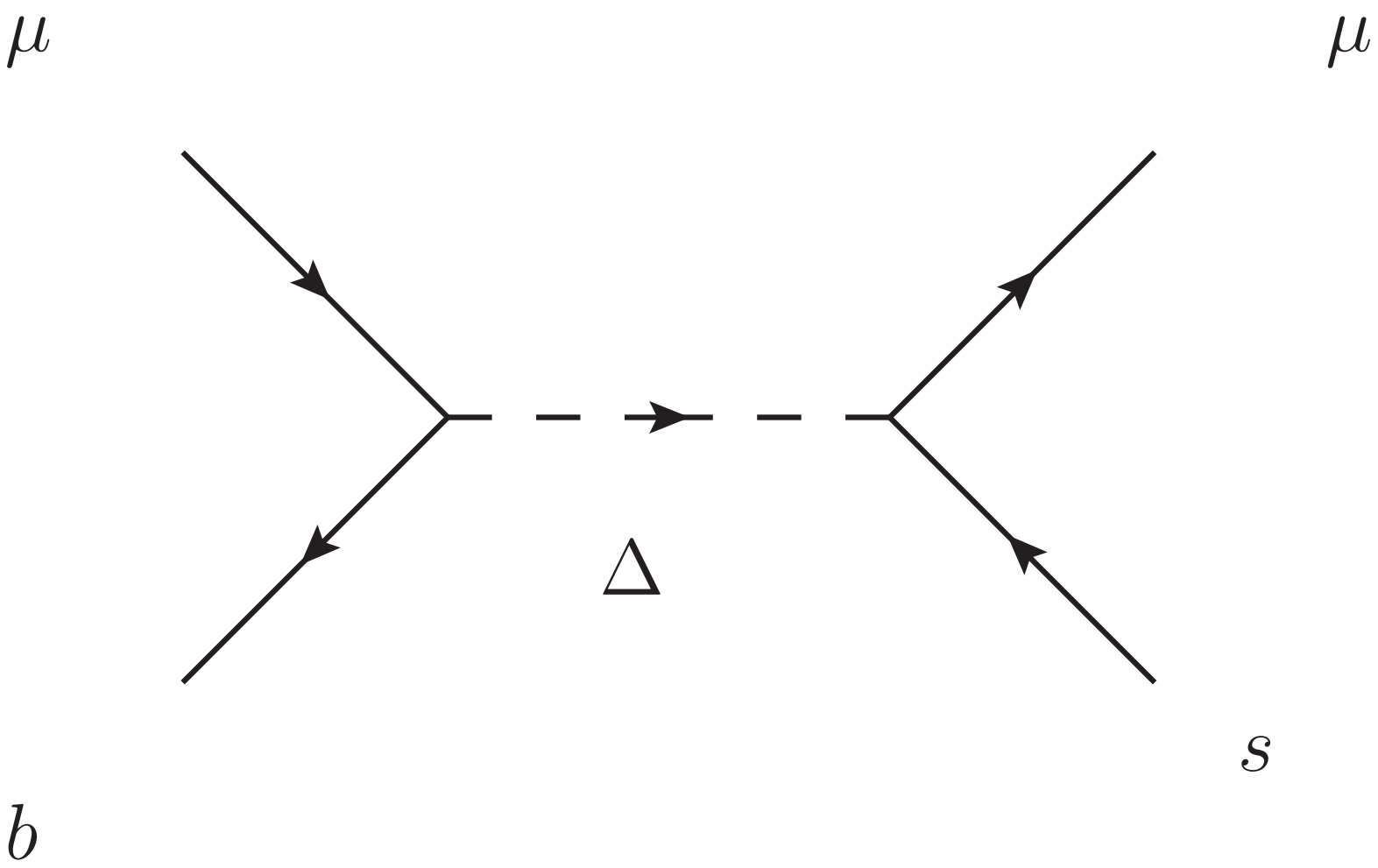
We considered $SU(2)$ triplet leptoquark $\Delta \sim (3, 3)$:

$$\mathcal{L}_{LL} = -\lambda \Delta (QL) + h.c. \tag{4}$$

Or $SU(2)$ doublet leptoquark $\Delta \sim (3, 2)$:

$$\mathcal{L}_{RL} = -\lambda \Delta \left(d_R L\right) + h.c. \tag{5}$$

Leptoquark diagram



λ and R_K

$$\lambda \equiv \begin{pmatrix} \lambda_{de} & \lambda_{d\mu} & \lambda_{d\tau} \\ \lambda_{se} & \lambda_{s\mu} & \lambda_{s\tau} \\ \lambda_{be} & \lambda_{b\mu} & \lambda_{b\tau} \end{pmatrix} \tag{6}$$

R_K probes e, μ columns, s, b rows:

$$0.7 \lesssim \mathrm{Re}[\lambda_{se}\lambda^*_{be} - \lambda_{s\mu}\lambda^*_{b\mu}] \frac{(24\mathrm{TeV})^2}{M^2} \lesssim 1.5 \tag{7}$$

λ and other constraints

Conservative with direct collider detection:
$M > 1$ TeV

B_s mixing from box diagram probes different combination:

$$(\lambda_{se}\lambda^*_{be} + \lambda_{s\mu}\lambda^*_{b\mu} + \lambda_{s\tau}\lambda^*_{b\tau})^2 \lesssim \frac{M^2}{(12\,\text{TeV})^2} \tag{8}$$

$R_K \sim \lambda^2/M^2$ vs. $\sim \lambda^4/M^2$
Combined: $M < \mathcal{O}(50)$ TeV, in reach of future colliders

I am being optimistic for the future of Particle Physics...

Selected flavour data

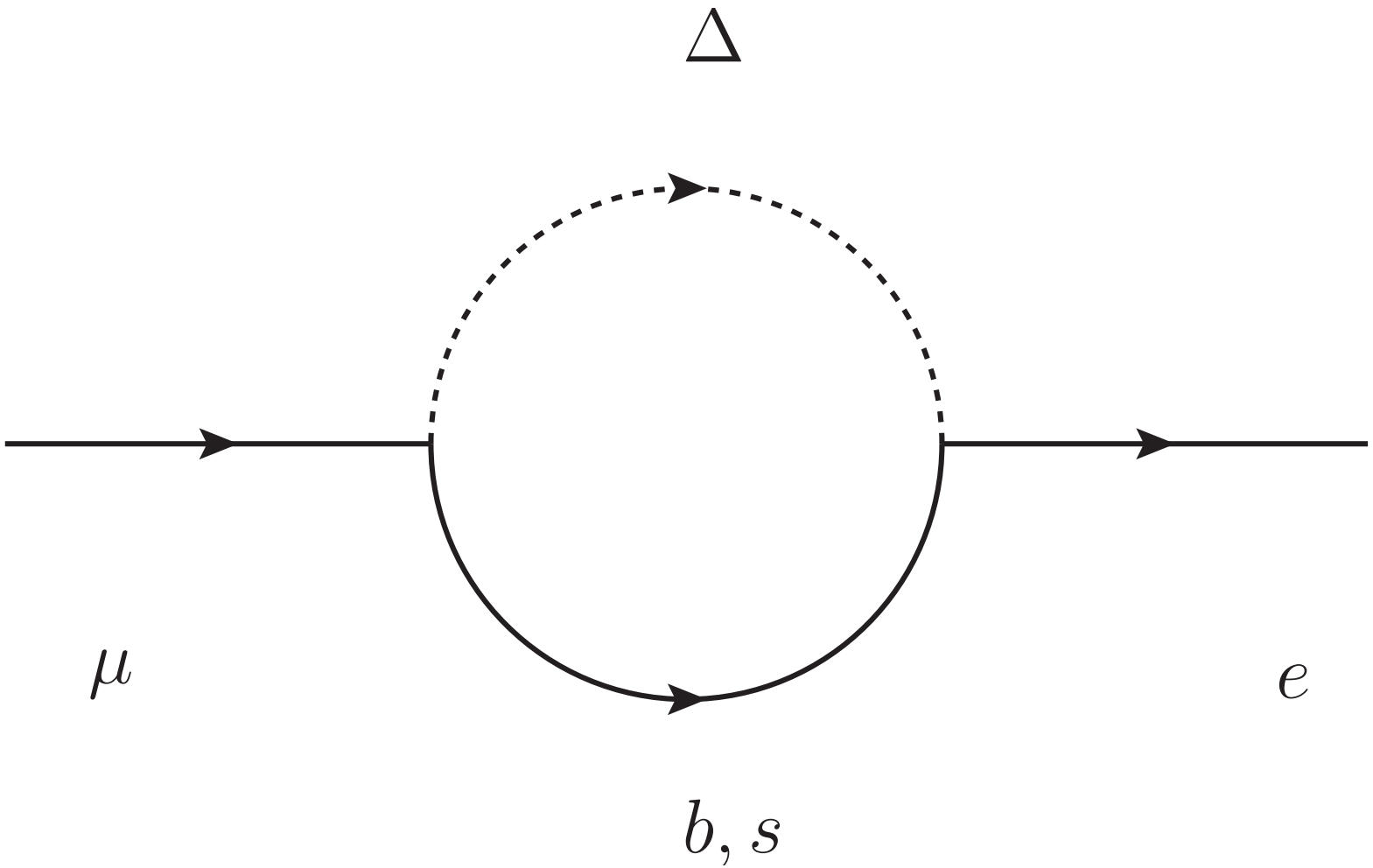
observable	current 90 % CL limit	constraint	future sensitivity
$\mathcal{B}(\mu \to e\gamma)$	$5.7 \cdot 10^{-13}$ [22]	$\lvert\lambda_{qe}\lambda^*_{q\mu}\rvert \lesssim \frac{M^2}{(34\,\mathrm{TeV})^2}$	$6 \cdot 10^{-14}$ [23]
$\mathcal{B}(\tau \to e\gamma)$	$1.2 \cdot 10^{-7}$ [24]	$\lvert\lambda_{qe}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(0.6\,\mathrm{TeV})^2}$	
$\mathcal{B}(\tau \to \mu\gamma)$	$4.4 \cdot 10^{-8}$ [25]	$\lvert\lambda_{q\mu}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(0.7\,\mathrm{TeV})^2}$	$5 \cdot 10^{-9}$ [26]
$\mathcal{B}(\tau \to \mu\eta)$	$6.5 \cdot 10^{-8}$ [27]	$\lvert\lambda_{s\mu}\lambda^*_{s\tau}\rvert \lesssim \frac{M^2}{(3.7\,\mathrm{TeV})^2}$	$2 \cdot 10^{-9}$ [26]
$\mathcal{B}(B \to K\mu^\pm e^\mp)$	$3.8 \cdot 10^{-8}$ [28]	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(19.4\,\mathrm{TeV})^2}$	
$\mathcal{B}(B \to K\tau^\pm e^\mp)$	$3.0 \cdot 10^{-5}$ [14]	$\sqrt{\lvert\lambda_{s\tau}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\tau}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(3.3\,\mathrm{TeV})^2}$	
$\mathcal{B}(B \to K\mu^\pm \tau^\mp)$	$4.8 \cdot 10^{-5}$ [14]	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{b\tau}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{s\tau}\rvert^2} \lesssim \frac{M^2}{(2.9\,\mathrm{TeV})^2}$	
$\mathcal{B}(B \to \pi\mu^\pm e^\mp)$	$9.2 \cdot 10^{-8}$ [29]	$\sqrt{\lvert\lambda_{d\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{de}\rvert^2} \lesssim \frac{M^2}{(15.6\,\mathrm{TeV})^2}$	

COMET, MEG, Mu2e, Mu3e

Future LFV sensitivity probes the Leptoquark parameter space

COMET and Mu2e to 10^{-16} sensitivity

$\mu \to e$ diagram



Data-Driven

I didn't even do the caption myself:
http://www.setheliot.com/blog/wp-content/uploads/2015/02/image2.png

Simplest data-driven patterns

R_K probes e, μ columns:

$$0.7 \lesssim \mathrm{Re}[\lambda_{se}\lambda^*_{be} - \lambda_{s\mu}\lambda^*_{b\mu}]\frac{(24\mathrm{TeV})^2}{M^2} \lesssim 1.5 \qquad (9)$$

Lepton flavour isolation patterns:

$$\lambda^{[e]} \equiv \begin{pmatrix} \lambda_{de} & 0 & 0 \\ \lambda_{se} & 0 & 0 \\ \lambda_{be} & 0 & 0 \end{pmatrix}, \quad \lambda^{[\mu]} \equiv \begin{pmatrix} 0 & \lambda_{d\mu} & 0 \\ 0 & \lambda_{s\mu} & 0 \\ 0 & \lambda_{b\mu} & 0 \end{pmatrix} \qquad (10)$$

Hierarchical data-driven pattern

Given that fermion-Higgs Yukawa are hierarchical natural to expect a hierarchical λ pattern:

$$\lambda^{[\rho\kappa]} \sim \lambda_0 \begin{pmatrix} \rho_d\kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix} \tag{11}$$

LFV arises naturally

Driving $\lambda^{[\rho\kappa]}$ with data

$$\lambda^{[\rho\kappa]} \sim \lambda_0 \begin{pmatrix} \rho_d\kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix} \tag{12}$$

current flavour data implies:

$$\rho_d \lesssim 0.02\,, \quad \kappa \lesssim 0.5\,, \quad 10^{-4} \lesssim \rho \lesssim 1\,, \tag{13}$$

$$\rho_d/\rho \lesssim 1.6\,, \quad \kappa/\rho \lesssim 0.5 \tag{14}$$

κ from $\mu \to e\gamma$, ρ_d from rare K decays
$\rho_d\kappa$ from $\mu \to e$ conversion in near future

Correlating b-decays and LFV

$$\mathcal{B}(B \to K \mu^{\pm} e^{\mp}) \simeq 3 \cdot 10^{-8}\, \kappa^2 \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{15}$$

$$\mathcal{B}(\mu \to e\gamma) \simeq 2 \cdot 10^{-12}\, \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 \ldots \tag{16}$$

Masses and mixing from family symmetries

Family symmetries explain fermion masses and mixing

Take subgroup of $U(3)^n$ (accidental in SM)
Charge SM fermions under it e.g.
$L_e, L_\mu, L_\tau \to L_i \sim 3$ of $SU(3)_F$
Then familon $\phi \sim \bar{3}$ gets VEV $\langle\phi\rangle$ breaking $SU(3)_F$

$$\mathcal{L}_H = -H(\phi^i L_i)(\phi^j e_{R_j}) + h.c. \tag{17}$$

$$Y^{ij} \sim \langle\phi^i\rangle\langle\phi^j\rangle$$

Linking flavour structures of Higgs and Leptoquark

$Y \sim Y(\langle\phi\rangle)$ implies $\lambda \sim \lambda(\langle\phi\rangle)$
Family symmetries that explain Y patterns lead to
theory-driven λ patterns
that link Higgs and Leptoquarks

Several theory-driven patterns match the data-driven patterns

A_4 example

Based on (non-zero θ_{13}):
IdMV, Pidt (JHEP) `http://arxiv.org/abs/1211.5370`

Familon with VEV $\langle \phi \rangle = (u, 0, 0)$
Coupling as $\Delta Q(\phi^j L_j)$ (quarks trivial under A_4)

$$\lambda^{[\mu]} \equiv \begin{pmatrix} 0 & \lambda_{d\mu} & 0 \\ 0 & \lambda_{s\mu} & 0 \\ 0 & \lambda_{b\mu} & 0 \end{pmatrix} \tag{18}$$

Leptoquark lepton flavour isolation
$\lambda^{[e]}$ also a natural theory-driven matching data-driven pattern.
Lepton flavour isolation means no $\mu \to e$

A_4 examples with $\mu \to e$

$\kappa'' \equiv \langle \xi'' \rangle / \Lambda \sim 0.2$ controls NLO and NNLO:

$$\lambda^{[1'']} \sim \lambda_0 \begin{pmatrix} \rho_d & \kappa'' \rho_d & \kappa''^2 \rho_d \\ \rho & \kappa'' \rho & \kappa''^2 \rho \\ 1 & \kappa'' & \kappa''^2 \end{pmatrix}, \quad \lambda^{[1']} \sim \lambda_0 \begin{pmatrix} \kappa''^2 \rho_d & \rho_d & \kappa'' \rho_d \\ \kappa''^2 \rho & \rho & \kappa'' \rho \\ \kappa''^2 & 1 & \kappa'' \end{pmatrix}. \tag{19}$$

Prediction for $\mu \to e$ is related with representations under A_4 and with smallness of the leptonic reactor mixing angle (θ_{13})

E.g. $\mathcal{B}(\mu \to e\gamma) \simeq 2 \cdot 10^{-12} \, \frac{(0.2)^4}{\rho^2}$

Summary

Clues for Flavor from rare lepton and quark decays

- Clues from rare decays may be first glimpse of BSM
- Leptoquarks are appealing new physics scenario
- Assuming R_K, obtain for λ data-driven patterns
- Patterns that are matched by (FS) theory-driven patterns, with correlations to processes such as $\mu \to e$