Flavour anomalies

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Outline

Motivation

Flavour anomalies

Implications: NP scales and models

Outlook

What we know

(Ordered by elegance)

spin 1

electromagnetism U(1)

weak interactions SU(2)

strong interactions SU(3)

spin 1/2

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R d_R	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	c_R s_R	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	t_R b_R	$Q = +2/3$ $Q = -1/3$
$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$-$ e_R	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$-$ μ_R	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$-$ τ_R	$Q = 0$ $Q = -1$

spin 0

Higgs - sets mass scale of entire Standard Model

But: naturalness? Dark matter? Point to TeV BSM physics

Why BSM with flavour?

The garbage of the past often becomes the treasure of the present (and vice versa).
-- A Polyakov

Fermi's original description of beta decay (1934)

$$H_W = -G_F\,(\bar{p}\gamma^\mu n)\,(\bar{e}\gamma_\mu \nu)$$

In modern terminology, a nonrenormalizable, dimension-6 operator.

After several further discoveries and insights, including

- parity violation — Lee, Yang 1956, Wu et al, Goldhaber et al 1957
- V-A structure of weak interactions — Feynman, Gell-Mann 1957, Shudarshan, Marshak 1957
- universality of weak decays — Gell-Mann, Levy 1960
- electroweak symmetry breaking — BEHGHK, Glashow, Salam, Weinberg
- charm to explain $K_L \to \mu\mu$ suppression — Glashow, Iliopoulos, Maiani 1970
- third generation to explain CPV — Kobayashi, Maskawa 1972 (Christenson et al 1964)

the SM was complete. Charm, W, Z, H & the third generation discovered in due course.

$$\sqrt{2}\, G_F = 1/v^2 = g^2/4M_W^2$$

Flavour anomalies

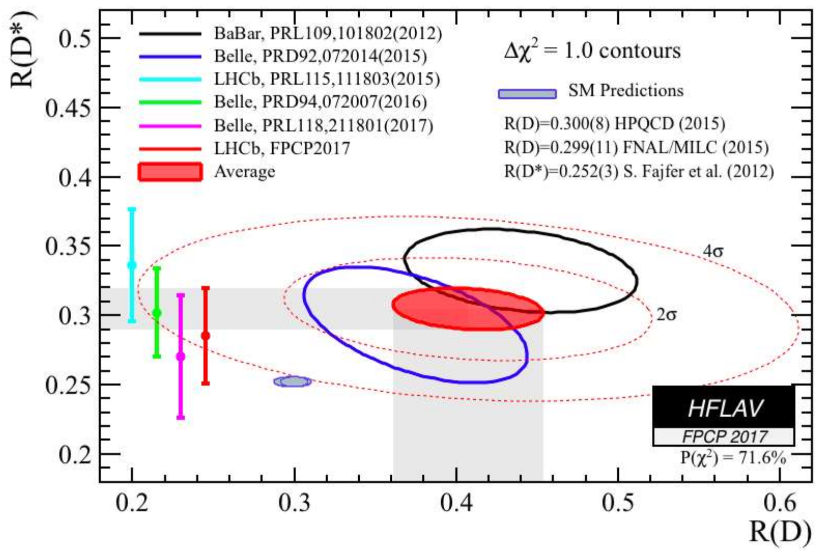
The naive SM cutoff is many orders of magnitude above the weak scale. However, NP may appear before then.

Apart from long-standing theoretical arguments (naturalness) and circumstantial evidence (coupling, matter unification) there is a number of experimental indications for BSM physics which would have to be near the weak scale.

These occur mostly in quark flavour physics.

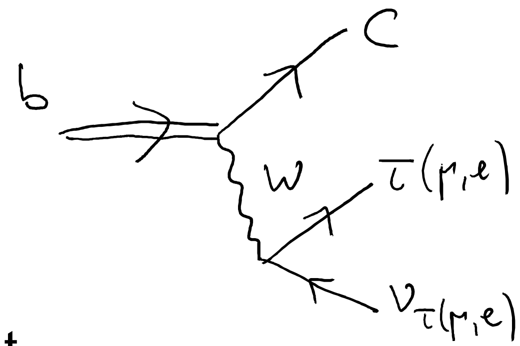
Anomaly I: (non-rare) semileptonic decays

For some time B-factories and LHCb have consistently shown semileptonic B ->D (D*) τν decay rates larger than expected



$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\ell\nu_\ell)}$$

4.1 sigma effect
SM **tree-level** effect



Theory error negligible relative to experiment

Can be interpreted as BSM effect

Avoiding excessive contributions to Bc decay and measured differential decay distribution favour a purely left-handed coupling

$$(\bar{c}_L \gamma^\mu b_L)\,(\bar{\nu}_\tau \gamma_\mu \tau_L)$$

Eg Ligeti et al 2015,16, Grinstein et al 2016, …

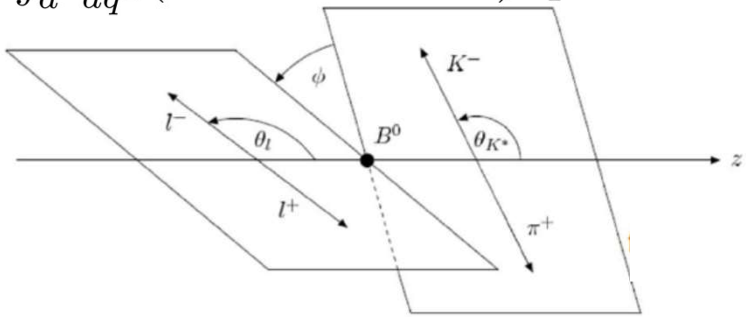
Rare semileptonic B decays

many new results from LHCb, ATLAS, CMS, Belle. Some anomalies

Branching ratios (differential in dilepton mass): $B \to K^{(*)}\mu\mu$, $B \to K^{(*)}ee$, $B_s \to \phi\mu\mu$

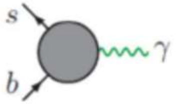
Lepton universality ratios

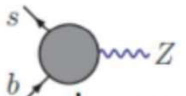
$$R_{K^{(*)}}[a,b] = \frac{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}\mu^+\mu^-)dq^2}{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}e^+e^-)dq^2}$$



differential angular distribution for
B->Vll : 3 angles, dilepton mass q^2
-> angular differential observables P_i

Sensitive to effective couplings





+boxes

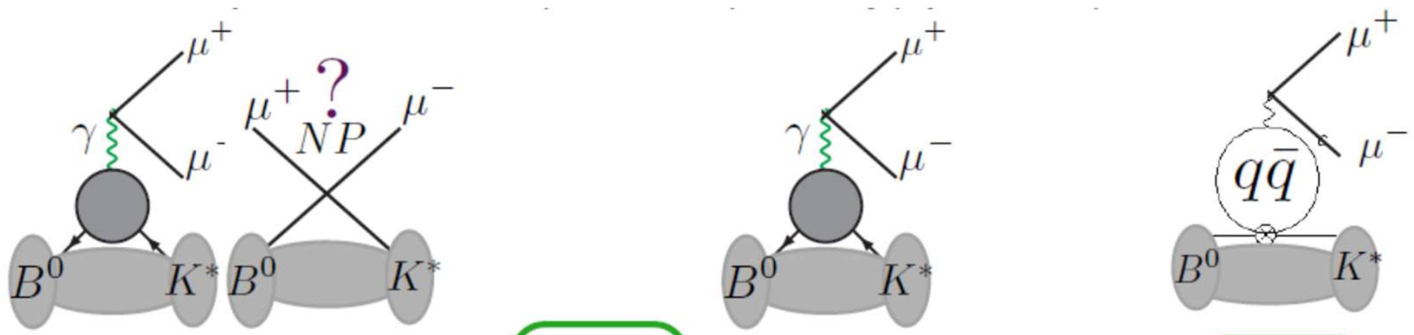
$(\bar{s}\sigma^{\mu\nu}P_R b)F_{\mu\nu}$	C_7	(BSM constrained by inclusive)
$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$	C_9	+ BSM?
$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu\gamma^5 l)$	C_{10}	+ BSM?

alternative chiral basis: $2\,C_L\,(\bar{s}_L\gamma_\mu b_L)\,(\bar{\mu}_L\gamma^\mu\mu_L)\,,\quad 2\,C_R\,(\bar{s}_L\gamma_\mu b_L)\,(\bar{\mu}_R\gamma^\mu\mu_R)$

in SM: $C_L \sim 4$, $C_R \sim 0$ (at $\mu=m_b$): accidental pure V-A x V-A structure

Rare decays: amplitude anatomy

C_9 enters through the vector helicity amplitudes (lepton vector current)



$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2)C_9 - V_{-\lambda}(q^2)C_9' + \boxed{\frac{2\,m_b m_B}{q^2}}\left(\tilde{T}_\lambda(q^2)C_7 - \tilde{T}_{-\lambda}(q^2)C_7'\right) - \boxed{\frac{16\,\pi^2 m_B^2}{q^2}}h_\lambda(q^2)$$

photon pole at $q^2=0$

Main problem: shifts of C_9 are degenerate with form factor uncertainties and virtual-charm effects

less of an issue for C_{10} (leptonic axial current)

Both constrained by heavy-quark limit; power corrections?

SJ, Martin Camalich 2012, 2014

To see a BSM effect O(25%) need accuracy on any relevant form factors or form factor ratios (dep. on observable) better than that.

FF primarily obtained from light-cone sum rules

Ball&Braun; Ball& Zwicky; Bharucha,Straub,Zwicky 2015

Anomaly II: low branching ratios (eg B->K l l)

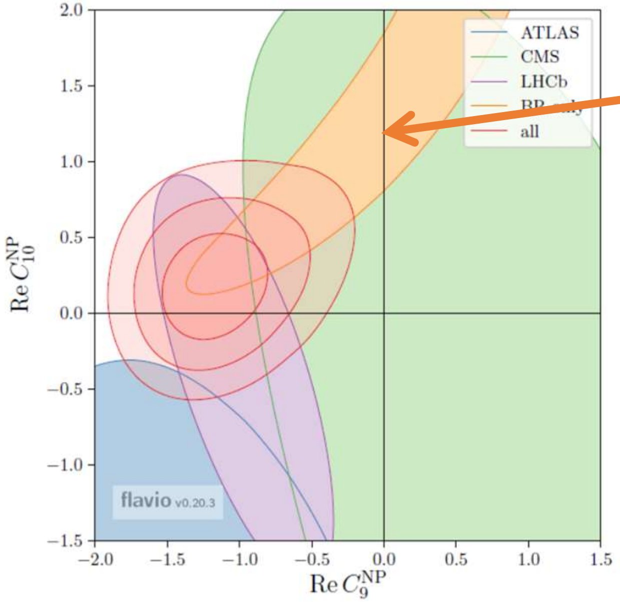
Schematically (neglecting some normalisations and small imaginary parts),

$$H_V = C_7 T + C_9 V + h \qquad\qquad H_A = C_{10} V$$

$$BR \propto (|H_V|^2 + |H_A|^2) = \frac{1}{2}(C_7 T + h_0 + 2 C_R V)^2 + \frac{1}{2}(C_7 T + h_0 + 2 C_L V)^2$$

C_7, h_0, and C_R are small in the SM, hence BR essentially is determined by the product $C_L \cdot V$. Weak sensitivity to C_R (as long as small) or C_7.

Altmannshofer et al 2017



Explains the shape of the BR band:
part of a circle around (-4, +4) (centre far outside plot region) (where $C_L^{SM} + C_L^{NP} = 0$)

Suggests 20-25% suppression of C_L w.r.t SM

But perfectly degenerate with form factor V !
To interpret this as evidence of BSM physics need precision on V much better than 25%.
Form factor estimates from light-cone sum rules

Angular observables

Numerous independent observables. Each a distribution in dilepton mass.

$$I_2^c = -F\,\frac{\beta^2}{2}\left(|H_V^0|^2 + |H_A^0|^2\right),$$

$$I_2^s = F\,\frac{\beta^2}{8}\left(|H_V^+|^2 + |H_V^-|^2\right) + (V \to A)$$

"longitudinal" rate (sim. to scalar BR)

"transverse" rate

Usually reported as BR and FL

$$I_6^s = F\beta\,\mathrm{Re}\left[H_V^-(H_A^-)^* - H_V^+(H_A^+)^*\right]$$

Lepton forward-backward rate asymmetry

Usually reported as AFB or P2

$$I_4 = F\,\frac{\beta^2}{4}\mathrm{Re}\left[\left(H_V^- + H_V^+\right)\left(H_V^0\right)^*\right] + (V \to A).$$

$$I_5 = F\left\{\frac{\beta}{2}\mathrm{Re}\left[\left(H_V^- - H_V^+\right)\left(H_A^0\right)^*\right] + (V \leftrightarrow A)\right.$$

Often discuss P4' and P5' instead

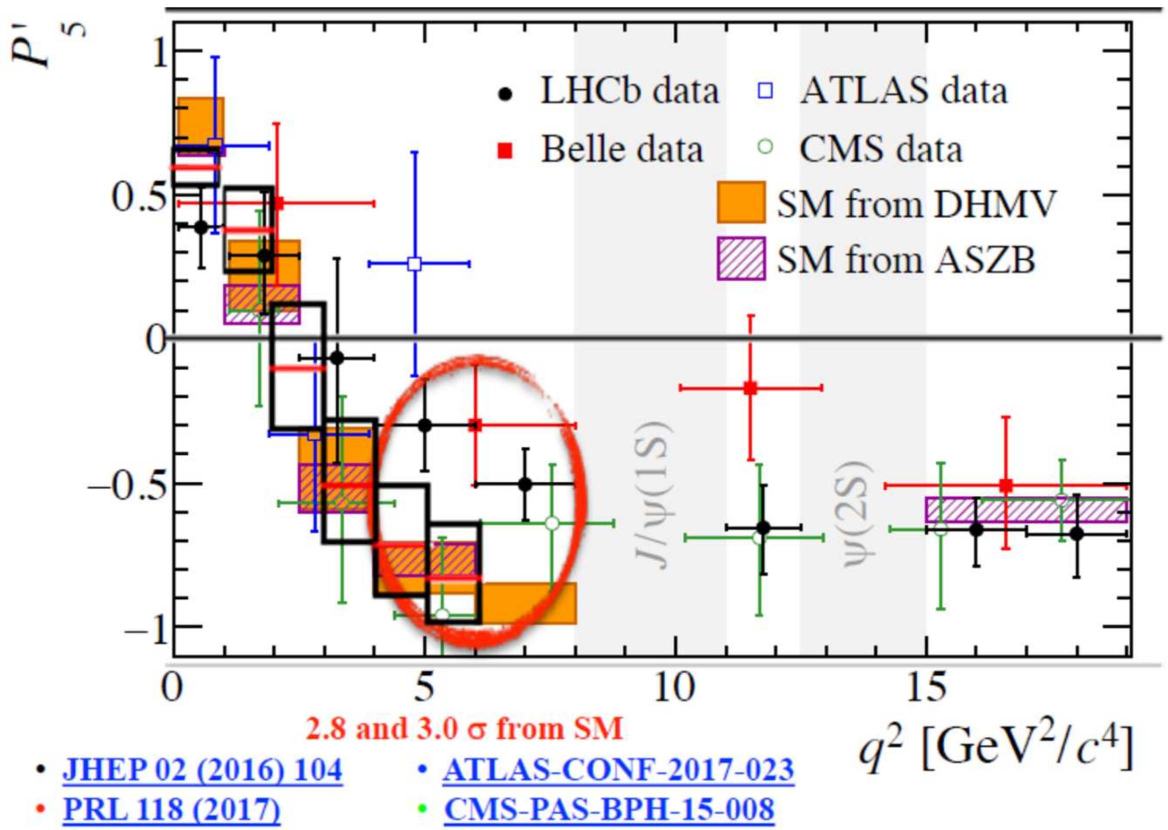
$$I_3 = -\frac{F}{2}\mathrm{Re}\left[H_V^+(H_V^-)^*\right] + (V \to A)$$

$$I_9 = F\,\frac{\beta^2}{2}\mathrm{Im}\left[H_V^+(H_V^-)^*\right] + (V \to A)$$

Require presence of "wrong-helicity" amplitudes (suppressed in SM)

Probe right-handed currents

Anomaly III: The (in)famous P5'

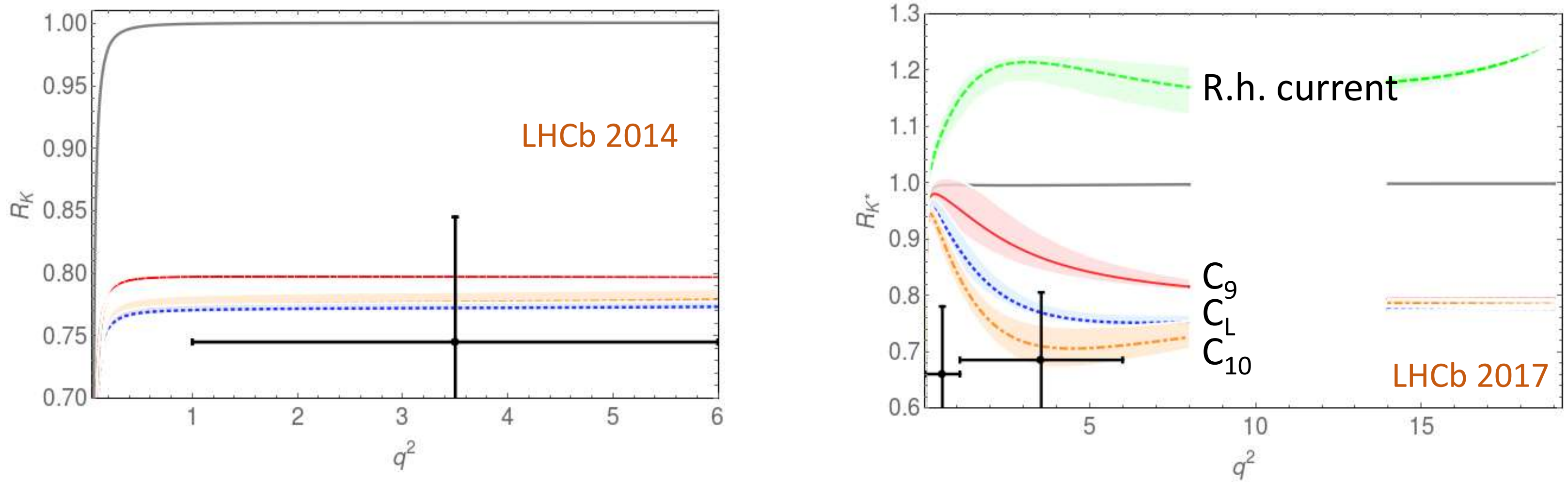


Simone Bifani, seminar at CERN (overlaid predictions from SJ&Martin Camalich 2014)

Modest discrepancy around 4-6 GeV, consistent with reduced C_9

SM theory is subtle – form factors, long-distance virtual-charm somewhat uncertain

Anomaly IV: Lepton-universality violation (LUV)



Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446

$$R_{K^{(*)}}[a,b] = \frac{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}\mu^+\mu^-)dq^2}{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}e^+e^-)dq^2}$$

Theory uncertainties completely negligible relative to experimental ones.

p(SM) = 2.1×10^{-4} (3.7σ)

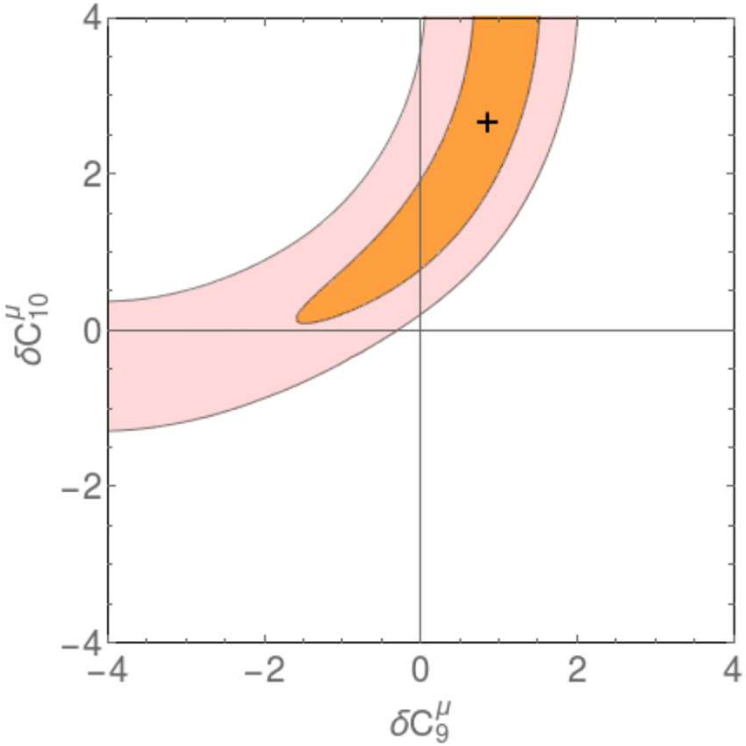
Suggests nonzero, muon-specific C_{10}^{BSM} (as opposed to a pure C_9 effect)

Combined fits: LUV only

Assume here that the BSM effect is in the muonic mode

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446
Also Capdevila et al, Ciuchini et al, Altmannshofer et al, D'Amico et al, Hiller & Nisandzic

Obs.	Expt.	SM	$\delta C_L^\mu = -0.5$	$\delta C_9^\mu = -1$	$\delta C_{10}^\mu = 1$	$\delta C_9'^\mu = -1$
R_K [1, 6] GeV^2	0.745 ± 0.090	$1.0004^{+0.0008}_{-0.0007}$	$0.773^{+0.003}_{-0.003}$	$0.797^{+0.002}_{-0.002}$	$0.778^{+0.007}_{-0.007}$	$0.796^{+0.002}_{-0.002}$
R_{K^*} [0.045, 1.1] GeV^2	0.66 ± 0.12	$0.920^{+0.007}_{-0.006}$	$0.88^{+0.01}_{-0.02}$	$0.91^{+0.01}_{-0.02}$	$0.862^{+0.016}_{-0.011}$	$0.98^{+0.03}_{-0.03}$
R_{K^*} [1.1, 6] GeV^2	0.685 ± 0.120	$0.996^{+0.002}_{-0.002}$	$0.78^{+0.02}_{-0.01}$	$0.87^{+0.04}_{-0.03}$	$0.73^{+0.03}_{-0.04}$	$1.20^{+0.02}_{-0.03}$
R_{K^*} [15, 19] GeV^2	–	$0.998^{+0.001}_{-0.001}$	$0.776^{+0.002}_{-0.002}$	$0.793^{+0.001}_{-0.001}$	$0.787^{+0.004}_{-0.004}$	$1.204^{+0.007}_{-0.008}$



Theory uncertainties negligible.

1sigma and 3sigma confidence regions

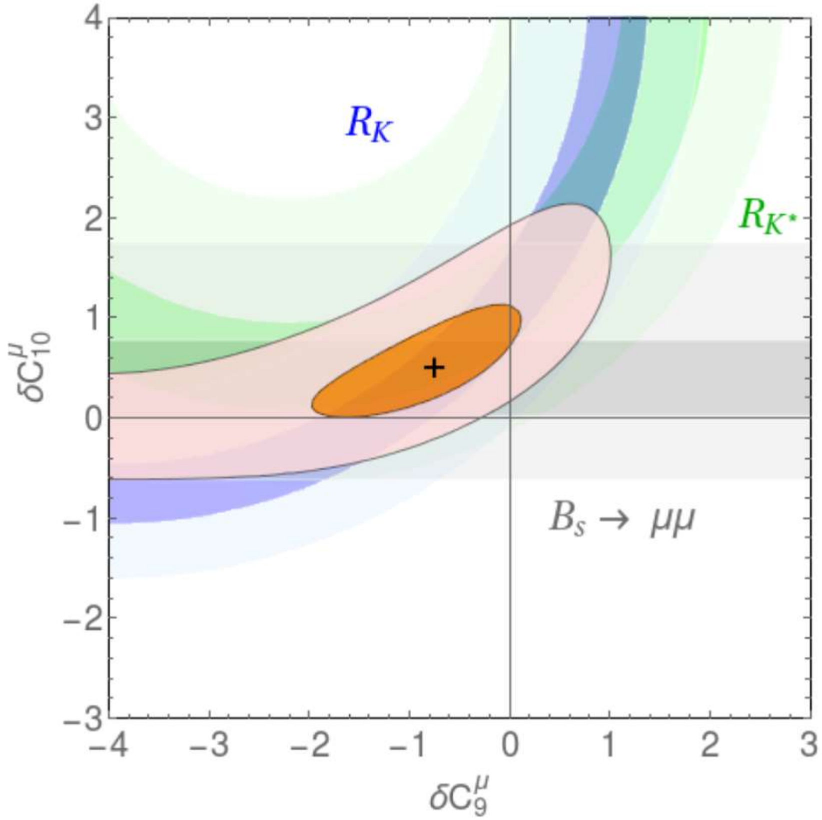
$C_{10}^{BSM}>0$ favoured

$p = 0.158$

SM pull 3.78 sigma

Considerable degeneracy (flat direction in χ^2)

Adding Bs->mu mu



Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446

Selective probe of C_{10} (and C_{10}')

Theory error negligible relative to exp (will hold till the end of HL-LHC !)

Considerably narrows the allowed fit region

p = 0.191

SM point excl. at 3.76 σ

Fit prefers nonzero BSM effect $C_L = (C_9-C_{10})/2$

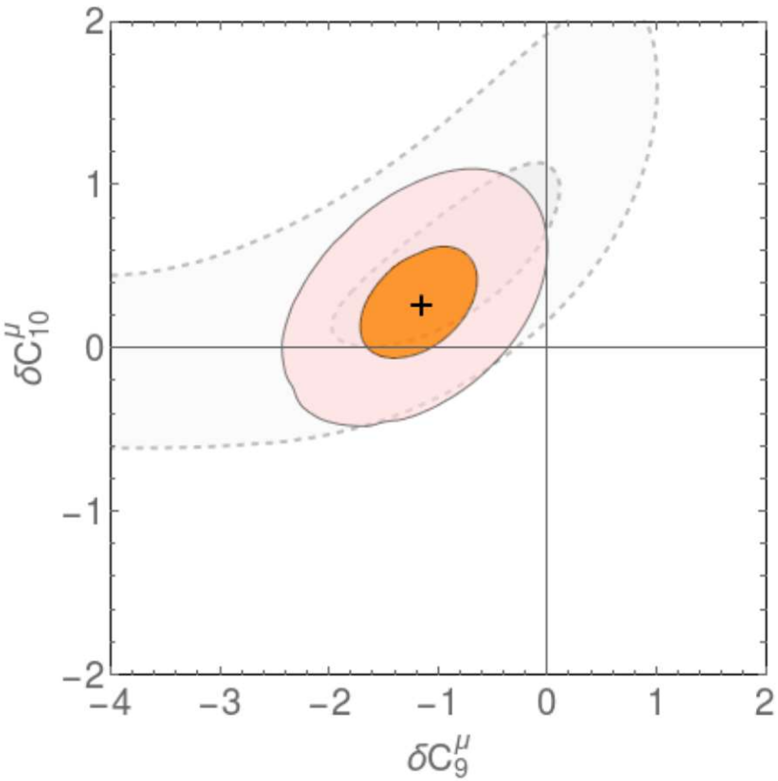
$C_R = (C_9+C_{10})/2$ not well constrained and consistent with zero

1-parameter C_L fit: best fit -0.61. 1σ [-0.78, -0.46], p = 0.339

SM point (origin) excluded at 4.16 sigma

Adding B->K*μμ,ee angular data

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446



Serves to determine best-fit region even better.

SM pull 4.17 σ

p = 0.572 [63 dof]

(but p(SM) now up to to 0.086)

Wilson coefficient value C_L=0 again excluded at high confidence.

Anomaly V: direct CP violation in Kaons

Precisely known experimentally for a decade

$$(\varepsilon'/\varepsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$

average of NA48 (CERN) and KTeV

$$\left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 \simeq 1 - 6\,\mathrm{Re}(\frac{\varepsilon'}{\varepsilon})$$

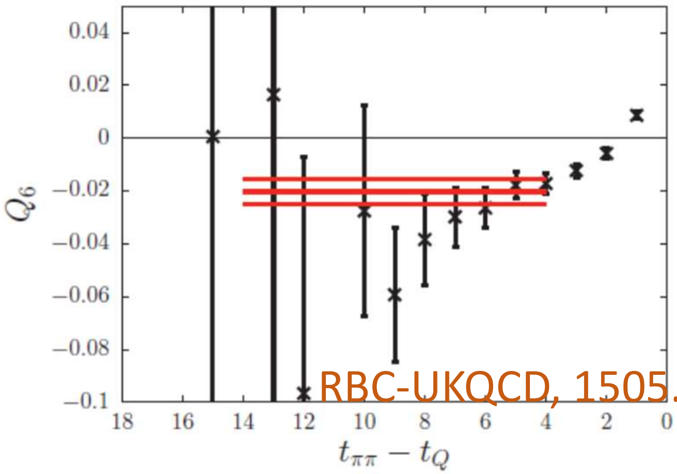
defines Re(ε'/ε) experimentally
left-hand side is measured

$$\eta_{00} = \frac{A(K_{\rm L} \to \pi^0\pi^0)}{A(K_{\rm S} \to \pi^0\pi^0)}, \qquad \eta_{+-} = \frac{A(K_{\rm L} \to \pi^+\pi^-)}{A(K_{\rm S} \to \pi^+\pi^-)}$$

(magnitudes directly measurable from decay rates)

Major progress in lattice QCD computations of nonperturbative matrix elements allows controlled errors for the first time

Good near-term prospects



RBC-UKQCD, 1505.07863v4

State of phenomenology (NLO)

$$(\varepsilon'/\varepsilon)_{\text{SM}} = (1.9 \pm 4.5) \times 10^{-4}$$

Buras, Gorbahn, SJ, Jamin arXiv:1507.06345

$$(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}$$

2.9σ discrepancy

(see also Kitahara, Nierste, Tremper 1607.06727)

(see also Kitahara, Nierste, Tremper 1607.06727)

parameterise hadronic matrix elements values from RBC-UKQCD 2015

quantity	error on ε'/ε	quantity	error on ε'/ε
$B_6^{(1/2)}$	4.1	$m_d(m_c)$	0.2
NNLO	1.6	q	0.2
$\hat{\Omega}_{\text{eff}}$	0.7	$B_8^{(1/2)}$	0.1
p_3	0.6	$\text{Im}\lambda_t$	0.1
$B_8^{(3/2)}$	0.5	p_{72}	0.1
p_5	0.4	p_{70}	0.1
$m_s(m_c)$	0.3	$\alpha_s(M_Z)$	0.1
$m_t(m_t)$	0.3		

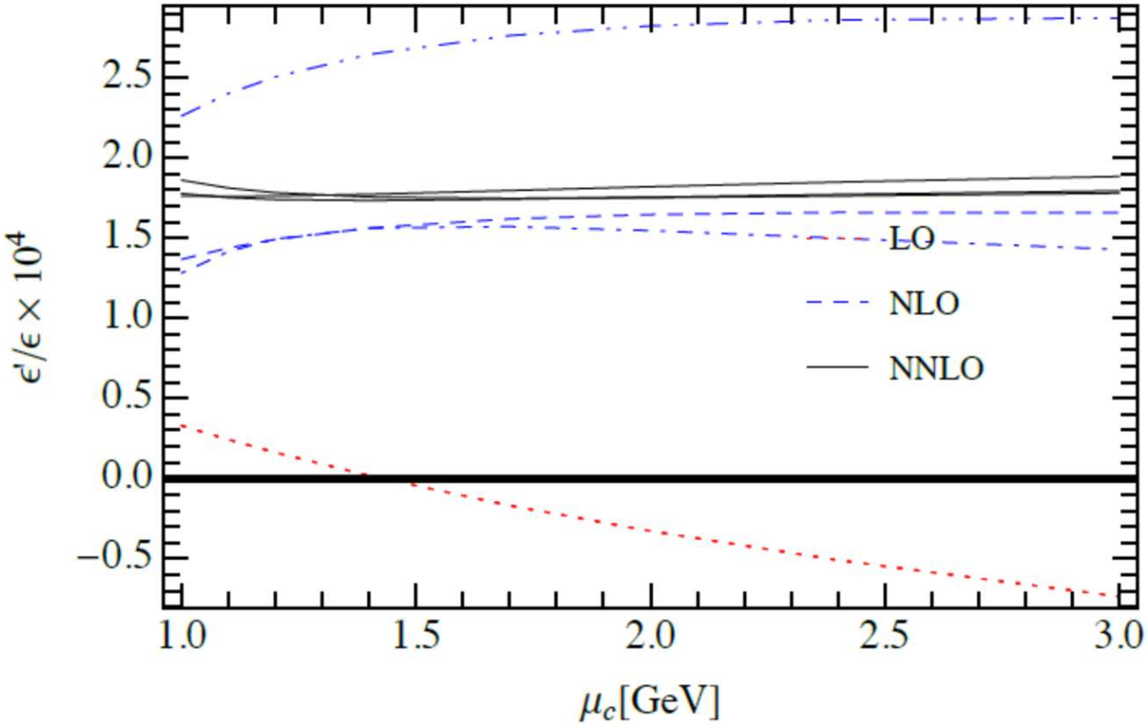
all in units of 10^-4

(still) completely dominated by $\langle Q_6 \rangle_0 \propto B_6^{1/2}$

next are NNLO and isospin breaking

NNLO computation (partial)

Cerda-Sevilla, Gorbahn, SJ, Kokulu, wip



NNLO QCD-penguin corrections tiny; excellent behaviour of perturbation theory; cuts residual perturbative error in half – this is not the reason for the apparent tension!

Summary: flavour anomalies

observable	Anomaly	Significance (sigma)
BR(B ->{K,K*,phi} mu mu) at low dilepton mass q2	Lowish w.r.t expectation	1-2 ?
B->K*mu mu angular distribution (low q2)	P5' off for some q2	2-3 ?
RD(*) = BR(B->D(*)tau nu)/BR(B->D(*)l nu)	Enhanced w.r.t. SM	4.1
Lepton-universality ratios (RK, RK*)	Below SM	3.7 (3 observables combined)
ε'/ε (direct CPV in KL->ππ)	Below SM	2.9

LHCb: rapidly increasing dataset

R_K, R_K* will see important cross-check from Belle 2 (lower luminosity, but excellent control over the electronic final state)

Some possible implications

The scale of new physics

Eg Di Luzio, Nardecchia 2017

Non-rare and rare semileptonic B-decay anomalies point to (at leats) the two following BSM interactions

$$\frac{1}{\Lambda^2}\left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\nu}_\tau\gamma_\mu\tau_L\right) \qquad \frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\tau_L\right)$$

numerically $\Lambda \sim 3$ TeV and $\Lambda \sim 30$ TeV. The uncertainty on these is well below a factor of 2; the question is whether one or both anomalies are genuine.

Recall in the case of the Fermi theory, GF ~ g^2/M_W^2

Redoing the calculation here, $M_{NP} = g_{NP}\,\Lambda \leq 4\pi\,\Lambda$. For the rare decay anomalies, this gives a NP scale of at most 300-400 TeV.

An improved argument employs partial-wave unitarity. This gives a worst-case NP energy scale of below 100 TeV.

If the NP is less than maximally flavour-violating, or the NP is weakly coupled, the scale will be 1-2 orders of magnitudes lower.

While these bounds are (so far) very high, the fact that there are any at all should be very encouraging, and further refinements may be possible.

Non-rare semileptonic decay: b→c τ ν(τ)

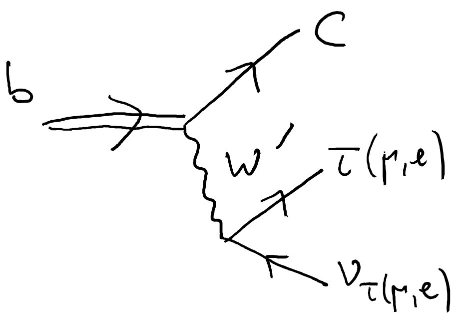
Recall favoured BSM effective interaction

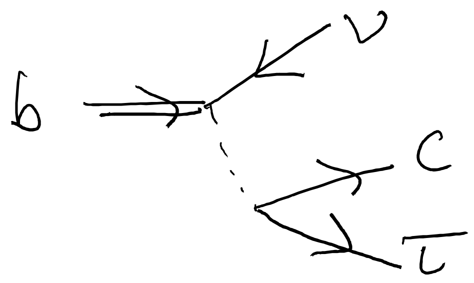
$$\frac{1}{\Lambda^2}\left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\nu}_\tau\gamma_\mu\tau_L\right)$$

numerically Λ ~ 3 TeV   Eg Di Luzio, Nardecchia 2017

Less if new physics has flavour suppression

Possible mediation by W' (could be composite) or leptoquarks,





Isidori et al, Quiros et al, Ligeti et al, Becirevic et al, Crivellin et al, …

In principle R(D(*)) could also be affected by suppressing the couplings to light leptons; disfavoured by B-factory data

Rare semileptonic decay

Accommodating *all* b->s l l anomalies *requires* a muon-specific C_L – type interaction

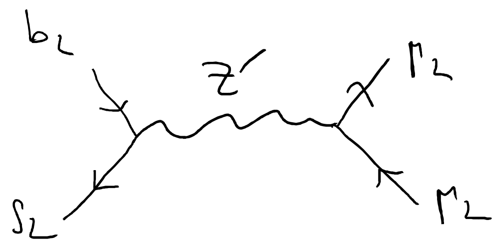
$$\frac{1}{\Lambda^2}\left(\bar{s}_L \gamma^\mu b_L\right)\left(\bar{\mu}_L \gamma_\mu \tau_L\right)$$

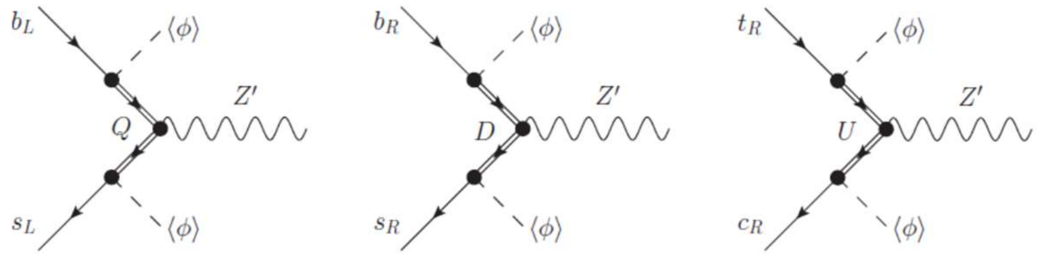
with Λ ~ 30 TeV

However, C_R is weakly constrained and can also be present. So for example a pure C_9 effect is possible (P5' may prefer this).

Anomaly-free Z' model with gauged L_μ - L_τ , nonminimal (dim-6) coupling to quarks, can eg come from heavy vectorlike quarks:

Altmannshofer, Gori, Pospelov, Yavin





Also Crivellin et al, …

The small coupling to quarks suppresses contributions to Bs mixing

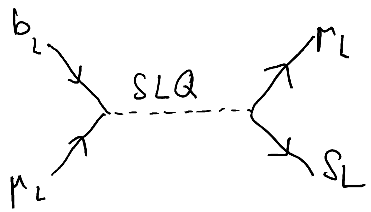
Leptoquark-mediated rare decay

Scalar or vector leptoquarks exchange can also generate a C_L effect.

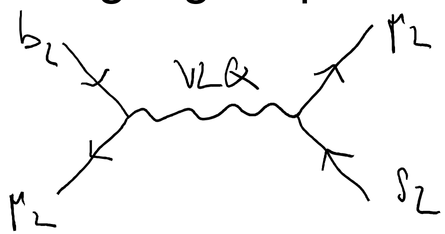
Eg Gripaios, Nardecchia, Renner

Tree-level exchange viable for (eg Hiller, Nisandzic 2017)

- scalar in SM gauge representation $(\bar{3}, 3, 1/3)$



- vector in SM gauge representation $(\bar{3}, 1, 2/3)$ or $(\bar{3}, 3, -2/3)$

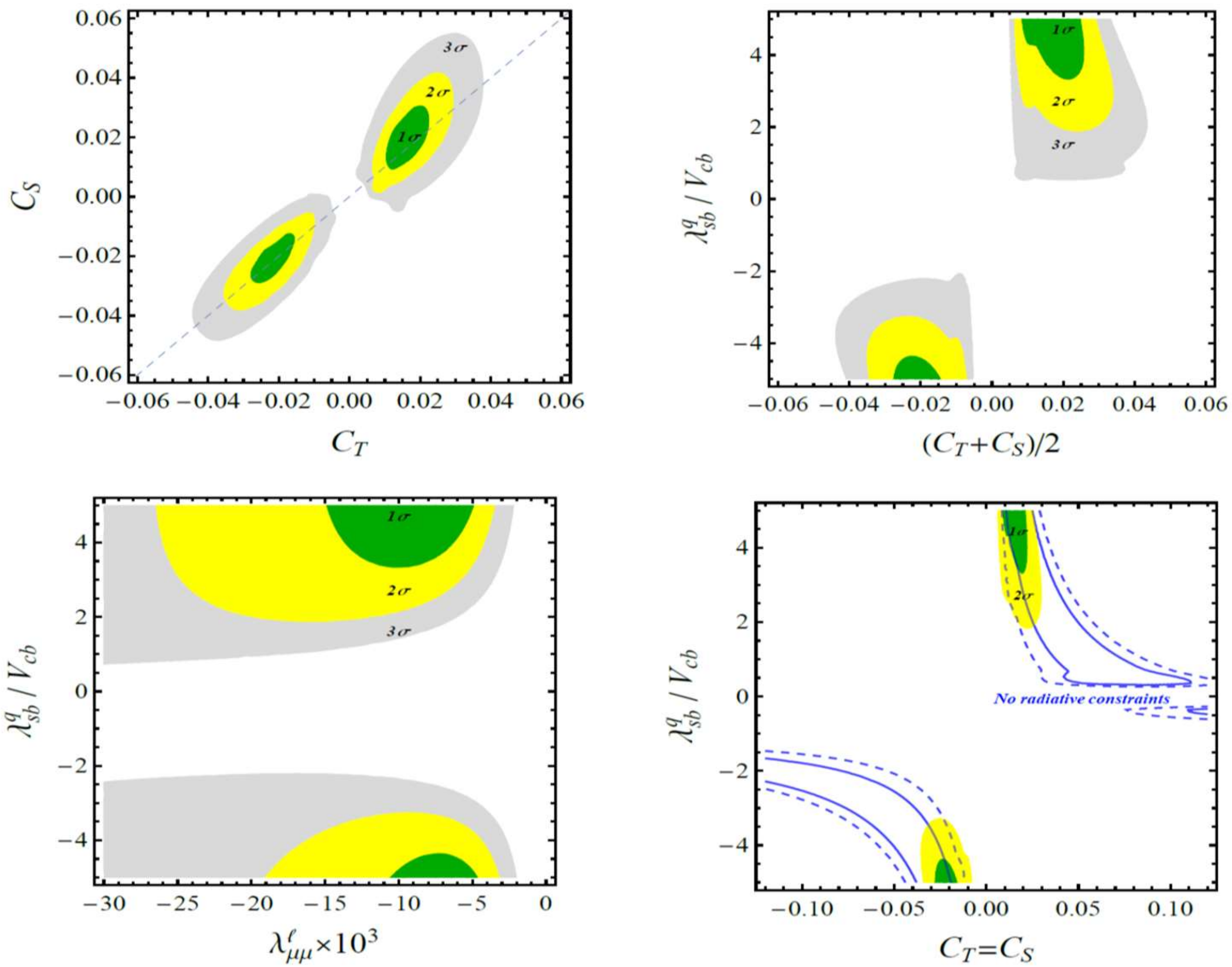


Contributions to Bs mixing absent at tree level.

More possibilities at loop level, can try to employ the same leptoquark to mediate RD and RK*

Eg Bauer,Neubert; Becirevic et al

Combined explanations



Isidori, Greljo arXiv:1706.07808

Natural vector leptoquark?

The SM representation $(\bar{3}, 1, 2/3)$ appears in the restriction of the Pati-Salam (SU(4) x SU(2) x SU(2)) adjoint to the SM

The associated conserved current can create spin-1 vector leptoquark states with these quantum numbers. Several partially-composite models of this type have recently appeared

3-site Pati-SU(4) x SU(2) x SU(2) model

Bordone, Cornella, Fuentes-Martin, Isidori arXiv:1712.01368

[SU(4) x SO(5) x U(1)] / [SU(4) x SO(4) x U(1)] pNGB Higgs model

Barbieri, Tesi arXiv:1712.06844

SU(4) x SU(2) x SU(2) Randall-Sundrum (warped ED) model

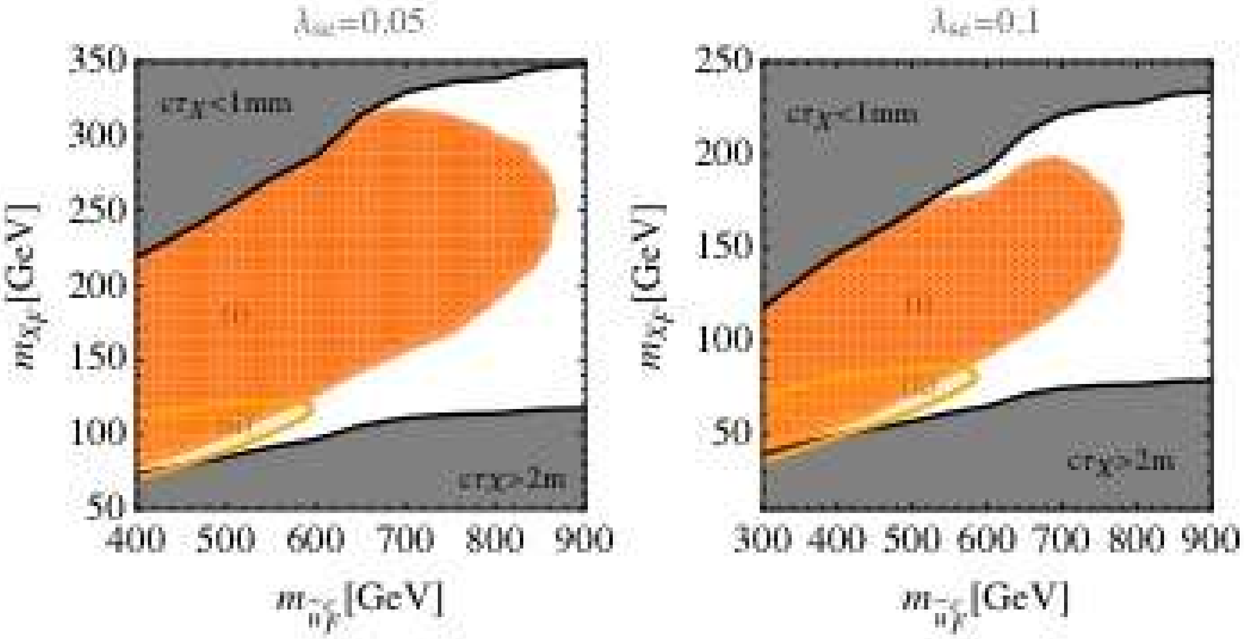
Blanke, Crivellin arXiv:1801.07256

Natural scalar leptoquark explanations?

The representations under the SM gauge group that work seem 'unusual' – not present in MSSM, not easy in composite models

To explain only the theoretically robust lepton-universality ratios in rare decays, one can also ***enhance the electron decay rate***. This does not require interference with the SM, so various chiralities work.

- Eg hyperfolded SUSY with SU(2) singlet "stop" of charge 4/3 can generate $b_R \to s_R\, e_R^+\, e_R^-$ Interesting interplay with collider searches.

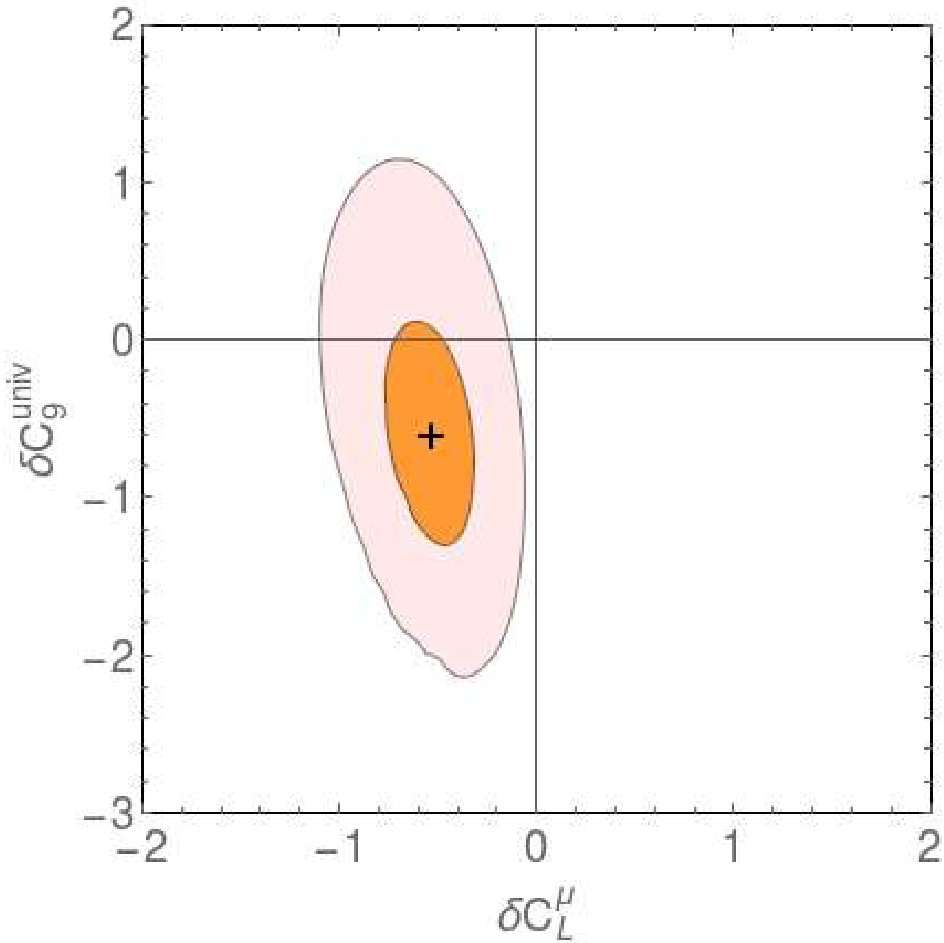


Faroughy, SJ, Kamenik, Perez, Sato, Zupan w.i.p.

- composite right-handed electron scenario Carmona, Goertz arXiv:1712.02536

Must C9 show LUV ?

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446



Modified C_{10} needed to suppress RK* (both bins)

Modest preference for modified C_9 (over C_{10}) is due to angular observables in B->K* mu mu

This means a model with (for example) nonzero C_L^{μ} and in addition an ordinary, **lepton-flavour-universal, C_9**, can describe the data similarly well or better

Eg. 'charming BSM' scenario

SJ, Kirk, Lenz, Leslie arXiv:1701.09183

Conclusions

Currently, there are conspicuous tensions/discrepancies with the SM in a range of rare (and not so rare) decay observables.

In particular, rare semileptonic decay anomalies have been quite persistent and have a consistent minimal BSM explanation. Main issue, if any, are systematics (theory and experiment) not statistics.

Two of these, RK and RK*, have negligible theory systematics. Putting these beyond reasonable doubt must be a priority.
- independent measurements at Belle2, a very different setup.
- MC people: are improvements to LHCb systematics possible?

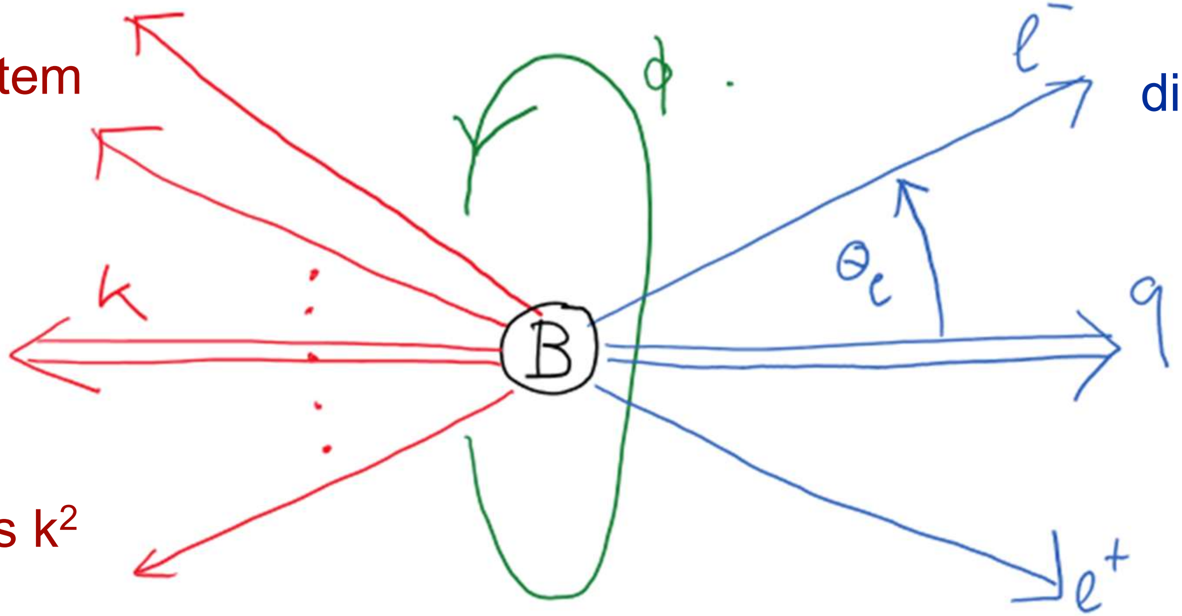
A genuine effect will provide an upper bound on the mass scale of new physics.

If any of the B-physics anomalies are real effects, they may point to leptoquark and/or Z' effects. These generally lie within the reach of future colliders. Possible connections with naturalness only recently explored.

Semileptonic decays

hadronic system

dilepton



hadronic mass k^2

dilepton mass q^2

hadronic angles & energies
equivalently:
  angular momentum L'
  helicity λ'
  (+ more if >2 hadrons)

one hadronic/leptonic
relative angle Φ
if >1 hadron

leptonic angle
equivalently:
  angular momentum L
  helicity λ

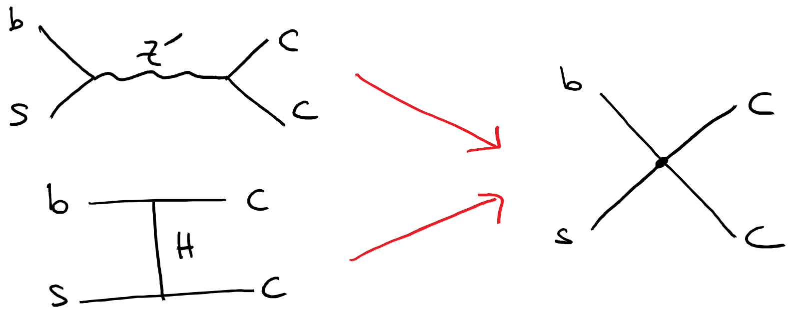
B has spin zero => $\lambda = \lambda'$

Observing Φ requires interference $A(\lambda_1)\,A(\lambda_2)^*\ \exp(i\,(\lambda_1 - \lambda_2)\Phi)$

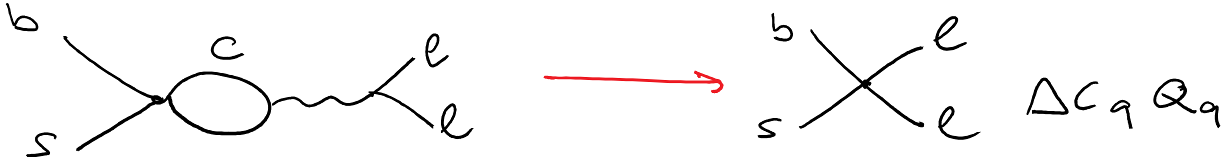
Charming BSM scenario

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

e.g. 1)



2)



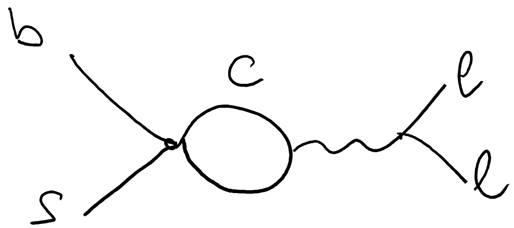
very efficient way to generate C9(NP) = O(1)

$$C_7^{\text{eff}}(4.6\text{GeV}) = 0.02\,C_1(M_W) - 0.19\,C_2(M_W)$$
$$C_9(4.6\text{GeV}) = 8.48\,C_1(M_W) + 1.96\,C_2(M_W)$$

(In SM, O(50%) of total in both cases)

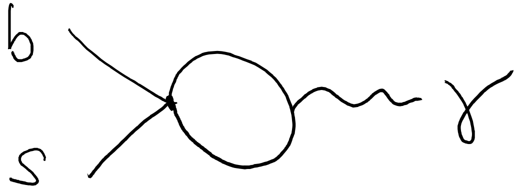
Observables

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



$$\Delta C_9^{\text{eff}}(q^2) = \left(C^c_{1,2} - \frac{C^c_{3,4}}{2}\right) h(q^2, m_c, \mu) - \frac{2}{9} C^c_{3,4}$$

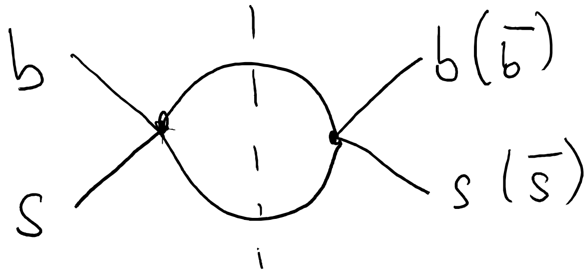
$$C^c_{x,y} = 3\Delta C_x + \Delta C_y$$



$$\Delta C_7^{\text{eff}}(q^2) = \frac{m_c}{m_b}\left[(4C^c_{9,10} - C^c_{7,8}) y(q^2, m_c, \mu) + \frac{4\,C^c_{5,6} - C^c_{7,8}}{6}\right]$$

note that h and y are q2-dependent

At one loop, radiative decay constrains C5..C10, but not C1..C4. Focus on the latter. Then consider lifetime (mixing) observables



$\Delta\Gamma_s$ and τ_{B_s}/τ_{B_d} calculable in OPE for general C1 .. C4

High NP scale – global analysis

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

Blue – $B \to X_s\gamma$, green – lifetime ration, brown –lifetime difference