Flavour physics: global view

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Precision frontier: beyond QED

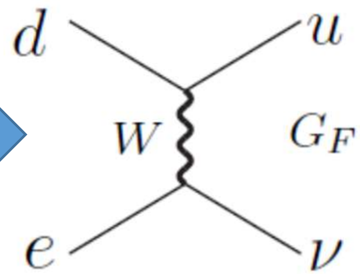
Some past indirect discoveries

- 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
- CP violation — Christenson et al 1964
- electroweak symmetry breaking — BEHGHK, Glashow, Salam, Weinberg 1960-67
- charm to explain $K_L \to \mu\mu$ suppression — Glashow, Iliopoulos, Maiani 1970
- third generation to explain CPV — Kobayashi, Maskawa 1972

Neutral currents, charm, W,Z,H, 3rd gen. later discovered.

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

(Fermi 1934)



$$G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

post-GSW

The SM

spin 1

electromagnetism U(1)
weak interactions SU(2)
strong interactions SU(3)

universal couplings

3 generations

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

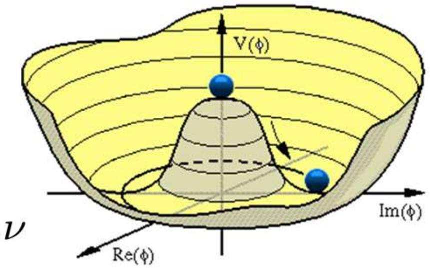
Higgs - sets mass scale of entire Standard Model

Origin of masses? Flavour mixings? What determines the weak scale?

Dynamics

At length scales above an attometre we have approximately (up to gravity)

SU(3)^5 flavour symmetric kinetic/gauge terms

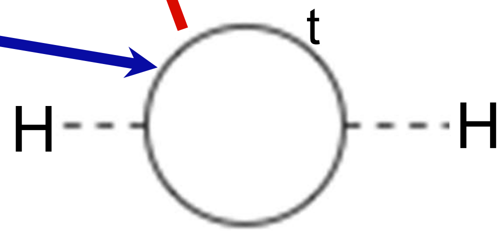


EW scale setting

$$\mathcal{L}_{\rm SM} = \sum_f \bar\psi_f \gamma^\mu D_\mu \psi_f - \frac{1}{4}\sum i, a \frac{g_i}{4} F^{ia}_{\mu\nu} F^{ia\mu\nu}$$

$$-\bar u_R Y^U \phi^{c\dagger} q_L - \bar d_R Y^D \phi^\dagger q_L - \bar e_R Y^E \phi^\dagger l_L - \mu^2 \phi^\dagger\phi - \frac{\lambda}{2}\left(\phi^\dagger\phi\right)^2$$

flavour-breaking fermion masses and Higgs couplings

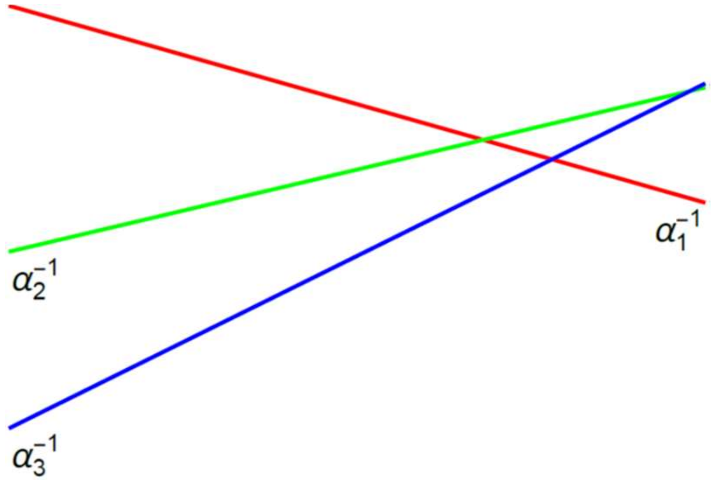


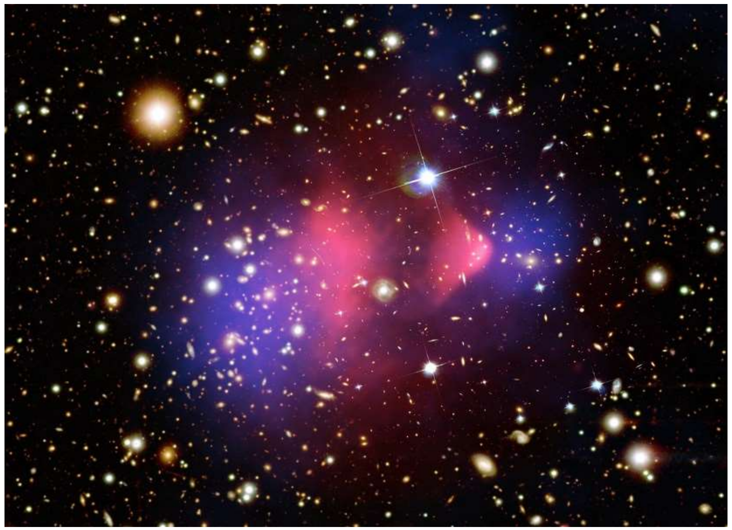
$\propto y_t^2\, M^2$

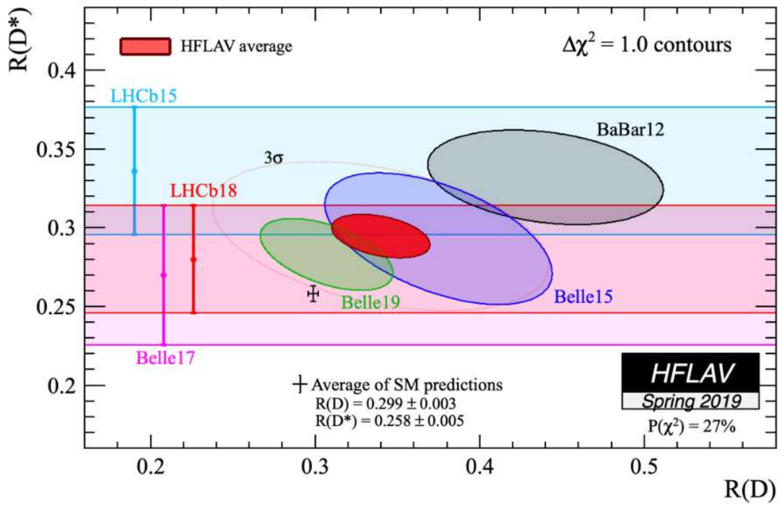
Quadratic divergence from flavour-breaking sources -> any cure likely to be flavour-breaking (happens in SUSY, composite Higgs, …)

Beyond the SM

$$\Delta m_H^2 \propto y_t^2 \Lambda_{\mathrm{UV}}^2$$



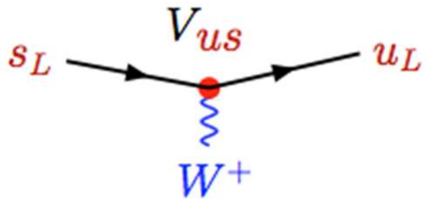




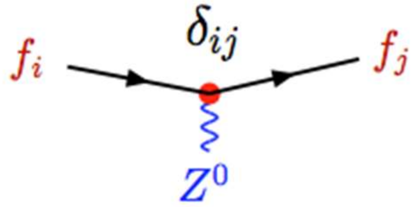
Outline

0) Motivation
1) Rare decays
2) Accessing BSM through RGE
3) Kaons & the lattice revolution
4) Non-rare decays
5) Anomalies & BSM

Flavour physics & rare decays



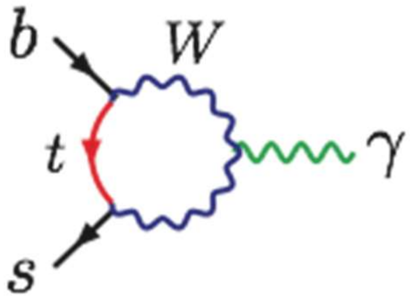
all flavour violation in charged weak current



(tree level) neutral current conserves flavor

strong & electromagnetic preserve flavour

Loop suppression of flavour-changing neutral current processes



-> enhanced BSM sensitivity

Where to look

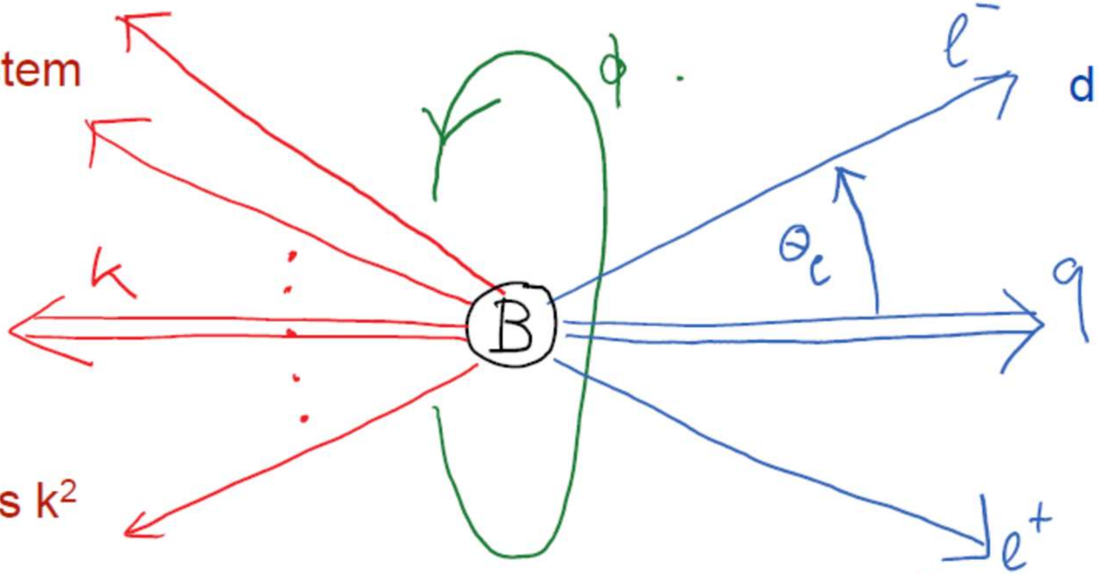
Observables with suppressed and/or controlled SM contribution

- flavour-changing neutral currents, eg
  - $b \to s \mu^+ \mu^-$ and $b \to s \gamma$
    - $B \to K^{(*)} \mu^+\mu^-$, $B \to K^{(*)} e^+e^-$, $B_s \to \phi \mu^+\mu^-$, $B \to K^{(*)} \gamma$ — Babar, Belle, LHCb, ATLAS, CMS, Belle2
    - $B \to X_s \mu^+\mu^-$, $B \to X_s \gamma$ — Babar, Belle, Belle2
  - $s \to d \nu\nu$
    - $K^+ \to \pi^+ \nu \nu$ — NA62 (CERN)
- lepton-flavour ratios, eg
  - $BR(B \to K^{(*)} \mu^+\mu^-)/BR(B \to K^{(*)} e^+e^-) - 1$
  - $BR(B \to D^{(*)} \tau\nu)/BR(B \to D^{(*)} l\nu) - (SM)$
  - Babar, Belle, LHCb, Belle2
- CP violation, eg
  - $K_L \to \pi\pi$ (ε_K, ε'_K) — …, NA48, KTeV
  - $K_L \to \pi^0 \nu\nu$ — KOTO

Rare semileptonic decay

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

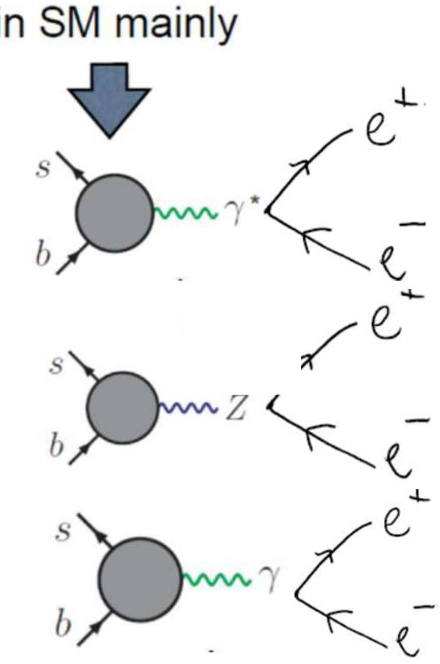
leptonic angle
equivalently:
 angular momentum L
 helicity λ

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

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

Rare B-decay: short-distance

BSM (and SM weak interactions) enter flavour physics through effective contact interactions (SMEFT/H_{weak})



C_9: dilepton from vector current

$$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$

C_{10}: dilepton from axial current

$$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma^5 l)$$

C_7: dilepton from dipole

$$(\bar{s}\sigma^{\mu\nu} P_R b)F_{\mu\nu}$$

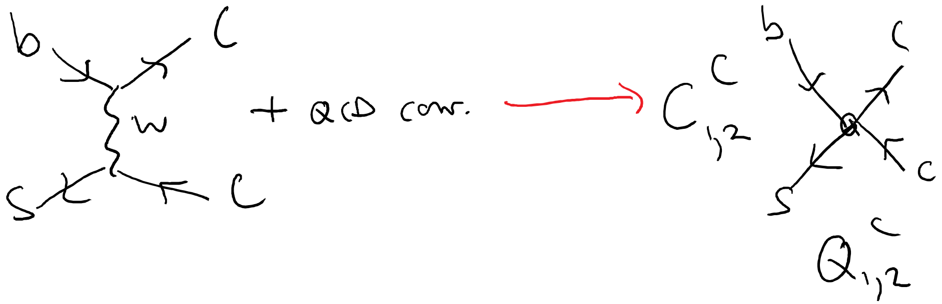
+parity conjugate "right-handed currents" - C_7', C_9', C_{10}'
suppressed by m_s/m_b in SM

Alternative basis with chiral leptons l_L, l_R

$C_L = (C_9 - C_{10})/2$ $\quad$ $C_R = (C_9 + C_{10})/2$

Importance of virtual charm

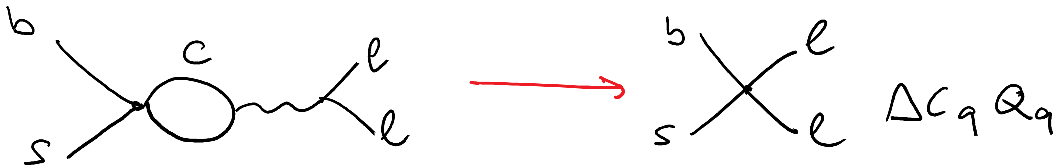
Also **purely hadronic** operators enter, in SM primarily:



$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i)$$

$$Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j)$$

RG mixes these into C_9 and C_7



+ dipole

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

$$C_9(4.6\text{GeV}) = 8.48\, C_1(M_W) + 1.96\, C_2(M_W)$$

SM: O(50%) of total in both cases!

At μ=m_b: $C_7^{\text{eff}} \sim -0.3$, $C_L \sim 4$, $C_R \approx 0$

- SM: accidentally almost left-chiral muon interactions
- Long-distance virtual charm important theory uncertainty

Flavour: the dogs that did not bark

From AC Doyle, “The Adventure of Silver Blaze” [with thanks to J Ellis]

> Gregory (Scotland Yard detective): "Is there any other point to which you would wish to draw my attention?"
> Holmes: "To the curious incident of the dog in the night-time."
> Gregory: "The dog did nothing in the night-time."
> Holmes: "That was the curious incident."

Quote and S Paget’s illustration via Wikipedia

Absence of an effect in a BSM-sensitive observable can be as important a clue as an anomaly.

Null tests of the SM

Clean null tests of SM from (mainly) B → K*ɣ and B→ K*μμ

$$P_1 \equiv \frac{I_3+\bar{I}_3}{2(I_{2s}+\bar{I}_{2s})} = \frac{-2\,\mathrm{Re}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2+|H_V^-|^2+|H_A^+|^2+|H_A^-|^2} \approx 0$$

$$P_3^{CP} \equiv -\frac{I_9-\bar{I}_9}{4(I_{2s}+\bar{I}_{2s})} = -\frac{\mathrm{Im}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2+|H_V^-|^2+|H_A^+|^2+|H_A^-|^2} \approx 0$$

(Melikhov 1998)
Krueger, Matias 2002
Lunghi, Matias 2006
Becirevic, Schneider 2011
Becirevic, Kou, et al 2012
SJ, Martin Camalich 2012

Vey suppressed in the absence of right-handed currents.
No effect seen in data.
'Pseudo-observables:' Wilson coefficients from global fit

$$C'_{7\gamma} = 0.018 \pm 0.037$$ Aebischer et al arXiv:1903.10434

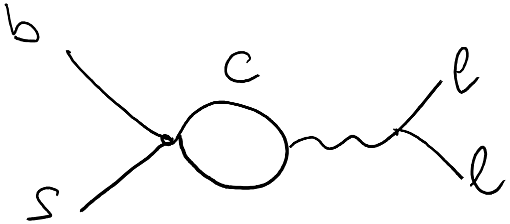
$$C'_{9V} = 0.09 \pm 0.15$$ Paul & Straub arXiv:1608.02556

ΔF=2: Neutral meson mixing also stringent constraints

Accessing BSM through RGE

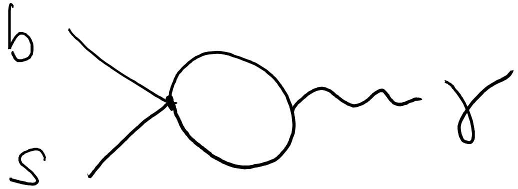
b->c cbar s operators BSM (20 in total)

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



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

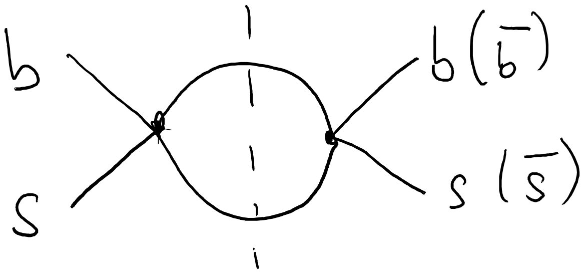
$$C^c_{x,y} = 3\Delta C_x + \Delta C_y$$



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

+ right-handed operators $(\bar{s}_R \Gamma c)(\bar{c}\Gamma' b)$ + rh dipole: C_i -> C_i'

These operators also contribute to B-meson lifetime differences.
Then consider lifetime (mixing) observables



$\Delta\Gamma_s$ and τ_{B_s}/τ_{B_d} calculable in OPE

b->s c c operators BSM: RGE

SJ, Kirk, Lenz, Leslie arxiv:1701.09183 and to appear

Some elements first arise at two loops – still give important constraints.

$$\begin{pmatrix} C_1(\mu_b) \\ C_2(\mu_b) \\ C_3(\mu_b) \\ C_4(\mu_b) \\ C_5(\mu_b) \\ C_6(\mu_b) \\ C_7(\mu_b) \\ C_8(\mu_b) \\ C_9(\mu_b) \\ C_{10}(\mu_b) \\ C_{7\gamma}^{\rm eff}(\mu_b) \\ C_{9V}(\mu_b) \end{pmatrix} = \begin{pmatrix} 1.1 & -0.27 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.27 & 1.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.92 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.33 & 1.9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.9 & 0.33 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.92 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.0 & 0.05 & 2.70 & 1.70 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.37 & 2.0 & 2.30 & -0.55 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.07 & 0.07 & 1.80 & 0.04 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.01 & -0.02 & -0.29 & 0.82 \\ 0.02 & -0.19 & -0.015 & -0.13 & 0.56 & 0.17 & -1.0 & -0.47 & 4.00 & 0.70 \\ 8.50 & 2.10 & -4.30 & -2.00 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} C_1(M_W) \\ C_2(M_W) \\ C_3(M_W) \\ C_4(M_W) \\ C_5(M_W) \\ C_6(M_W) \\ C_7(M_W) \\ C_8(M_W) \\ C_9(M_W) \\ C_{10}(M_W) \\ C_{7\gamma}^{\rm eff}(M_W) \\ C_{9V}(M_W) \end{pmatrix}$$

Enormous RG effects - **but lepton-flavour universal**

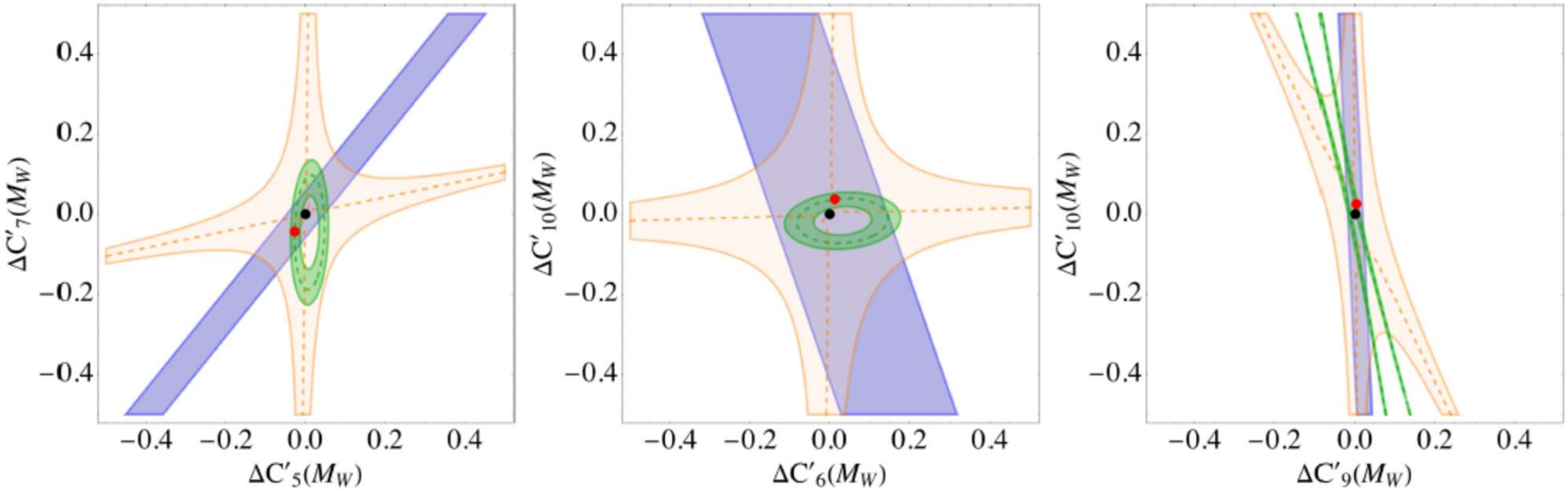
SJ, Kirk, Lenz, Leslie arxiv:1701.09183

Right-handed 4-quark ops constrained by both C_7' and C_9'

Global analysis

SJ, Kirk, Lenz, Leslie to appear

'RH currents' – strong mixing into (rh) dipole



Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

Null results: Implications

Delta C<0

Delta C>0

SJ, Kirk, Lenz, Leslie, to appear

Coeff.	$\Delta\chi^2 \leq 1$	Λ_-(TeV)	Λ_+(TeV)
ΔC_5	$[-0.01, 0.01]$	9.7	10.5
ΔC_6	$[-0.02, 0.02]$	5.6	5.8
ΔC_7	$[-0.01, 0.01]$	8.8	9.7
ΔC_8	$[-0.02, 0.02]$	6.2	6.9
ΔC_9	$[-0.001, 0.005]$	22.3	12.6
ΔC_{10}	$[0.01, 0.05]$	-	3.8
$\Delta C'_1$	$[-0.01, 0.02]$	11.9	5.5
$\Delta C'_2$	$[-0.04, 0.09]$	4.5	2.8
$\Delta C'_3$	$[-0.04, 0.02]$	4.5	7.0
$\Delta C'_4$	$[-0.07, 0.03]$	3.2	5.1
$\Delta C'_5$	$[-0.02, 0.03]$	5.9	4.8
$\Delta C'_6$	$[-0.07, 0.10]$	3.3	2.8
$\Delta C'_7$	$[-0.03, 0.02]$	5.2	6.6
$\Delta C'_8$	$[-0.05, 0.04]$	3.7	4.3
$\Delta C'_9$	$[0.002, 0.010]$	-	8.6
$\Delta C'_{10}$	$[-0.08, -0.06], [0.02, 0.05]$	7.1	3.5

$(\bar{s}_R \Gamma c)(\bar{c}\Gamma' b)$

stringently

constrained

Rare B-decay anomalies

Rare B-decay: observables

Branching ratios

leptonic (differential in dilepton mass)
$B_s \to \mu\mu$, $B_d \to \mu\mu$,

Nonperturbative QCD fully controlled (decay constant from lattice)

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

Lepton universality ratios

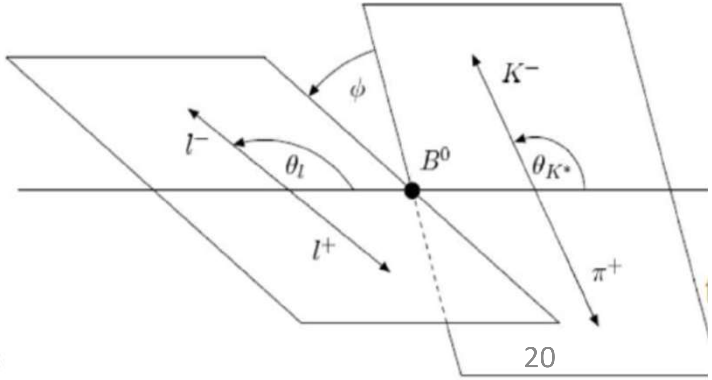
$$R_{K^{(*)}}[a,b] = \frac{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}\mu^+\mu^-)dq^2}{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}e^+e^-)dq^2}$$

Form factors, 4-quark operator contributions, QED radiation cancel out to ~% level (relative to LHCb treatment)

eg Bordone,Isidori,Pattori arXiv:1605.07633

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

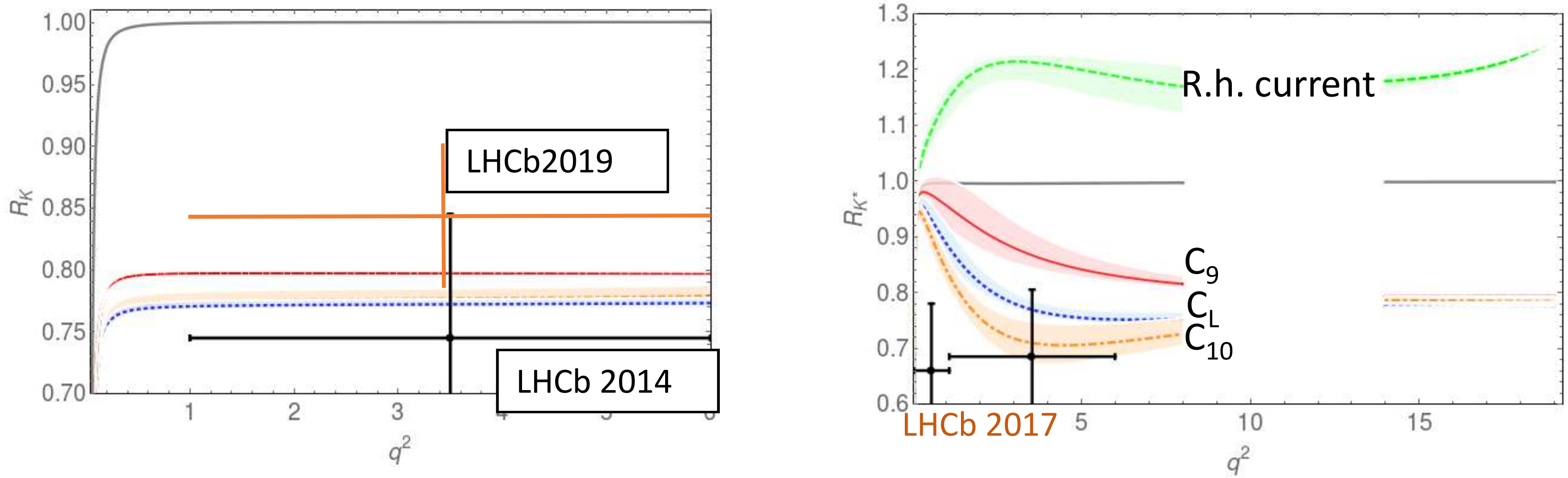
7 angular differential observables:
(A_{FB}, P_5', etc)



Lepton-flavour ratios

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

Fig. from Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446



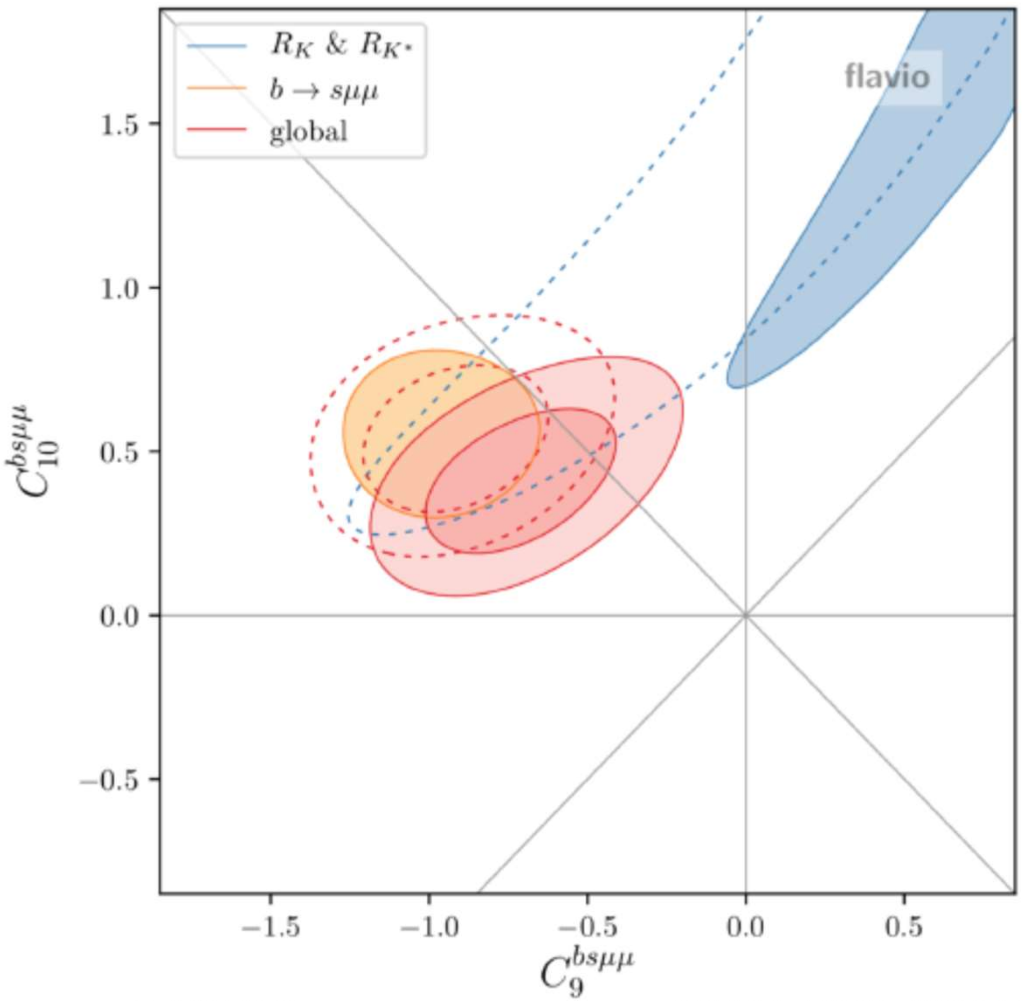
Theory uncertainties negligible relative to experiment.
~3.5σ away from SM, slightly reduced with LHCb update

coloured lines: scenarios with NP in muonic operators

Slight indication for a C_{10}^{BSM} effect – as opposed to pure C_9

Global fit: FCNC B decays

Fig. Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub 1903.10434



Assuming effect to be muon-specific:

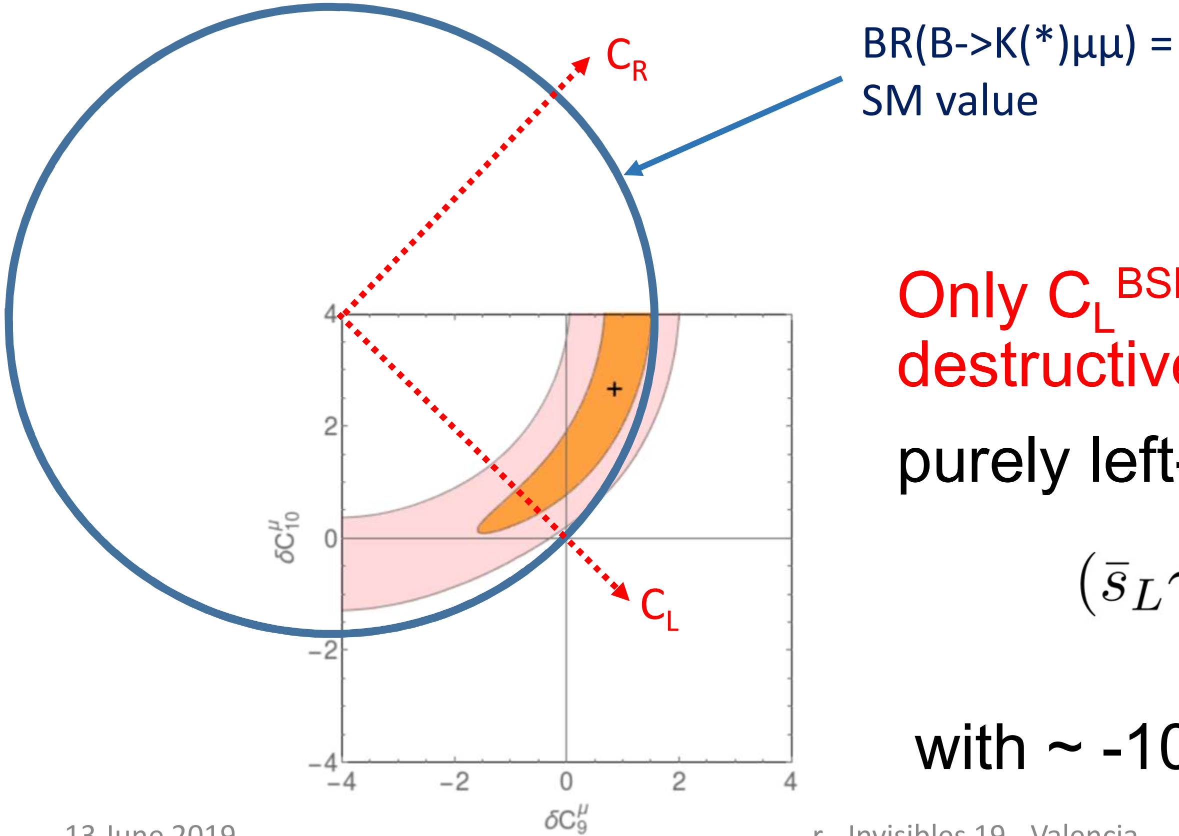
R_K and R_{K^*} on their own suggest a nonzero C_L value (displacement from SM along diagonal)

Including angular analysis data pins down both C_L and C_R (or C_9 and C_{10})

$R_K^{(*)}$ and the chirality of NP

Assume here that the BSM effect is in the muonic mode, and no right-handed currents.

Because in the SM, $|C_R|$, $|C_7| << |C_L|$,
BR ≈ const $|C_L^{SM} + C_L^{BSM}|^2$ + … ≈ const $|4 + C_L^{BSM}|^2$ +positive



Only C_L^{BSM} can interfere destructively: $R_K^{(*)}$ point to purely left-handed coupling

$$(\bar{s}_L \gamma^\mu b_L)\,(\bar{\mu}_L \gamma_\mu \mu_L)$$

with ~ -10% of SM value

Kaons & the lattice revolution
(small selection)

Test of CKM unitarity

CKM unitarity (first row): $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

V_{ud} from superallowed nuclear beta decays

$$\frac{\Gamma(K^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)} = \left|\frac{V_{us} f_K}{V_{ud} f_\pi}\right|^2 \frac{m_\pi^3}{m_K^3} \left(\frac{m_K^2 - m_\mu^2}{m_\pi^2 - m_\mu^2}\right)^2 (1 + \delta R_{K\pi})$$

$\delta R_{K\pi}$: isospin-breaking (including QED) corrections

Theory determination of $\delta R_{K\pi} \to$ determination of V_{us}

Chiral perturbation theory: $\delta R_{K\pi}$ = -0.0112(21) Cirigliano & Neufeld 2011

Recent lattice determination: $\delta R_{K\pi}$ = -0.0122(16) D Giusti et al 1711.06537

implies $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99985(49)$

($|V_{ub}|^2$ small compared to uncertainty.)

Lattice treatment of QED effects

Several issues, in particular:

massless gauge fields $\rightarrow$ IR divergences $\rightarrow$ regulator

IR-finiteness and infinite-volume limit only for sufficiently inclusive observables (Block-Nordsieck)

eg $\Gamma(K^+ \to \mu^+ \bar{\nu}) + \Gamma(K^+ \to \mu^+ \bar{\nu}\gamma)|_{E_\gamma < \Delta E}$

QED corrections affect the relations between bare lattice parameters and observables used to determine them

Possible lattice treatment: systematic expansion in α_{EM}

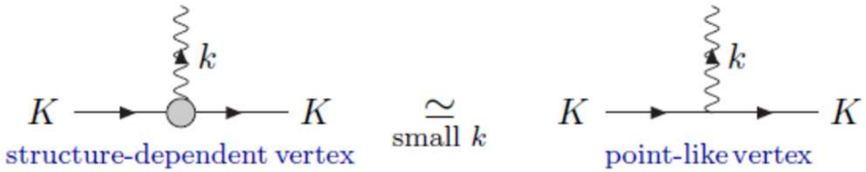
(including bare lattice parameters themselves)

+ suitable IR subtraction prescription

Carrasco,Giusti,Lubicz,Martinelli,Sachrajda, Sanfilippo,Simula,Tantao,Tarantino,Testa (see eg talk by C Sachrajda at Lattice 2018)

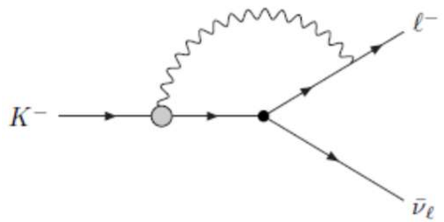
Calculation of $\delta R_{K\pi}$

Compute $\Gamma(K^+ \to \mu^+ \bar{\nu}) + \Gamma(K^+ \to \mu^+ \bar{\nu}\gamma)|_{E_\gamma < \Delta E}$ ($\Delta E \sim 20$ MeV)



C Sachrajda @ Lattice 2018

$$\boxed{\Gamma_0 + \Gamma_1(\Delta E) = \lim_{V\to\infty} (\Gamma_0 - \Gamma_0^{\mathrm{pt}}) + \lim_{V\to\infty} (\Gamma_0^{\mathrm{pt}} + \Gamma_1(\Delta E))\,.}$$



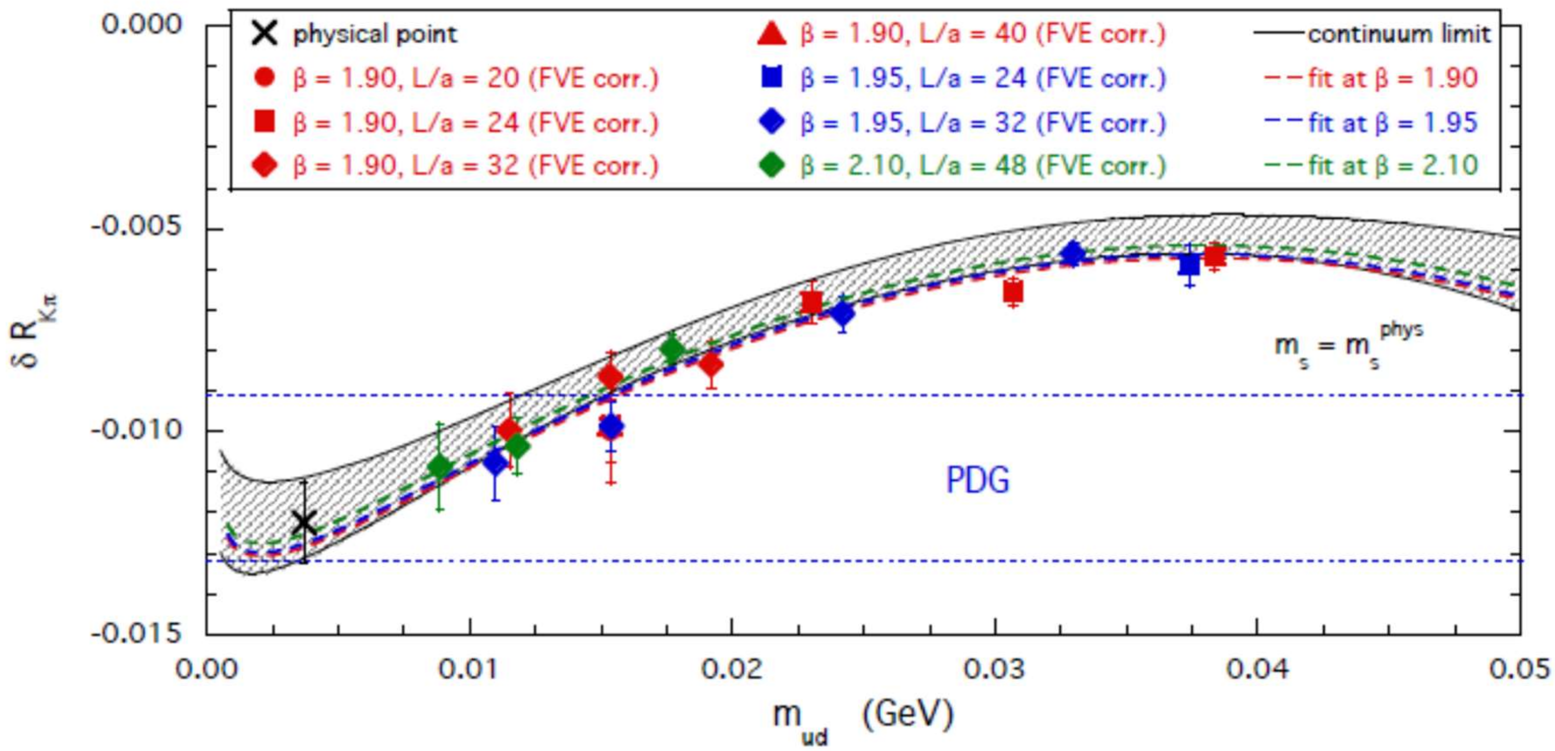
Γ_0 nonperturbative lattice computation (with IR regulator)

Γ_0^{pt} calculated in (lattice) perturbation theory

Both terms IR finite & infinite-volume limit exists.

Divergent V-dependence in Γ_0^{pt} universal. Cancels out in $\dfrac{\Gamma(K^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)}$

Allows unambiguous extraction of $\delta R_{K\pi}$



physical point
β = 1.90, L/a = 20 (FVE corr.)
β = 1.90, L/a = 24 (FVE corr.)
β = 1.90, L/a = 32 (FVE corr.)
β = 1.90, L/a = 40 (FVE corr.)
β = 1.95, L/a = 24 (FVE corr.)
β = 1.95, L/a = 32 (FVE corr.)
β = 2.10, L/a = 48 (FVE corr.)
continuum limit
fit at β = 1.90
fit at β = 1.95
fit at β = 2.10
$m_s = m_s^{phys}$
PDG
δ $R_{K\pi}$
m_{ud} (GeV)
0.000
-0.005
-0.010
-0.015
0.00
0.01
0.02
0.03
0.04
0.05

Direct CP violation in $K_L \to \pi\pi$

Precisely known experimentally for a decade

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

average of NA48 (CERN) and KTeV

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

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

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}, \qquad \eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$

(magnitudes directly measurable from decay rates)

very complicated multi-scale problem (weak scale, charm, QCD scale, **~10 4-quark operator K→ππ matrix elements needed**)

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

Good prospects

ε' master formula

Buras, Buchalla, Lautenbacher 1990; Buras, Jamin 1993;1996; Bosch et al 1999; Buras, Gorbahn, SJ, Jamin arXiv:1507.06345

$$\omega_+ = a\frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} = (4.53 \pm 0.02)\times 10^{-2}$$

from experiment
Cirigliano et al 2003

leading isospin breaking
Cirigliano et al 2003

neglect small imaginary part (for simplicity; could easily be restored)

$$\frac{\varepsilon'}{\varepsilon} = -\frac{\omega_+}{\sqrt{2}|\varepsilon_K|}\left[\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}(1-\Omega_{\rm eff}) - \frac{1}{a}\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2}\right]$$

from experiment

$$A_I \equiv \langle(\pi\pi)_I|\mathcal{H}_{\rm eff}|K\rangle$$

QCD isospin amplitudes factorise into Wilson coefficients (perturbative) and matrix elements (nonperturbative)

$$A_I = \langle(\pi\pi)_I|H_{\rm eff}|K\rangle = \sum_{i=1}^{10} C_i\langle(\pi\pi)_I|Q_i|K\rangle$$

known to NLO Buras et al 1992,1993; Ciuchini et al 1993
NEW: partial NNLO Cerda Sevilla, Gorbahn, SJ, Kokulu 2016
(NNLO ADMs: Gorbahn, Haisch; Gorbahn, Brod
NNLO weak scale: Misiak et al; Gambino et al)

NEW: first-ever calculation with controlled errors by RBC-UKQCD (2015)

State of phenomenology (NLO)

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

Buras, Gorbahn, SJ, Jamin arXiv:1507.06345

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

2.9σ discrepancy

(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
$\hat{\Omega}_{\rm eff}$	0.7	$B_8^{(1/2)}$	0.1
p_3	0.6	$\mathrm{Im}\lambda_t$	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

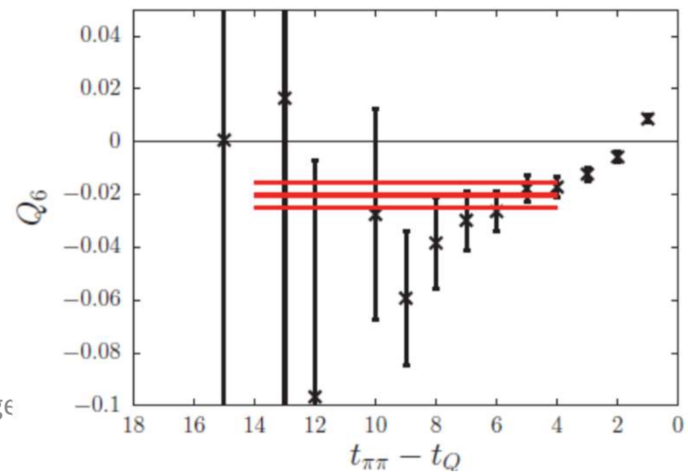
Lattice computation

RBC-UKQCD, 1505.07863v4

Several major obstacles – and how RBC/UKQCD address, such as

- compute ππ phase shifts, not accessible in Euclidean QFT (Maiani-Testa no-go) → Luescher finite-volume method
- K→ ππ matrix elements contain rescattering effects
  → Lellouch-Luescher finite-volume method
- physical light quark masses with good chiral symmetry
  → Domain-wall fermions (computationally expensive)
- vacuum contamination in $K_L \to (\pi\pi)_{I=0}$ (exponentially dominant)
  → smeared operators to maximize overlap with $(\pi\pi)_{I=0}$ state

New computation with several times more statistics ongoing (see e.g. talk by C Kelly at Lattice 2018)



Other prospects

Lattice will play an increasing role in both K- and B-physics, eg:

ΔM_K as a precision probe of CP-conserving new physics (long-distance calculation of

Heavy-light form factors for $B \to K^*$ ($K\pi$) transitions & ability to treat multiparticle states

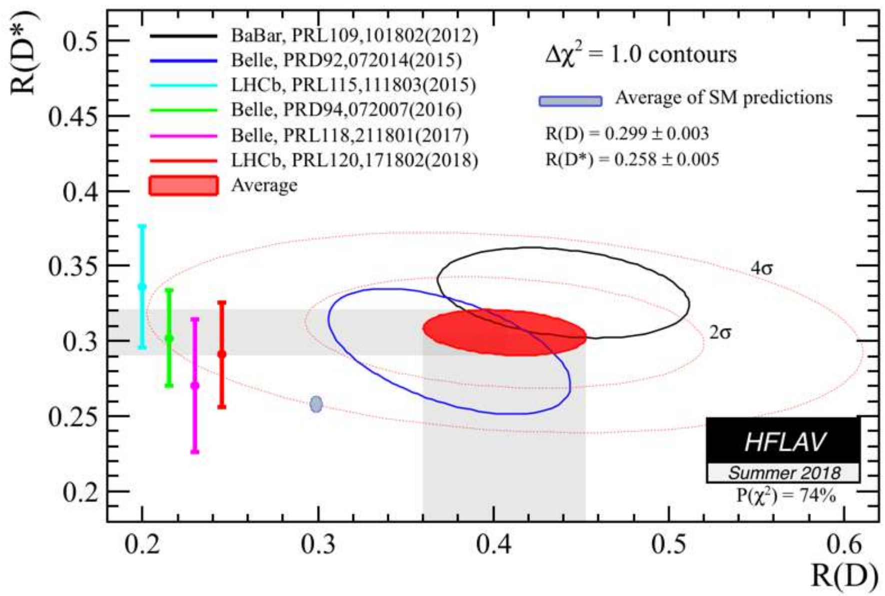
[see also poster on $3N \to 3N$ scattering]

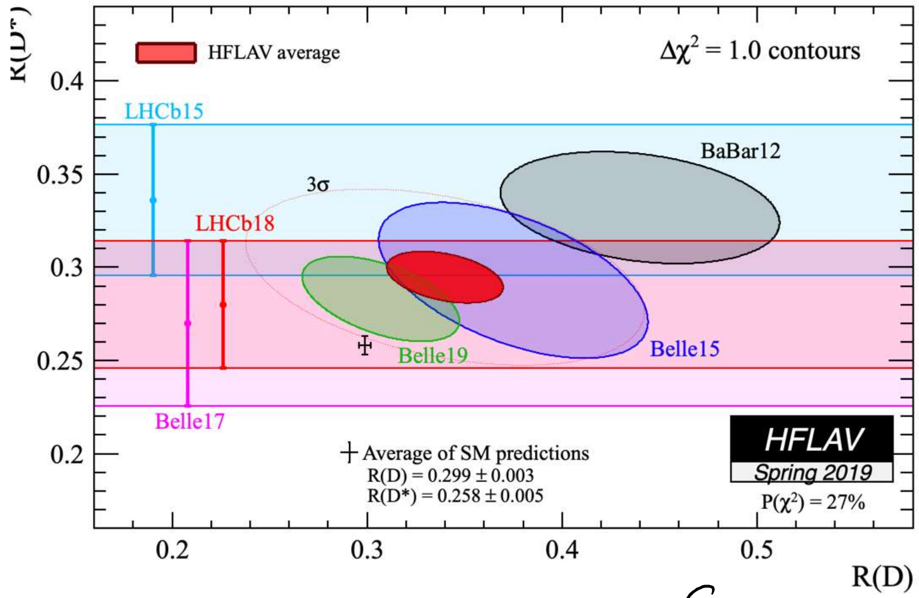
Virtual-charm contributions for $K \to \pi\nu\nu$ decays

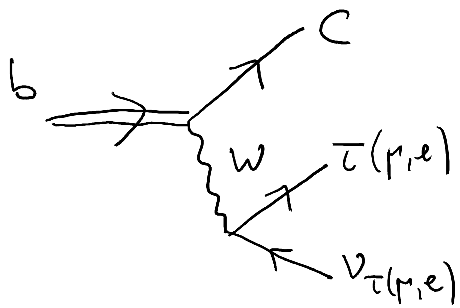
…

Non-rare B-decays

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



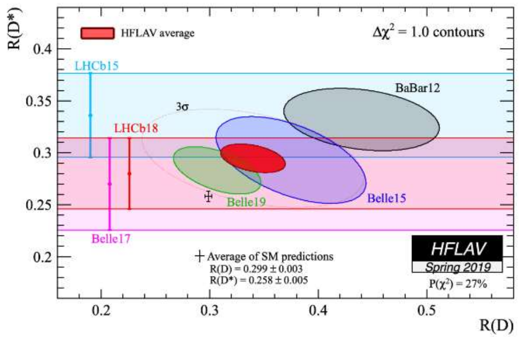




large effect – SM tree-level process!
theory error still (almost) negligible

How significant is this deviation?

HFLAV quote a 3.1σ discrepancy with SM



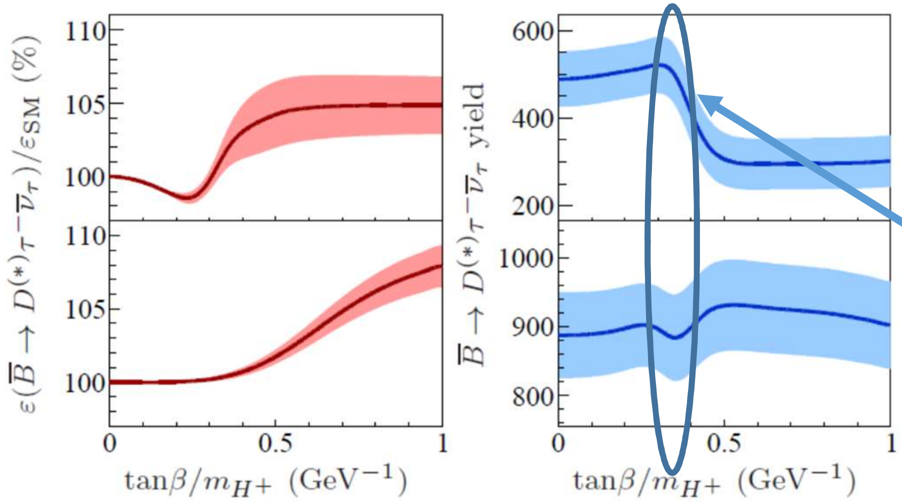
This is a statement that, within a model where (R_D, R_{D^*}) are free parameters, the SM values are excluded at 3.1σ.

By contrast, evaluating the p-value of the SM (where R_D and R_{D^*} have definite values!) from χ^2_{min} would give an exclusion of the SM at 2.7 σ (neglecting the small theory error), **slightly** down from 3.0 σ in 2018.

Caveat

$$\mathcal{L}_{\rm eff}^{\rm LE} \supset -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^\tau)(\bar\tau\gamma_\mu p_L \nu_\tau)(\bar c\gamma^\mu P_L b) + \epsilon_R^\tau(\bar\tau\gamma_\mu P_L\nu_\tau)(\bar c\gamma^\mu P_L b)$$
$$+\epsilon_{S_L}^\tau(\bar\tau P_L\nu_\tau)(\bar c P_L b) + \epsilon_{S_R}^\tau(\bar\tau P_L\nu_\tau)(\bar c P_R b) + \epsilon_T^\tau(\bar\tau\sigma_{\mu\nu}P_L\nu_\tau)(\bar c\sigma^{\mu\nu}P_L b)] + \text{H.c.},$$

BSM affects signal shape, hence fitted value of R_D, R_{D^*} through signal efficiencies and fitted background components



Babar 1303.0571
2HDMII (= ε_{SR}^τ model)

BSM starts to dominate
ε_{SR}^τ ~ 1 here !

For BSM << SM, the modifications are small.
Ultimately addressed through Wilson coefficient fits by the experiments (Hammer)

BSM implications of B-anomalies

Summary of (quark) flavour anomalies

observable	Anomaly	Significance (sigma)
BR(B →{K,K*,ϕ} μμ) at low dilepton mass q^2	Lowish w.r.t expectation	1-2 ?
B→K*μμ angular distribution (low q^2)	P_5' off for some q^2	2-3 ?
$R_{D(*)}$ = BR(B→D(*)τν)/ BR(B→D(*)lν)	Enhanced w.r.t. SM	3-4
Lepton-universality ratios (R_K, R_{K*})	Suppressed w.r.t. SM	3-4 (3 observables combined)
ε'/ε (direct CPV in K_L->ππ)	Below SM	3 ?

LHCb: substantial part of dataset not yet analysed.

Belle II has astarted

Scale of new physics

Di Luzio, Nardecchia 2017

B-decay anomalies point to (at least) the interactions

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

numerically $\Lambda \sim 3$ TeV and $\Lambda \sim 30$ TeV.

Uncertainties below factor 2 (if anomalies are genuine).

Recall in the case of the Fermi theory, $G_F \sim g^2/M_W^2$

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

Partial-wave unitarity: maximal NP scale of below 10 (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 the bounds are (so far) high, the fact that there are any at all should be encouraging, further refinements may be possible.

SU(2)$_W$ & model-independent constraints

Two purely left-handed SU(2) invariants once doublet structure of fermions considered (for each choice of generation indices)

$$O_S = (\bar{L}\gamma_\mu \bar{L})(\bar{Q}\gamma^\mu Q) \qquad O_T = (\bar{L}\gamma_\mu \sigma^I \bar{L})(\bar{Q}\gamma^\mu \sigma^I Q)$$

Both operators contribute to further processes that are experimentally constrained, in particular:

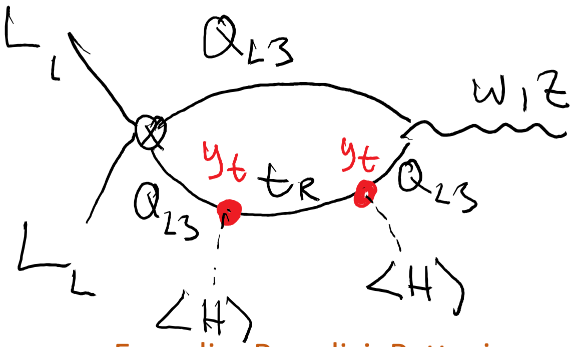
$B \to K^* \nu\nu \quad \to \quad C_{T,3323} \approx C_{S,3323}$

at one loop:

$Z \to \tau\tau$, $Z \to \nu\nu$

$\tau \to Z^*\mu$, $W^*\ \nu$ ($\to$ 3 leptons)

Problematic for very low Λ



Feruglio, Paradisi, Pattori
arXiv:1606.00524, arXiv:1705.00929

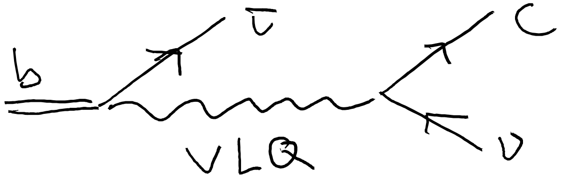
Tree-level mediators: leptoquarks

Scalar or vector leptoquarks can generate interactions

Eg Gripaios, Nardecchia, Renner, …
(Hiller, Nisandzic 2017)

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

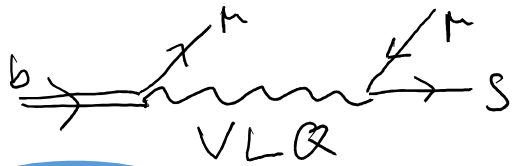
$(3, 1, -1/3)$ or $(3, 3, 2/3)$



$(3, 1, 2/3)$ or $(3, 3, 2/3)$

$$\frac{1}{\Lambda^2}\,(\bar{s}_L\gamma^\mu b_L)\,(\bar{\mu}_L\gamma_\mu\mu_L)$$

$(3, 3, -1/3)$

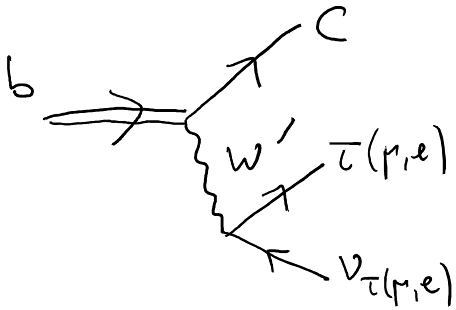


$(3, 1, 2/3)$ or $(3, 3, 2/3)$

(more possibilities at loop level Eg Bauer,Neubert; Becirevic et al)

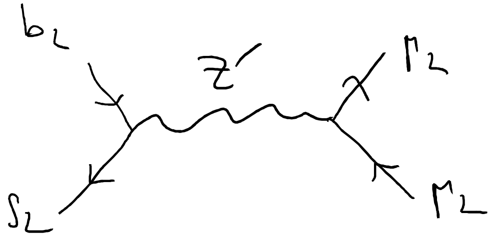
Tree-level mediators: W', Z'

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



$$(0,3,0)$$

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



$(0,3,0)$ or $(0,1,0)$

- appear as resonances in composite models (KK excitations in RS, vectors coupling to symmetry currents in 4D composite models)

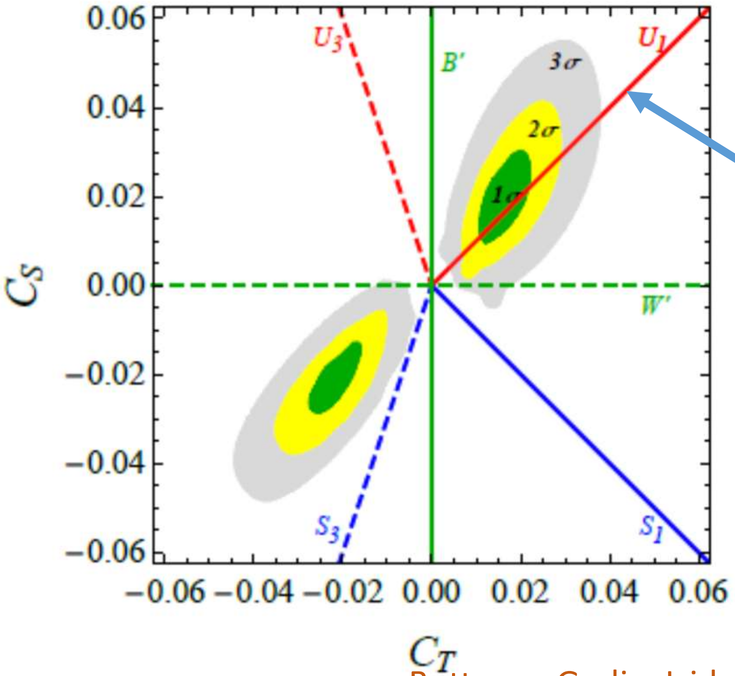
- Z' exchange contributes to B_s mixing at tree-level. Leptoquarks do not!

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

Global fit & single mediators

- Global fit to anomalies, previously mentioned constraints, and the coefficients of the two purely left-handed operators
- Compare to pattern predicted by a single mediator

(Axis scales depend on flavour structure of mediator couplings, fitted simultaneously.)



$(3, 1, 2/3)$

vector leptoquark

Buttazzo, Greljo, Isidori, Marzoca arXiv:1706.07808

Partial compositeness

SM fermions are mixtures of elementary and composite particles, eg

$$|t_L^{\mathrm{phys}}\rangle \approx \cos\phi_{t_L}|t_L\rangle + \sin\phi_{t_L}|T_L\rangle$$

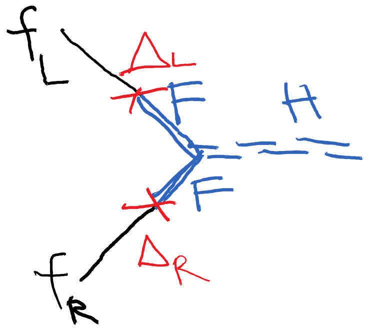
by virtue of

$$\mathcal{L}_{\mathrm{mix}} \supset -\lambda_{tL}\bar{t}_L T_L \qquad\qquad (\sin\phi_{t_L} = \lambda_{t_L}/(1+\lambda_{t_L}^2))$$

where T_L is a CFT spin ½ operator with dimension ~ 5/2 and $|T_L\rangle$ its lightest excitation (a Dirac fermion)

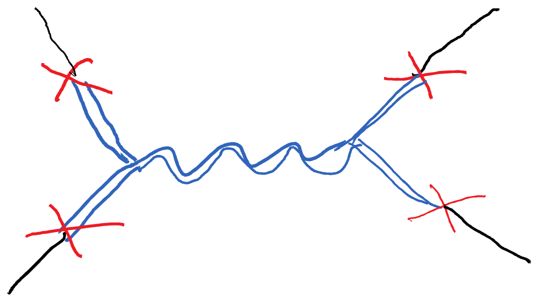
Can generate a potential for a pNGB (natural) Higgs & cause EWSB

can generate flavour hierarchies



$$Y_{ij} = (\Delta_L^\dagger M_L^{-1}\hat{Y} M_R^{-1}\Delta_R)_{ij}$$

leading BSM effects:



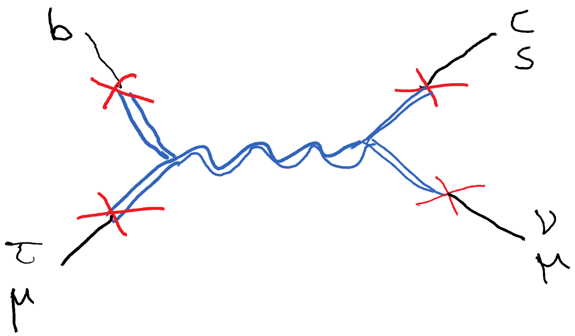
$$\sim \frac{g_*^2\Delta^4}{M^6}(\bar{f}\Gamma f)(\bar{f}\Gamma f)$$

Composite leptoquark

Minimal G is $SU(3)_C x SU(2)_L x SU(2)_R x U(1)_X$ [hypercharge & EWPT]

$Y = T_{3R} + X$

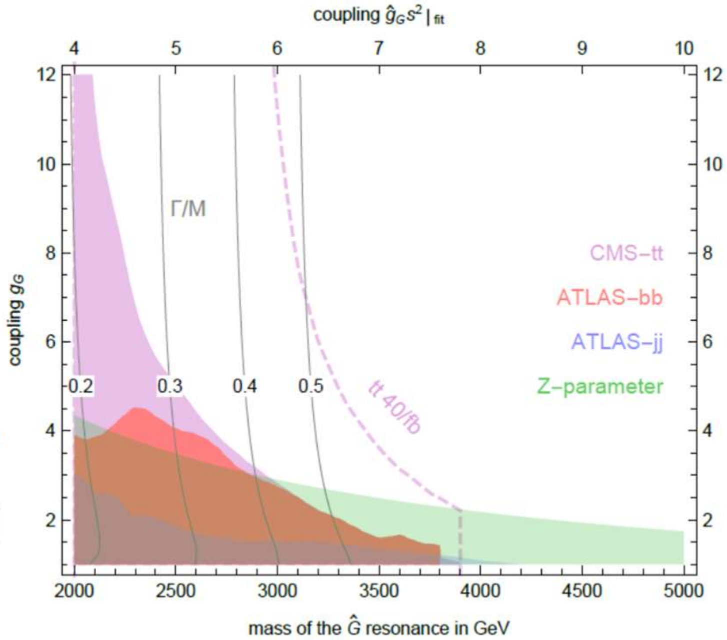
Increasing the SU(3) to SU(4) get **symmetry currents in** $(3,1,2/3)$ **of SM & vector leptoquarks** Barbieri, Murphy, Senia arXiv:1611.04930



Extend to [SU(4)xSO(5)xU(1)]/[SU(4)xSO(4)xU(1)] NGB Higgs model Barbieri, Tesi arXiv:1712.06844

Flavour structure based on approximate $U(2)^3$ symmetry Barbieri, Isidori, Pattori, Senia 1512.0156

Stringent LHC constraints, strong coupling



Summary & outlook

Flavour provides a plethora of observables sensitive to new physics

Stringent constraints on new physics, not only from meson-antimeson mixing

Significant progress in lattice calculations for flavour phenomenology

B-anomalies – independent verification by upcoming Belle2 experiment. If true, may point to partial compositeness. Related to grand unification?

BACKUP

A Z' model for $R_{K(*)}$

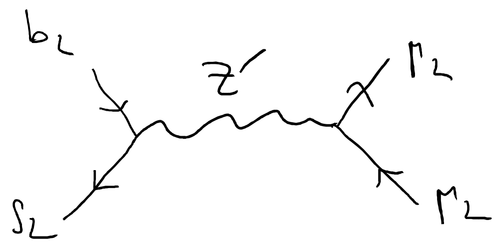
Accommodating *all* b->s l l anomalies *requires* a muon-specific C_L – type interaction

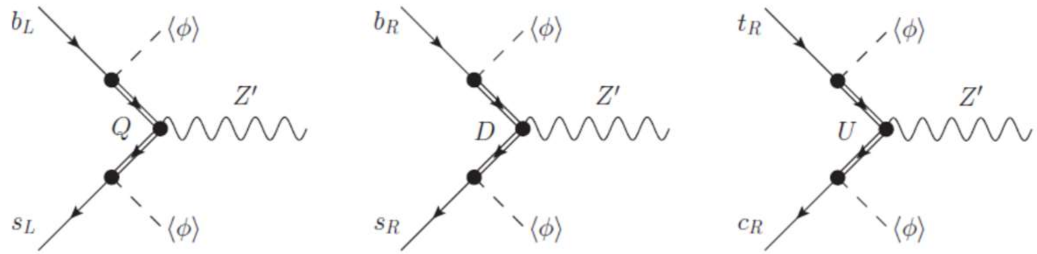
$$\frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$

with Λ ~ 30 TeV

However, C_R is weakly constrained and can also be present.

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





The small coupling to quarks suppresses contributions to Bs mixing

Also Crivellin et al, …

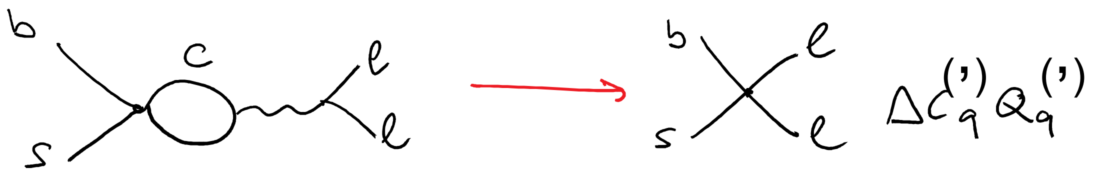
b->c cbar s operators BSM

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

As long as NP mass scale M is >(>) mb, most general BSM in $b \to c\bar{c}s$ **model-independently** captured by an effective Hamiltonian with 20 operators/Wilson coefficients (including SM)

$$
\begin{aligned}
Q_1^c &= (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i), & Q_2^c &= (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j), \\
Q_3^c &= (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i), & Q_4^c &= (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j), \\
Q_5^c &= (\bar{c}_R^i \gamma_\mu b_R^j)(\bar{s}_L^j \gamma^\mu c_L^i), & Q_6^c &= (\bar{c}_R^i \gamma_\mu b_R^i)(\bar{s}_L^j \gamma^\mu c_L^j), \\
Q_7^c &= (\bar{c}_L^i b_R^j)(\bar{s}_L^j c_R^i), & Q_8^c &= (\bar{c}_L^i b_R^i)(\bar{s}_L^j c_R^j), \\
Q_9^c &= (\bar{c}_L^i \sigma_{\mu\nu} b_R^j)(\bar{s}_L^j \sigma^{\mu\nu} c_R^i), & Q_{10}^c &= (\bar{c}_L^i \sigma_{\mu\nu} b_R^i)(\bar{s}_L^j \sigma^{\mu\nu} c_R^j),
\end{aligned}
$$

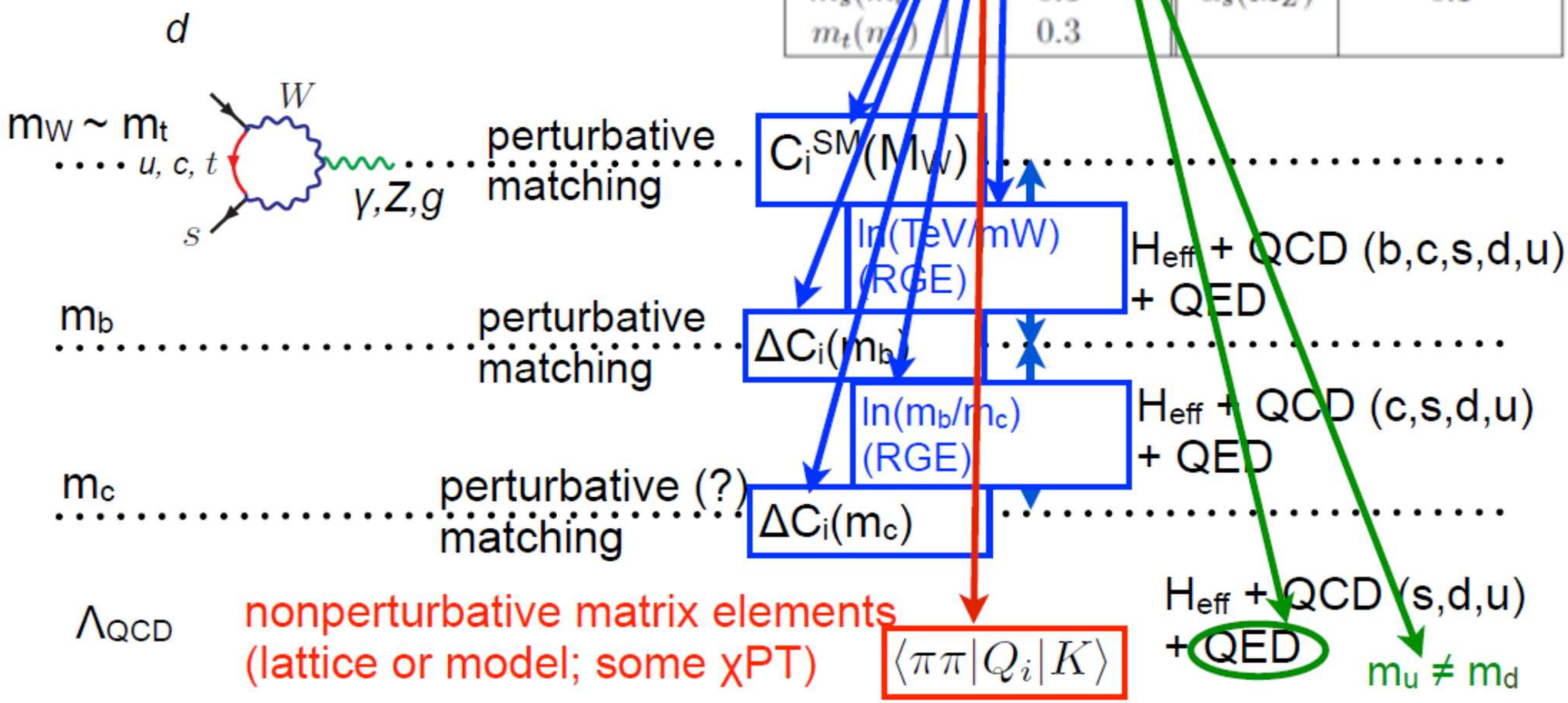
+ 10 parity conjugates



+ dipoles

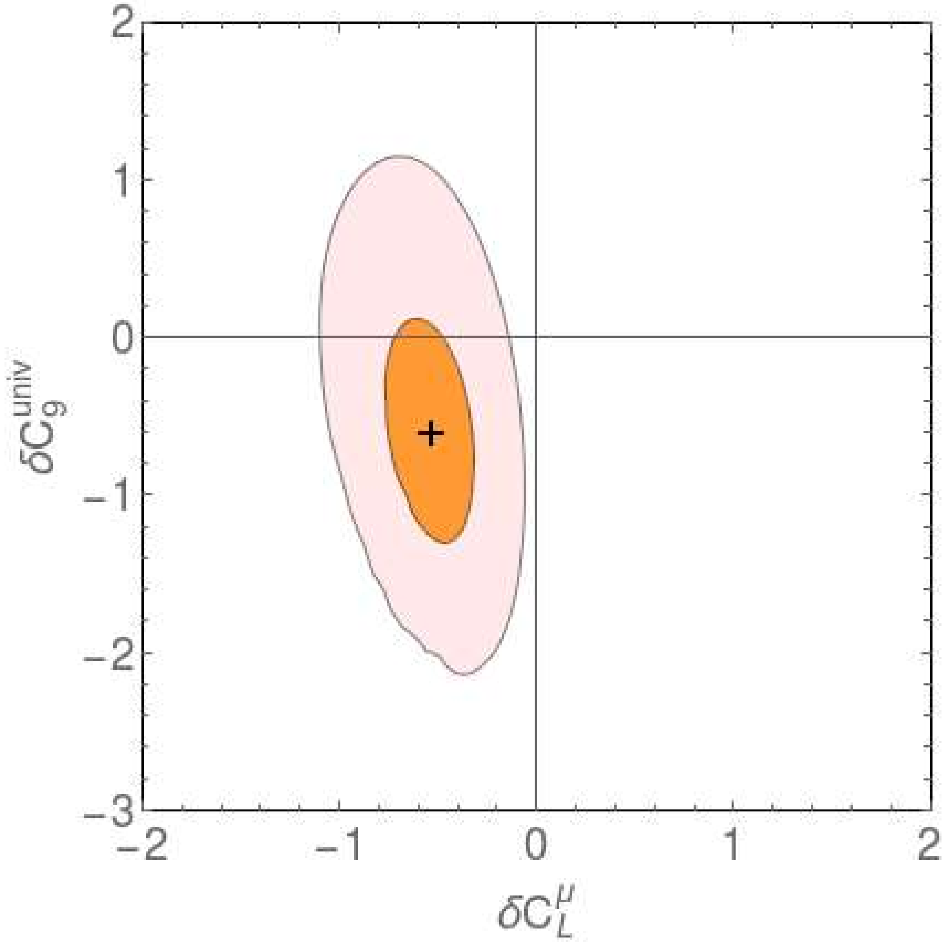
Standard Model

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
$\hat{\Omega}_{\rm eff}$	0.7	$B_8^{(1/2)}$	0.1
p_3	0.6	$\mathrm{Im}\lambda_t$	0.1
$B_8^{(3/2)}$	0.5	p_{72}	0.1
p_5	0.4	p_{70}	0.1
$m_s(m$	0.3	$\alpha_s(M_Z)$	0.1
$m_t(m$	0.3		



Must C_9 violate lepton flavour?

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



(also Alguero et al arXiv:1809.08447; post 2019 Moriond fits)

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

A model with (for example) nonzero $C_L{}^{\mu}$ and in addition an ordinary, **lepton-flavour-universal, C_9**, could describe the data as well or better

may be **radiatively generated**

$$(\bar{s}\gamma^{\mu}P_L b)(\bar{c}\gamma_{\mu}P_L c)$$

('charming BSM' scenario)

SJ, Kirk, Lenz, Leslie arXiv:1701.09183

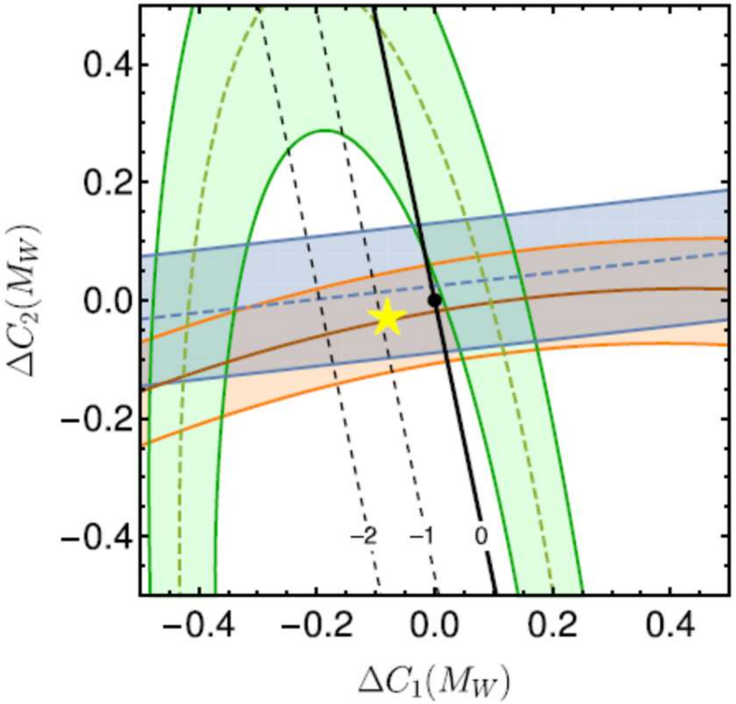
or $(\bar{s}\gamma^{\mu}P_L b)(\bar{\tau}\gamma_{\mu}P_L\tau)$

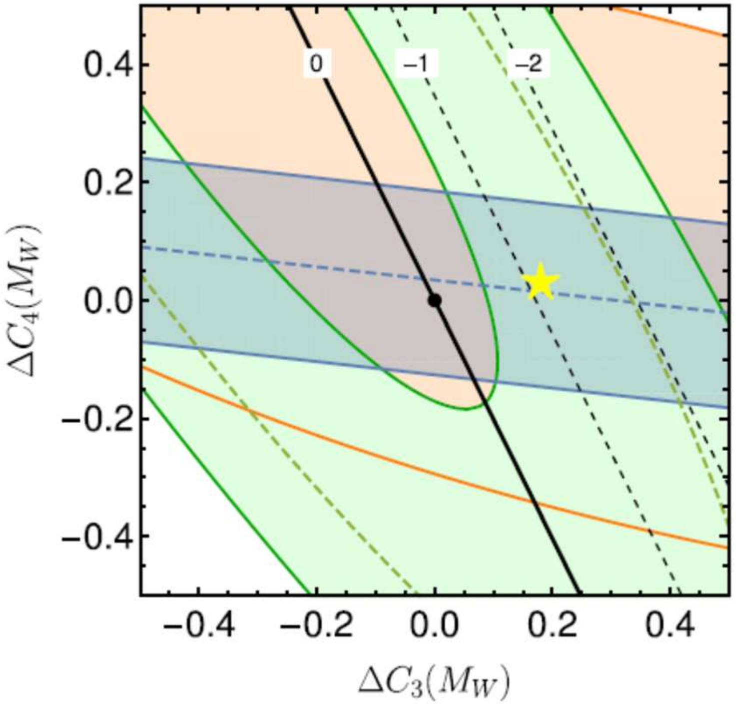
Bobeth & Haisch 1109.1826, Crivellin et al arXiv:1807.02068

Global analysis

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

'LH currents' – strong mixing into C_9





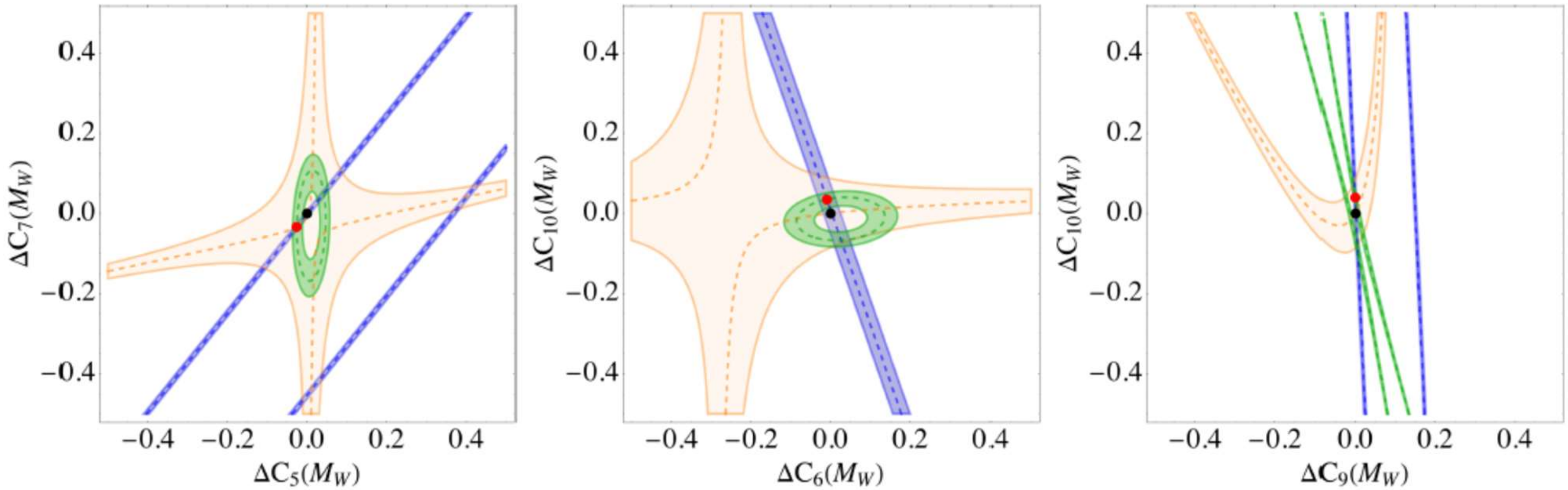
Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

Dashed/solid black: C9(BSM)

Global analysis

SJ, Kirk, Lenz, Leslie   to appear

‘LH currents’ – strong mixing into dipole

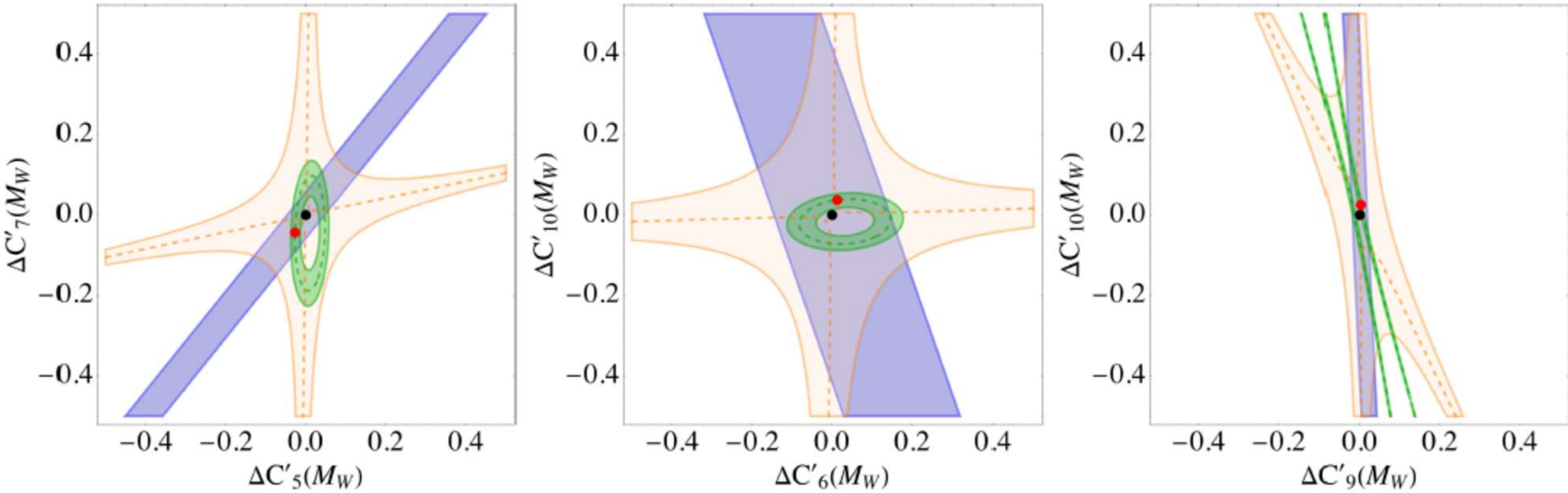


Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

Global analysis

SJ, Kirk, Lenz, Leslie   to appear

‘RH currents’ – strong mixing into dipole



Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

C_9 from BSM $(\bar{s}b)(\bar{\tau}\tau)$ operators

Bobeth, Haisch arXiv:1109.1826
Crivellin et al arXiv:1807.02068

Similarly strong RG mixing into C_9 as in charming BSM case

- This operator is automatically present for "left-handed" $R_{D(*)}$ explanations via $(\bar{c}_L\gamma^\mu b_L)\,(\bar{\nu}_\tau\gamma_\mu\tau_L)$

  This is a consequence of $SU(2)_W$ symmetry and the experimental bound on $B \to K^*\nu\nu$ Buras et al arXiv:1409.4557

- Radiatively generated C_9 is again O(1) and negative (and lepton-universal)