New Physics with (Mostly Heavy) Flavours

Sebastian Jäger (University of Sussex)

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Outline

Case for new physics with flavour

B-physics and anomalies

Implications: NP scales and mediators

A little bit on Kaons

Summary

History: Beyond Electrodynamics

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

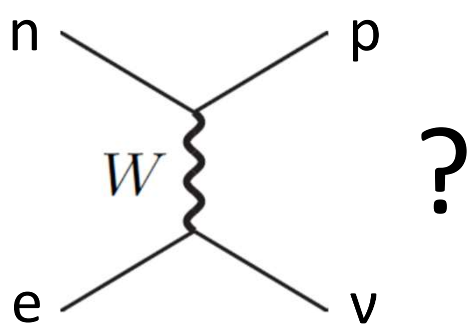
A Polyakov

Fermi's original description of beta decay (1934) (in modernised notation):

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

In modern language: nonrenormalizable, dim-6 operator.

The current-current structure (resembling a QED 2→2 scattering amplitude) is suggestive of a massive vector-boson mediator



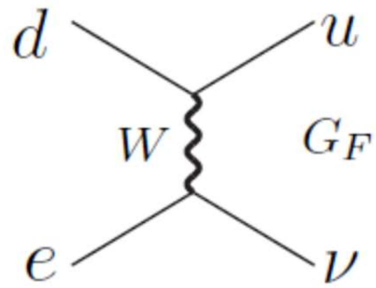
The precision frontier

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
CP violation	Christenson et al 1964
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

the SM was complete.

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



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

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

Renormalizable: may have cut-off >> M_W

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

Effective contact interactions

Heavy physics with mass scale M described by local effective Lagrangian at energies below M (many incarnations)

Effective Lagrangian dimension-5,6 terms describes **all** BSM physics to $O(E^2/M^2)$ accuracy. **Systematic & simple**. E.g.

Buchmuller, Wyler 1986
Grzadkowski, Misiak, Iskrzynski, Rosiek 2010

Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

operators (vertices) are catalogued for arbitrary (heavy) new physics

Only trace of BSM physics is in their (Wilson) coefficients

Much slower decoupling with M than in high-pT physics.

Possibility to probe well beyond energy frontier.

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

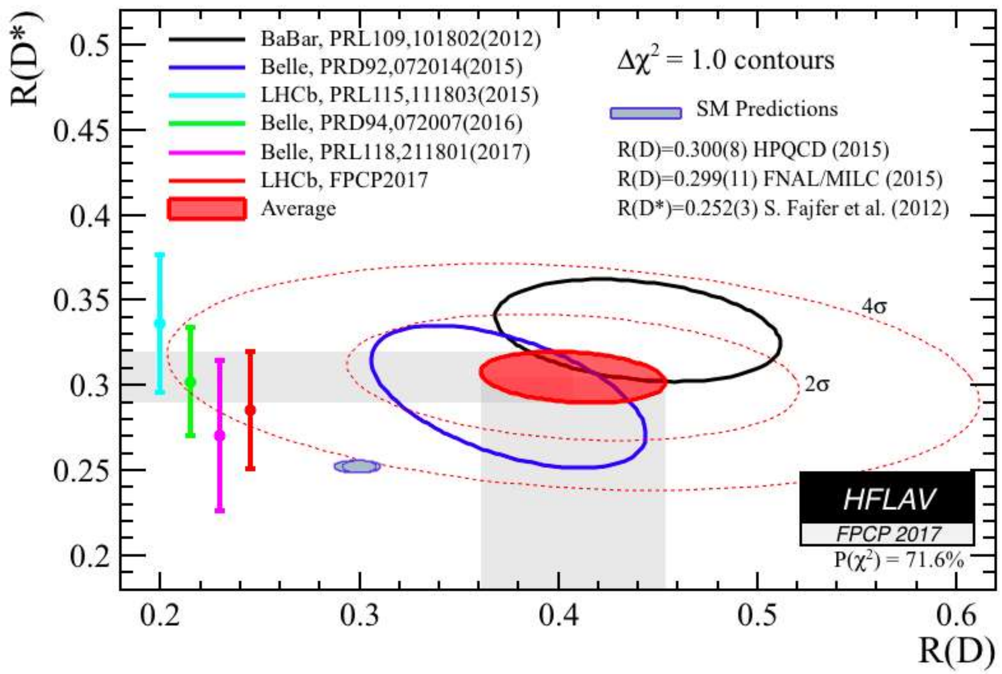
- CP violation, eg

  $K_L \to \pi\,\pi$ $(\varepsilon_K, \varepsilon'_K)$ — …, NA48, KTeV

  $K_L \to \pi^0 \nu \nu$ — KOTO

Anomaly I: semileptonic decays

For some time B-factories and LHCb have consistently shown semileptonic B ->D (D*) τν decay rates larger than expected (relative to the rate for light leptons).

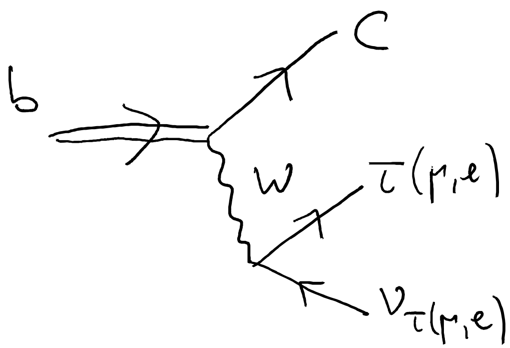


$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\ell\nu_\ell)}$$

4.1 sigma effect

ca 20% deviation

SM **tree-level**



A **large** effect; theory error negligible

What operators?

Several possible contact interactions

$$(\bar{c}\Gamma b)(\bar{\nu}_\tau \Gamma' \tau)$$

with different spin (Dirac) structure.

Several further clues:

- measured shape of differential decay distribution

  Eg Ligeti et al 2015,16

- avoiding excessive contributions to B_c decay

  Grinstein et al 2016, …

- interference with SM amplitude to enhance effect

favour a purely left-handed coupling $(\bar{c}_L \gamma^\mu b_L)\,(\bar{\nu}_\tau \gamma_\mu \tau_L)$
with coefficient ~ 10% of SM value

Rare semileptonic B-decay

many results from Babar, Belle, LHCb, ATLAS, CMS

Sensitive to several contact interactions:

C9: dilepton from vector current

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

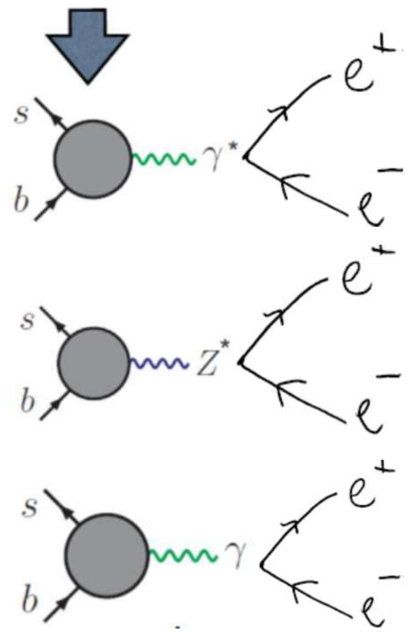
C10: dilepton from axial current

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

C7: dilepton from dipole

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

in SM mainly

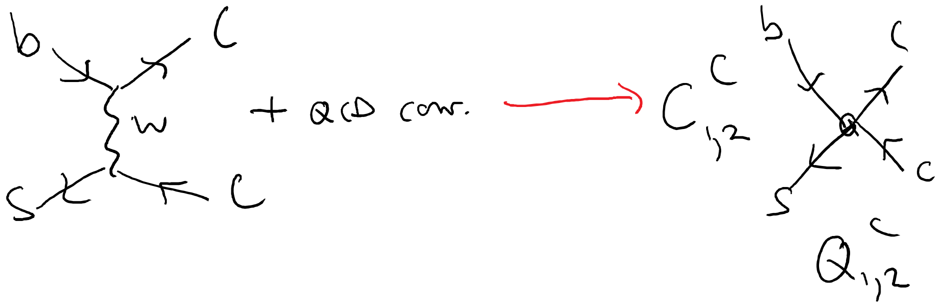


Alternative basis with chiral leptons

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

Impact of 4-quark operators

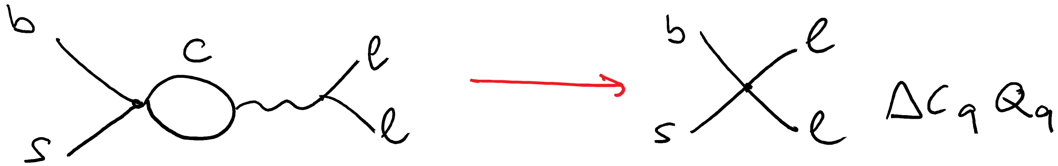
Also **purely hadronic** operators are important, primarily:



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

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

RG mixes these into C9 and C7



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

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

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

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

SM contribution is accidentally almost purely left-chiral

Rare B-decay: observables

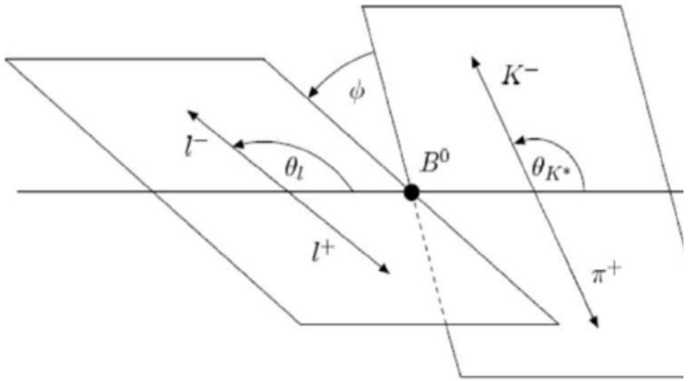
Branching ratios (differential in dilepton mass):

$B \to K^{(*)}\mu\mu$, $B \to K^{(*)}ee$, $B_s \to \phi\mu\mu$

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

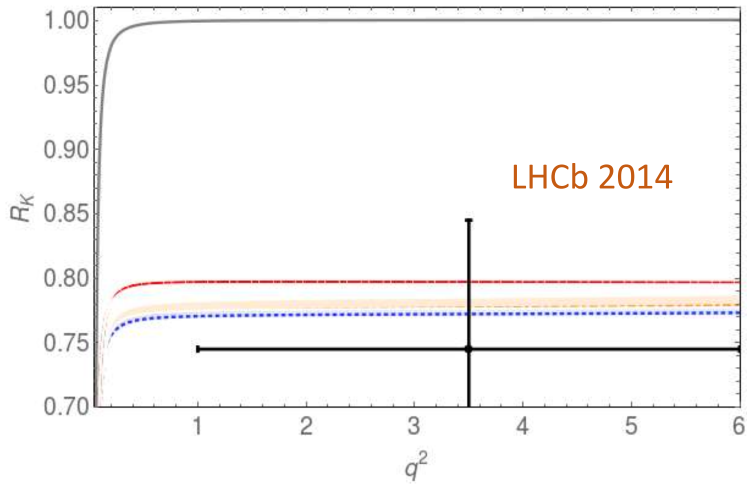


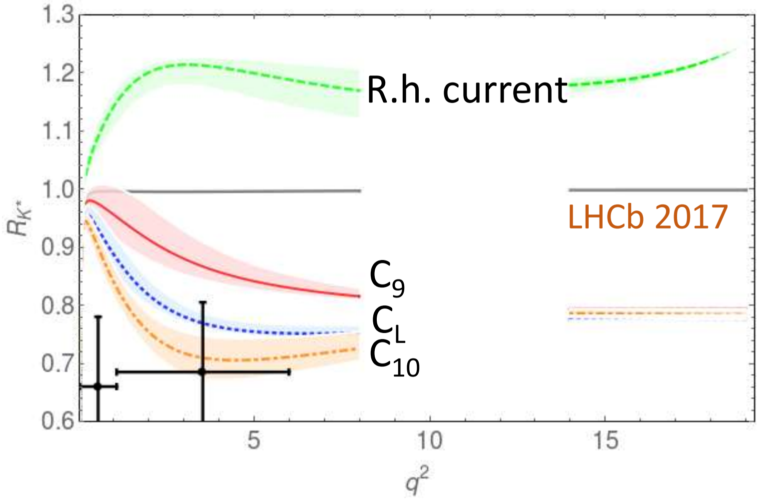
7 angular differential observables:
(A_{FB}, P_5', etc)

Anomaly II: Lepton-flavour ratios at LHCb

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

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





Theory uncertainties negligible relative to experiment.

p(SM) = 2.1 x 10^{-4} (3.7σ)

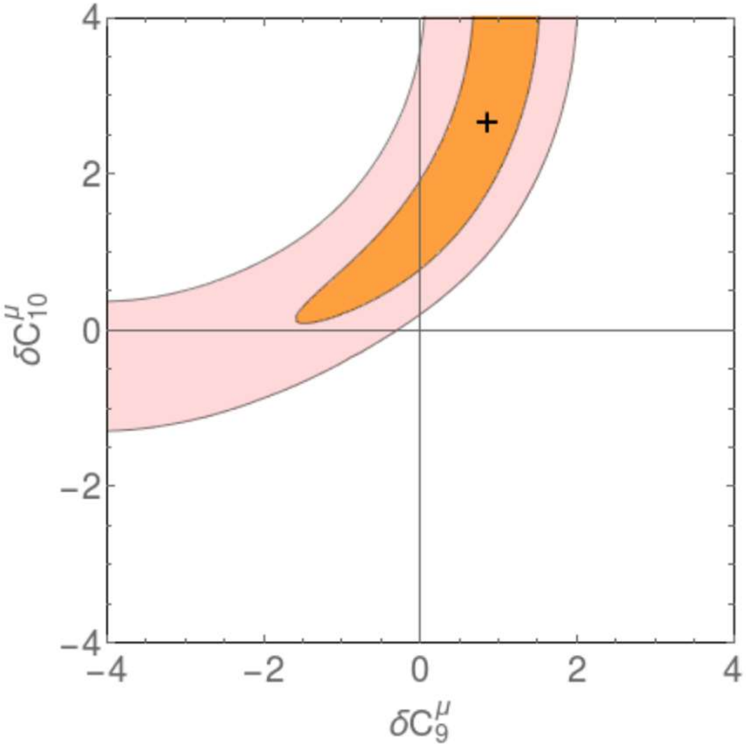
Suggests nonzero, muon-specific C_{10}^{BSM} - not pure C_9

Fit to new physics: 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.

1σ and 3σ confidence regions

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

$p(C_9$ & $C_{10}) = 0.158$

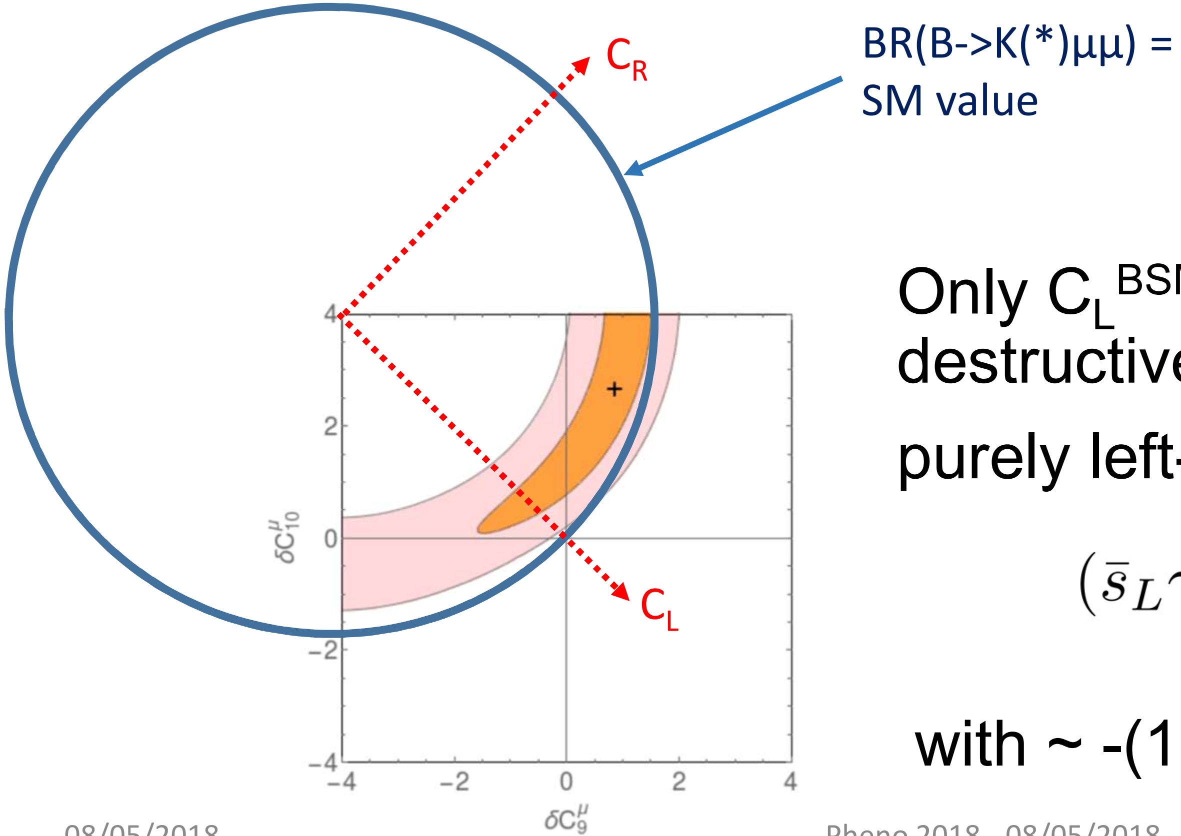
SM point excluded at 3.78 σ

Considerable degeneracy (flat direction in χ^2)

$R_K^{(*)}$ and C_L

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

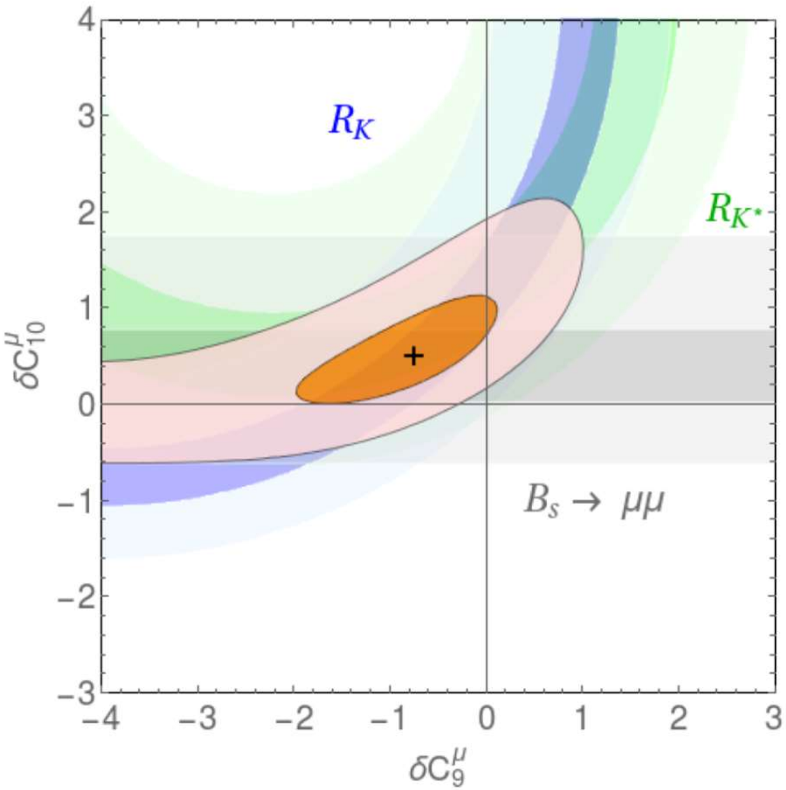


Only C_L^{BSM} can interfere destructively: $R_K^{(*)}$ point to purely left-handed coupling

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

with ~ -(10-15)% of SM value

Adding $B_s \to \mu\mu$



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 $C_L = (C_9 - C_{10})/2$

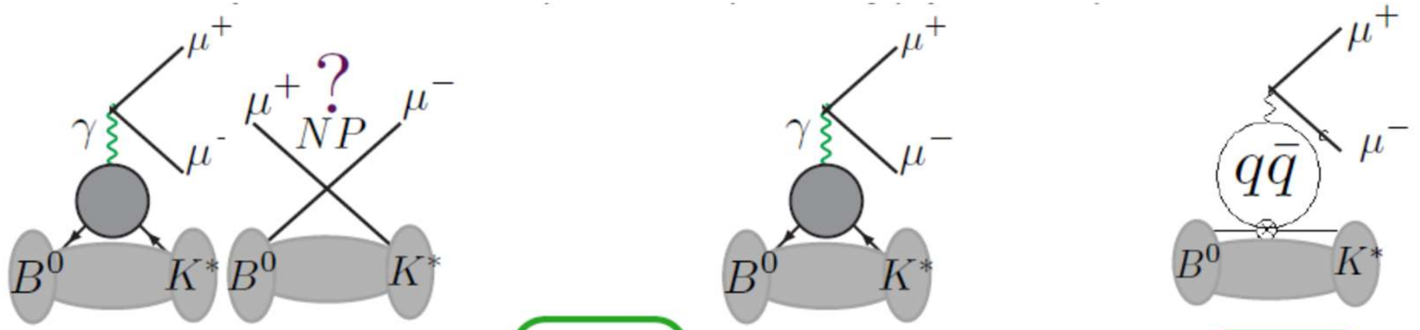
$C_R = (C_9 + C_{10})/2$ not well constrained and consistent with zero

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

Rare decays: amplitude anatomy

C_9 enters multiplied by a form factor, and with additive corrections:



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

photon pole at $q^2=0$

shifts of C_i degenerate with form factor uncertainties and virtual-charm effects. Cancels out only in lepton-flavour ratios (to <~ 1%)

Form factor *ratios* relevant to angular observables; constrained by heavy-quark limit; power corrections? SJ, Martin Camalich 2012, 2014

No controlled computation of most form factor in most of parameter space; typically light-cone sum rules. Ball&Braun; Ball& Zwicky; Bharucha et al 2015

Anomaly III: several low branching ratios

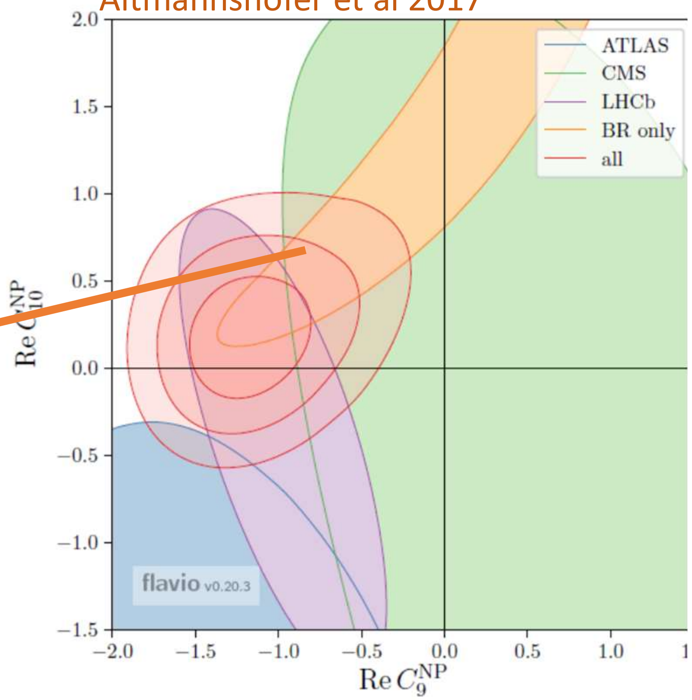
Schematically for B→Kμμ (neglecting small imaginary parts)

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

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

Global fit to b->s l l data

Altmannshofer et al 2017



C_7, h_0, and C_R are small in the SM

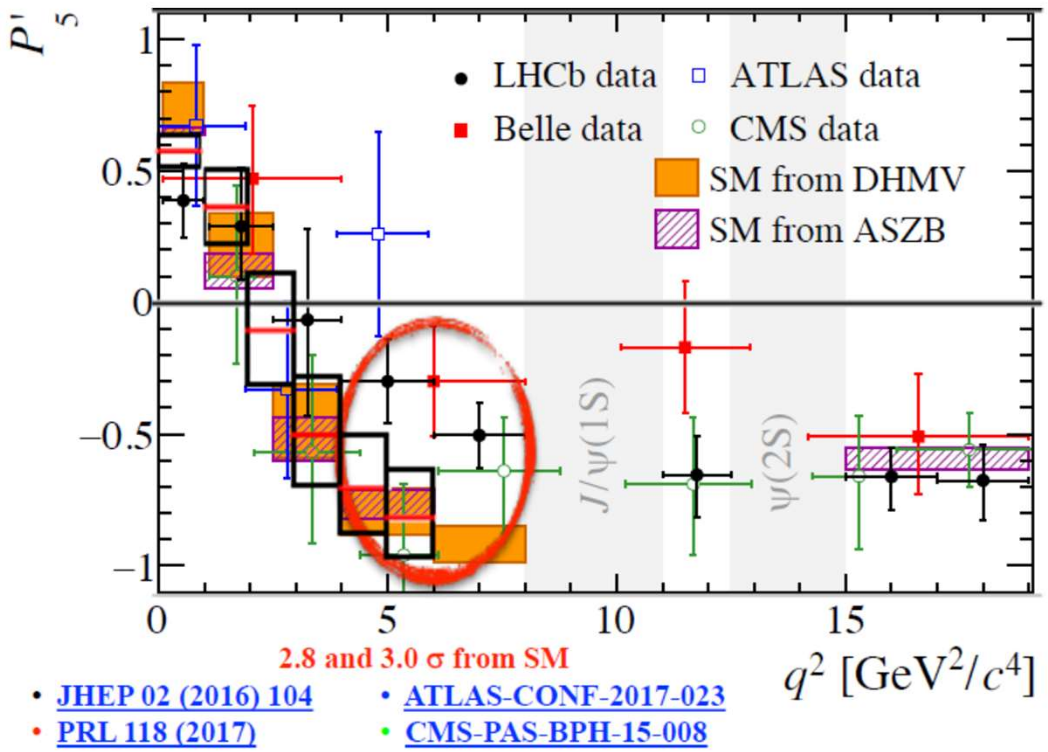
BR essentially is determined by the product $C_L \cdot V$ of a Wilson coefficient and a form factor (V cancelled out for R_K)

suggests 10-15% reduction of C_L

But perfectly degenerate with form factor V !

However, consistent global picture.

Anomaly IV: The (in)famous P5'



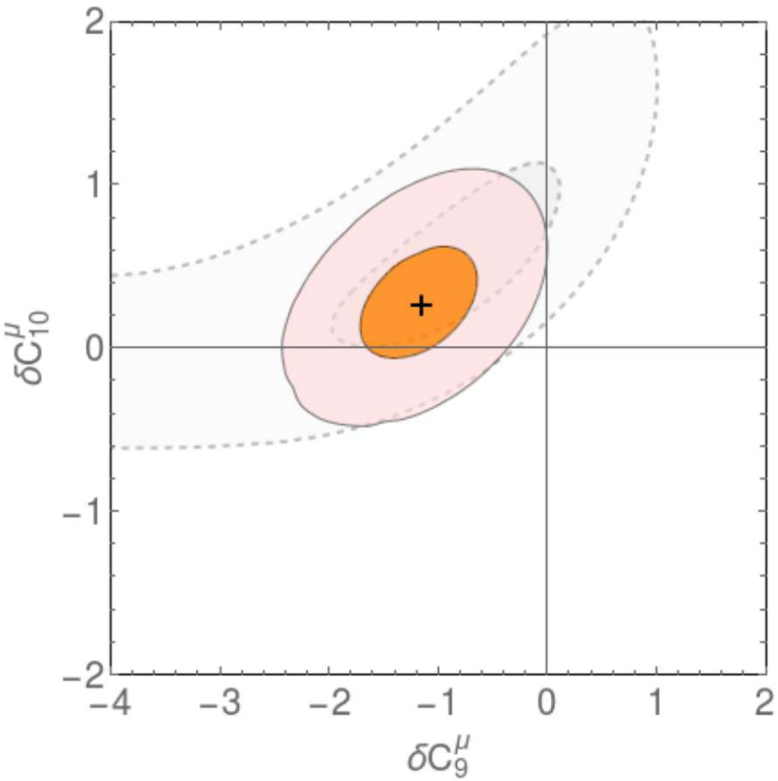
Simone Bifani, seminar at CERN (overlaid predictions from SJ&Martin Camalich 2014)

Modest discrepancy around 4-6 GeV, suggesting reduced C_9

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

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

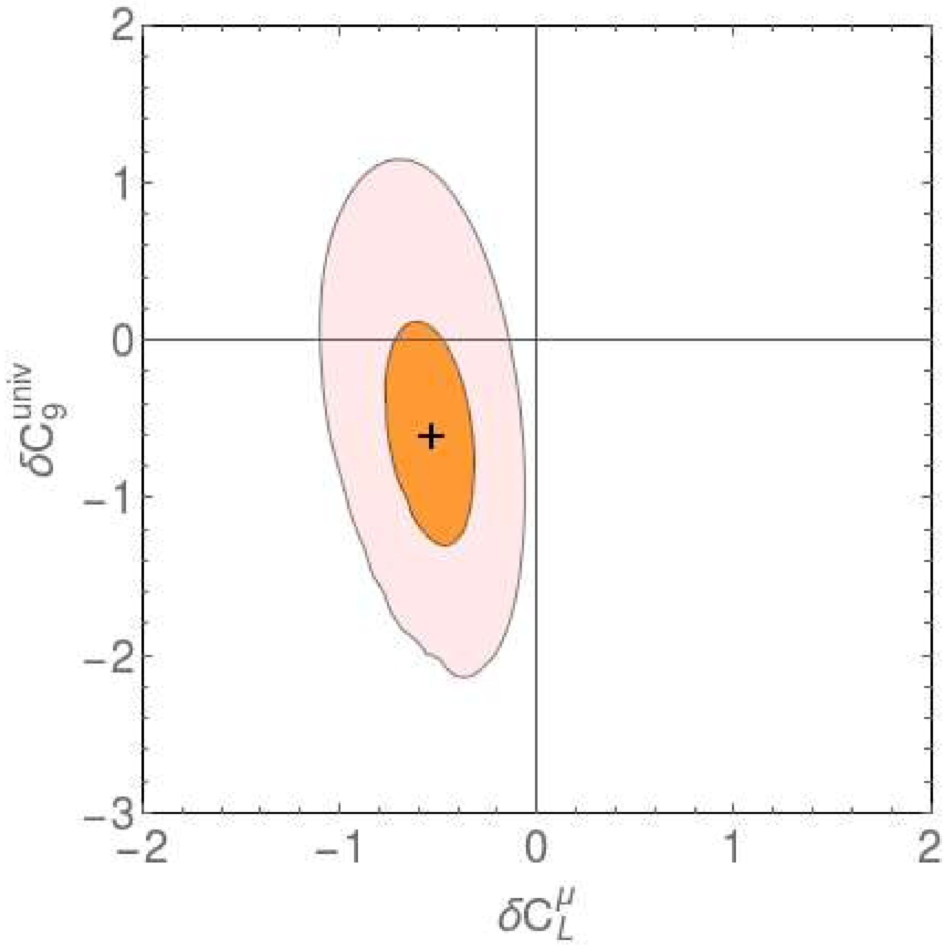
p = 0.572 [63 dof]

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

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

Must C_9 violate lepton flavour?

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



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

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

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

Eg. ‘charming BSM’ scenario

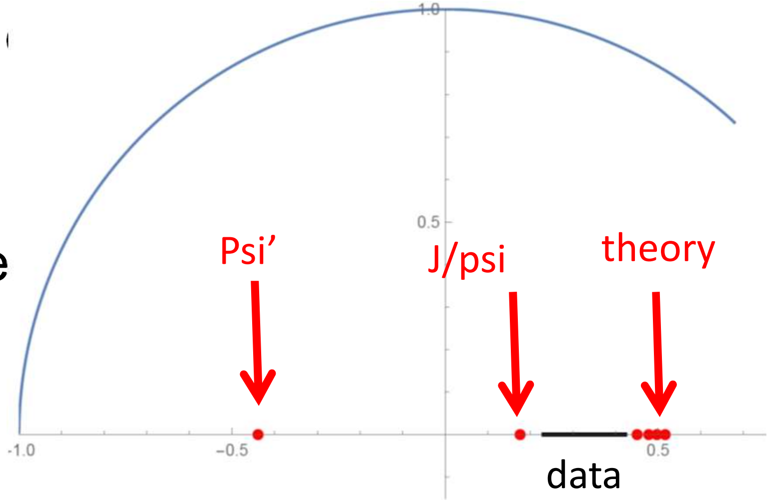
SJ, Kirk, Lenz, Leslie arXiv:1701.09183

Fits of hadronic parameters to data?

Bobeth, Chrzaszcz, Van Dyk, Virto 2017

Basic idea: reduce theory dependence of long-distance virtual charm by using data & analyticity

- use/assume analyticity of the virtual-charm dilepton mass
- Use theory input only at q2 <~ 0
- Data to fix/constrain the residues at the pole
- Conformal mapping to increase separation of the input data from the cut; polynomial fit



k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–

Results disfavour attributing effects to virtual-charm

No new information on form factors (but see LHCb’s fit to $B \to K\mu\mu$)

B-anomalies: summary & prospects

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)

LHCb: rapidly increasing dataset

All will be measured at Belle 2 in the next few years (lower luminosity, but different systematics and excellent control over the electronic final state)

Implications: scale of new physics

Di Luzio, Nardecchia 2017

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

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

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 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.

Possible mediators: b→c τ ν(τ)

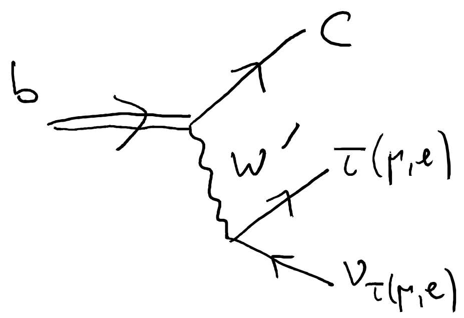
Recall favoured BSM effective interaction

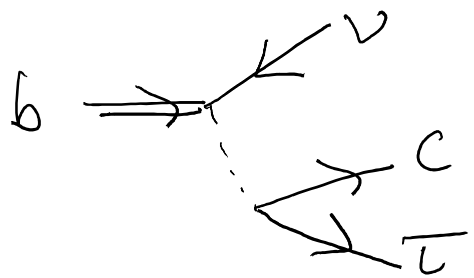
$$\frac{1}{\Lambda^2}\left(\bar{c}_L \gamma^\mu b_L\right)\left(\bar{\nu}_\tau \gamma_\mu \tau_L\right)$$

numerically Λ ~ 3 TeV

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

Possible mediators for b→sμμ: Z'

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

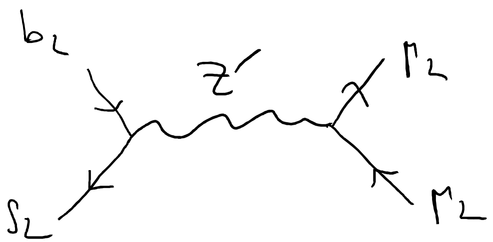
$$\frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$

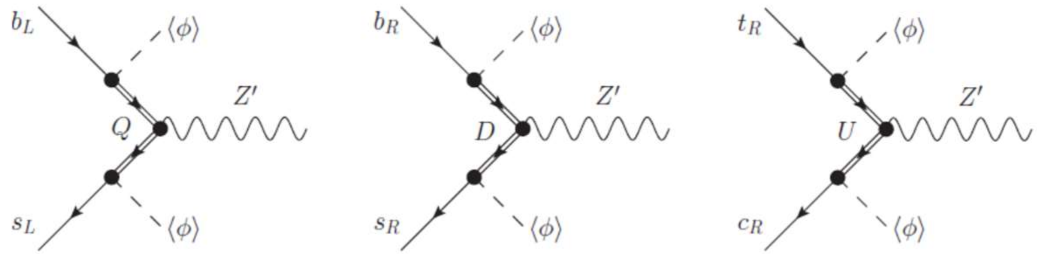
with $\Lambda \sim 30$ TeV

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, …

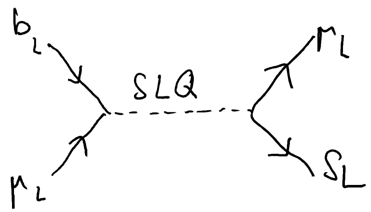
The small coupling to quarks suppresses contributions to Bs mixing

Leptoquark-mediated rare decay

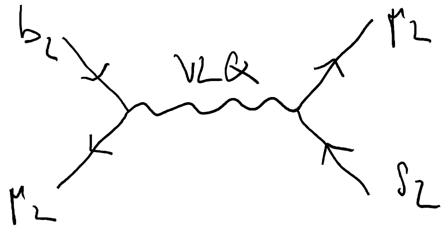
Scalar or vector leptoquarks exchange can also generate a C_L effect.
Eg Gripaios, Nardecchia, Renner

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

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



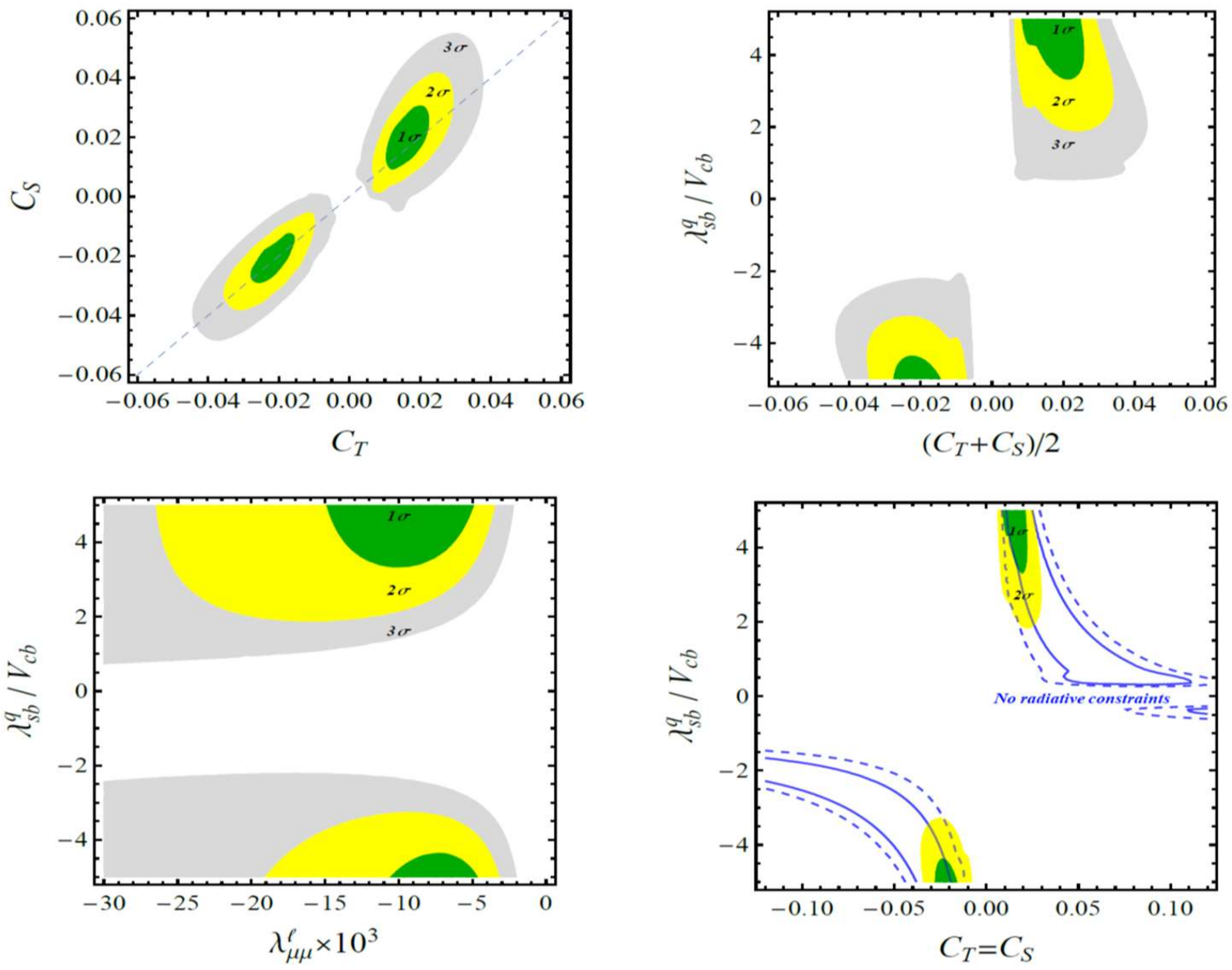
- vector in SM gauge representation $(\bar{3}, 1, 2/3)$ or $(\bar{3}, 3, -2/3)$



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

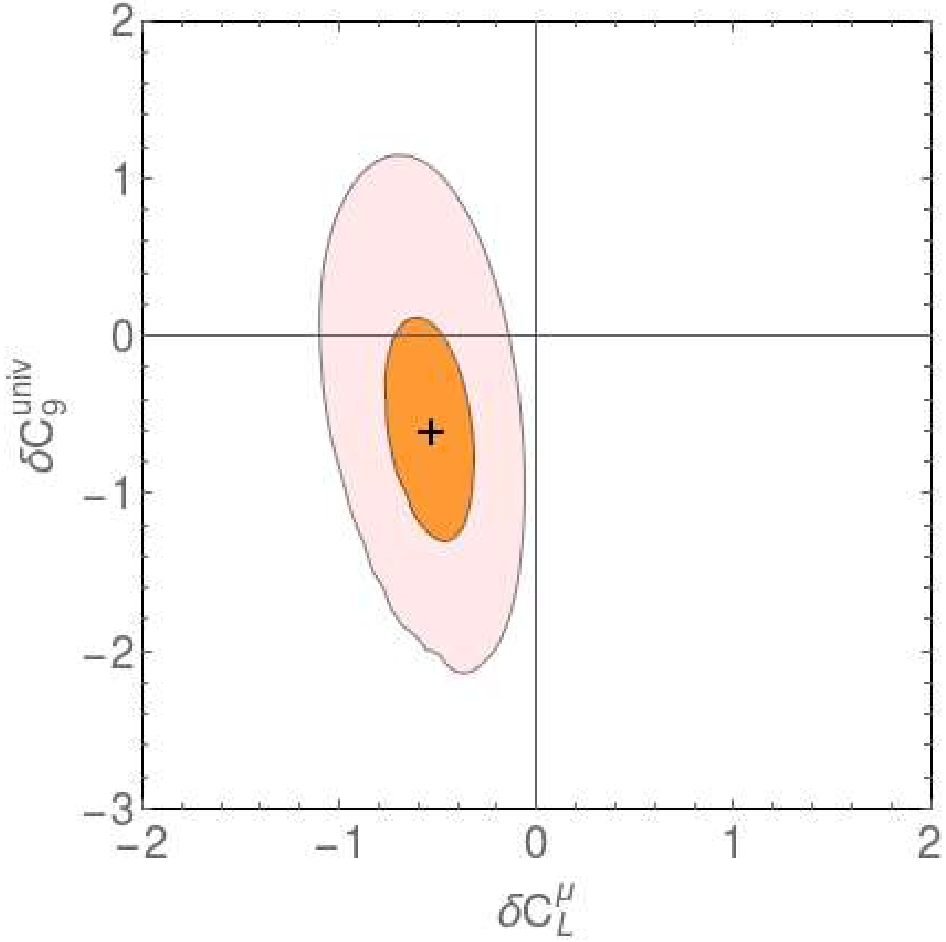
Barbieri, Tesi arXiv:1712.06844

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

Blanke, Crivellin arXiv:1801.07256

Must C_9 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 $C_L{}^\mu$ 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

Theory progress & anomaly V: CPV 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

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

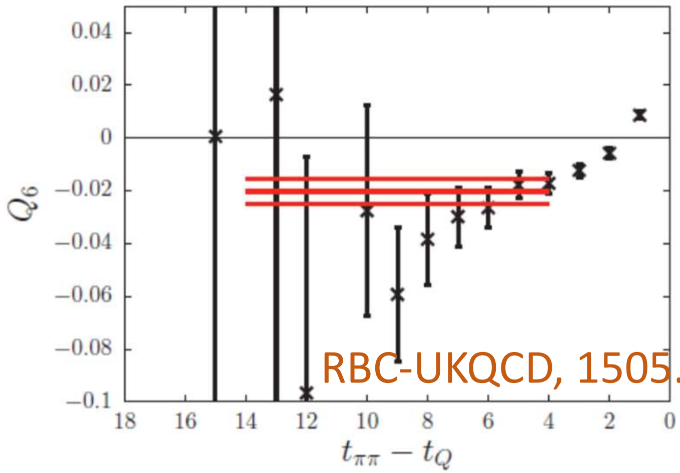
defines Re(ε'/ε) experimentally
left-hand side is measured

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

(magnitudes directly measurable from decay rates)

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)

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

(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	${\rm Im}\lambda_t$	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		

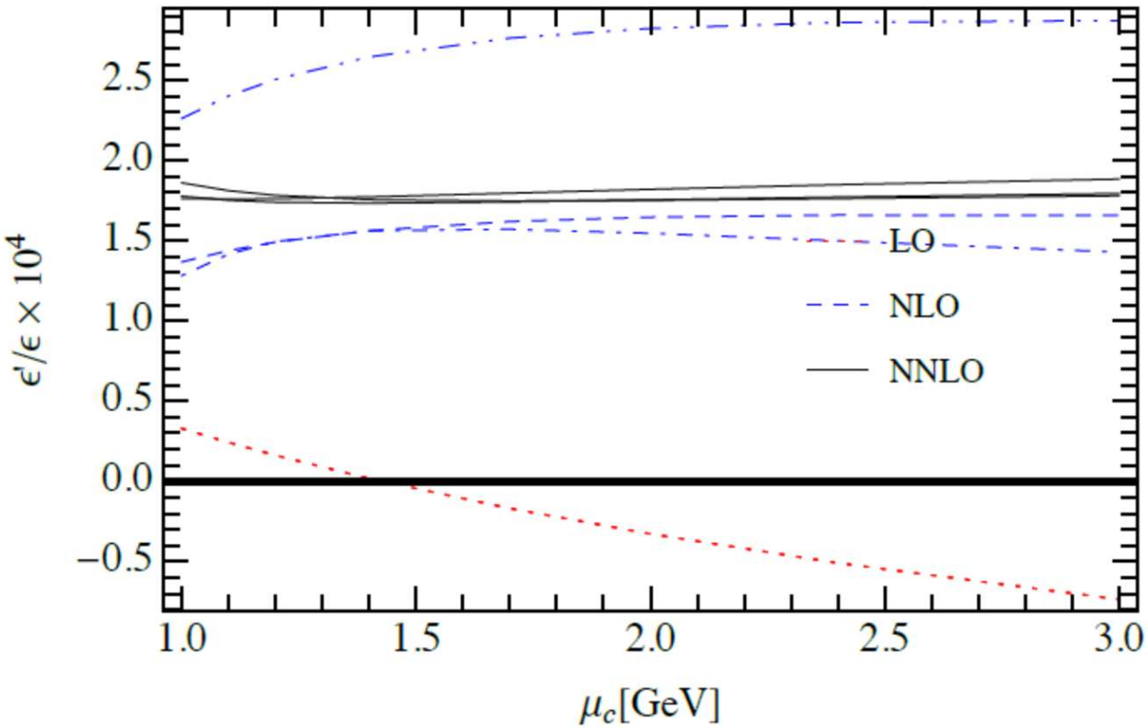
all in units of 10^-4

(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!

Conclusions

Physics with heavy (and not so heavy) flavours provides many search channels that can probe contact interactions with scales beyond the energy frontier

A variety of intriguing signs for departure from the SM, with good prospects for the significance

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

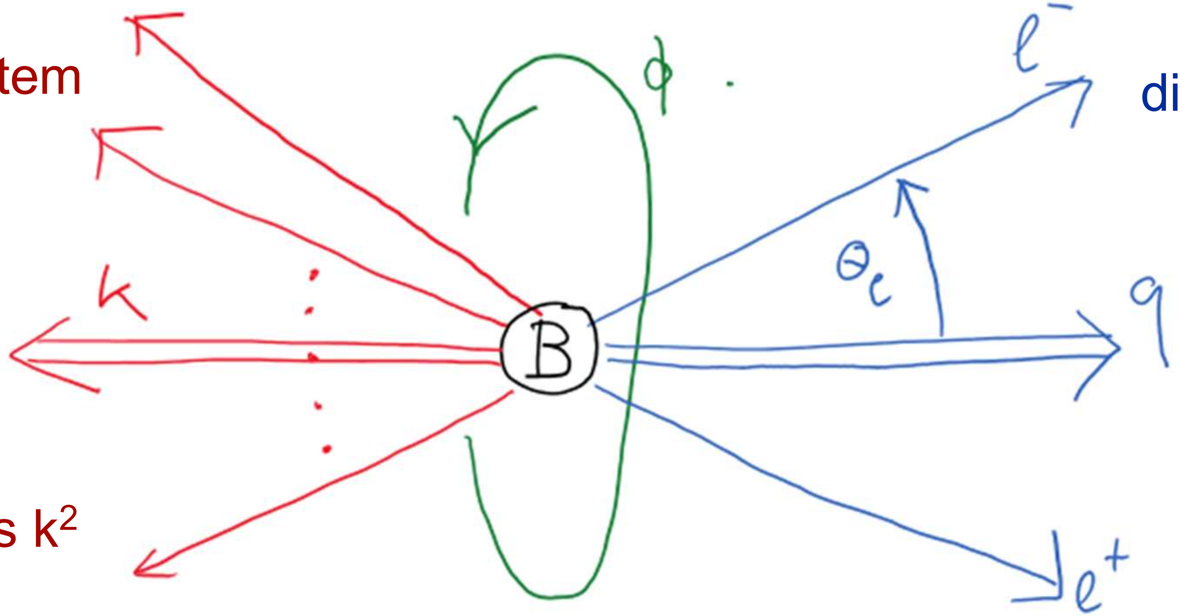
May point to leptoquark and/or Z' mediators, generally within the reach of future colliders. Possible connections with naturalness only recently explored.

BACKUP

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

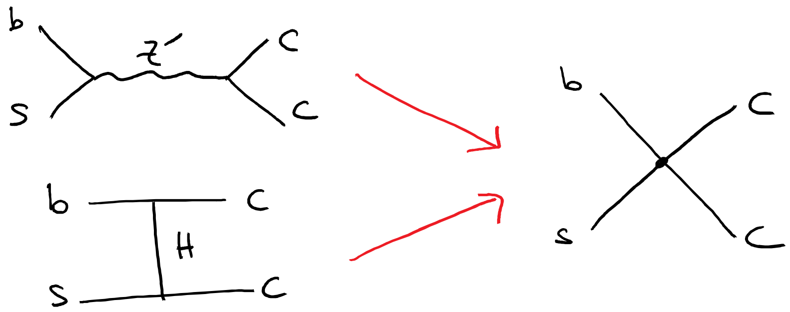
B has spin zero => $\lambda = \lambda'$

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

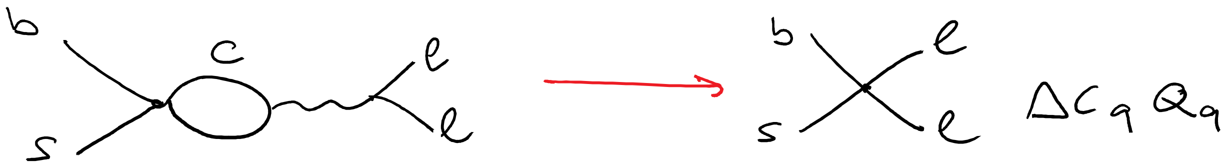
Charming BSM scenario

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

e.g. 1)



2)



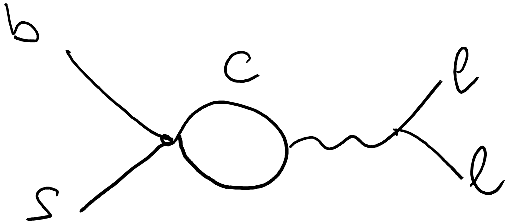
very efficient way to generate C9(NP) = O(1)

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

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

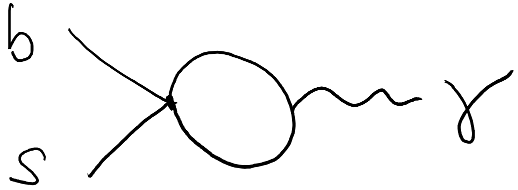
Observables

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



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

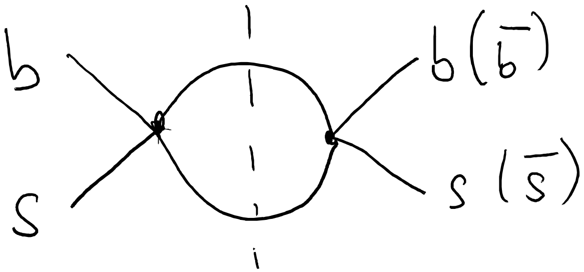
$$C^c_{x,y} = 3\Delta C_x + \Delta C_y$$



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

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