New physics in $b \to c\bar{c}s$ transitions?

Sebastian Jäger
University of Sussex

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Based on work with M Kirk, A Lenz, and K Leslie, PRD & w.i.p.

Outline and summary

Motivation

Model-independent analysis of new physics in $b \to c\bar{c}s$ transitions

Phenomenology

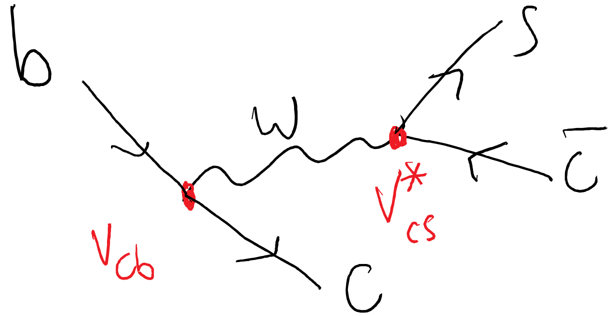
Summary

Charm and new physics

Postulated to explain non-observation of $K_L \to \mu^+\mu^-$ (GIM)

Discovery key to establishing SM

In B physics, charm appears in leading decays through a partonic $b \to c\bar{c}s$ transition. Large CKM factor.

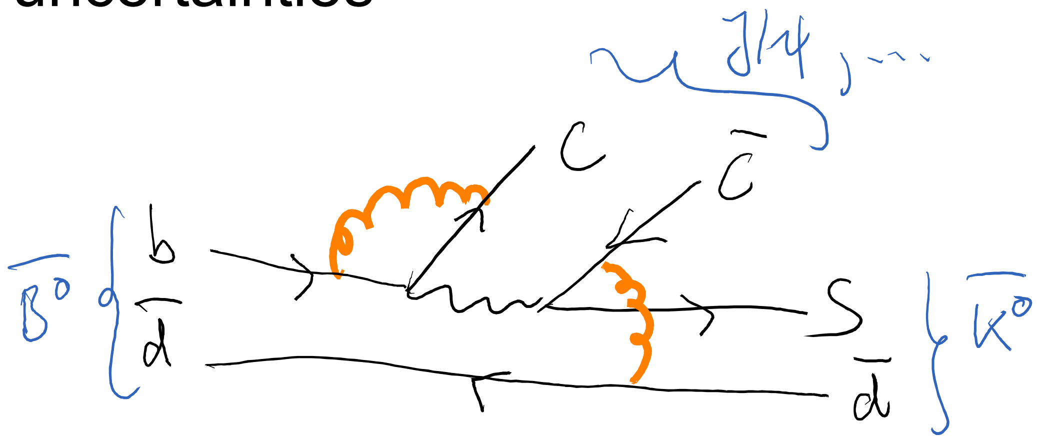


Usually one assumes BSM corrections to be negligible.

Is this assumption well grounded in data (or theory)?

Exclusive B-decay

Exclusive charmful hadronic B-decays suffer from large hadronic uncertainties



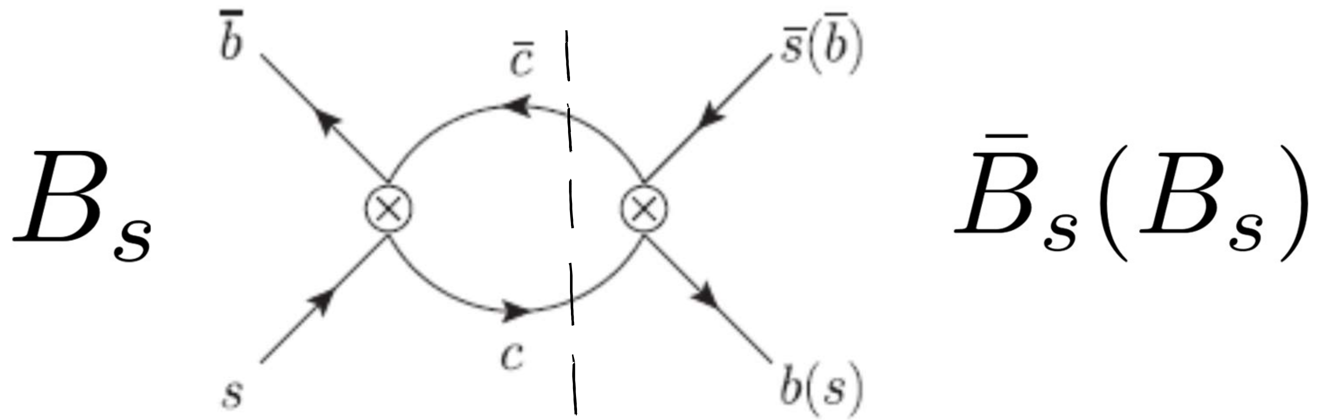
e.g data suggests corrections to (calculable) naïve factorisation O(100%)

Weak sensitivity to BSM contributions, especially if CP-conserving

Lifetime observables

B meson lifetime = free b quark lifetime + (calculable) power corrections

Many contributions cancel out in width difference $\Delta\Gamma_s$ and lifetime ratio τ_{B_s}/τ_{B_d}

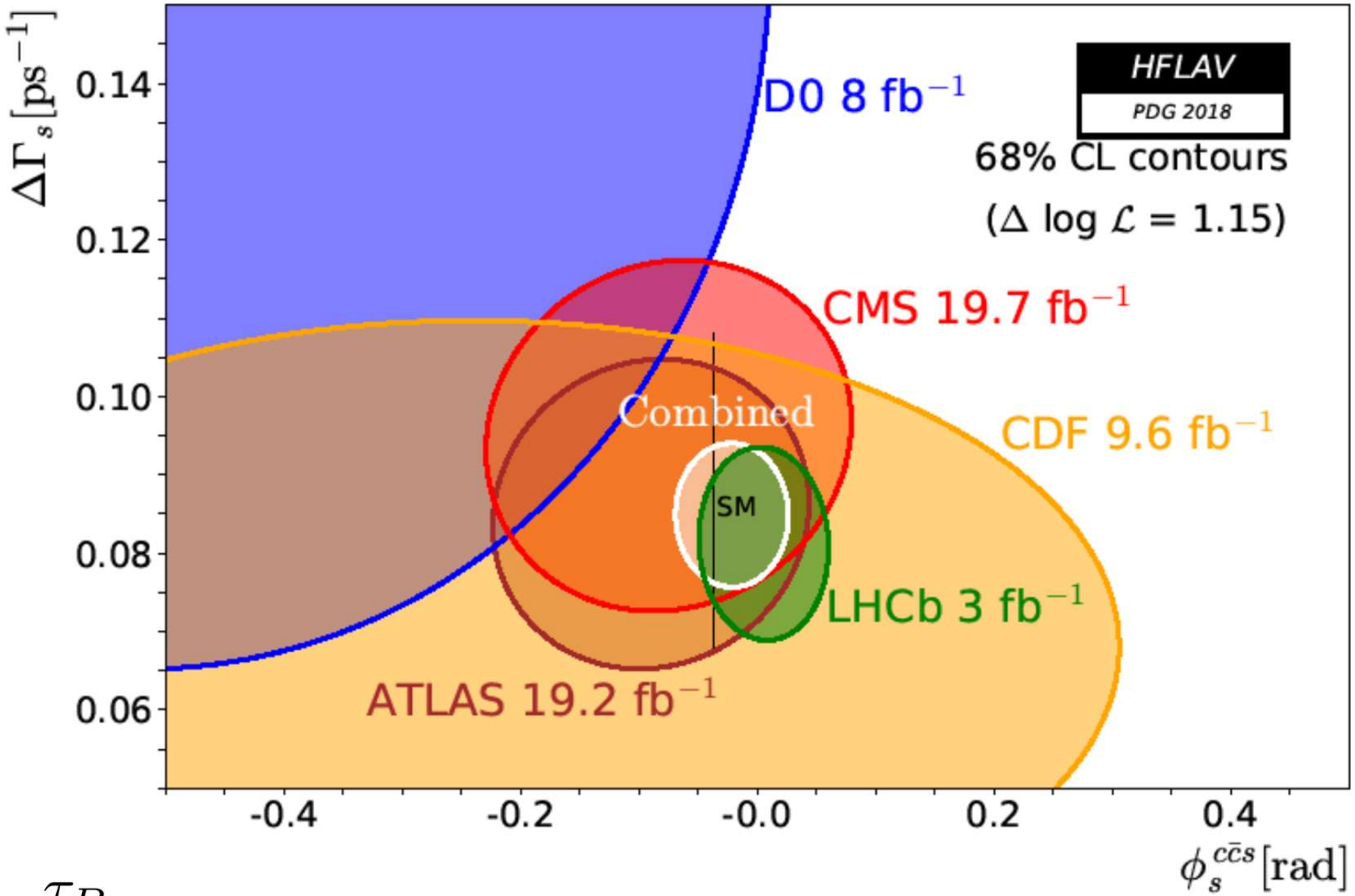


OPE -> local $\Delta B = 2$ operators. “Bag factors” (matrix elements) from lattice.

Enhanced sensitivity to b->c cbar s transition, BSM

Bobeth et al 2014 (2x),
Brod, Lenz, Tetlalmatzi-Xolocotzi, Wiebusch 2014,
also Bauer and Dunn 2011

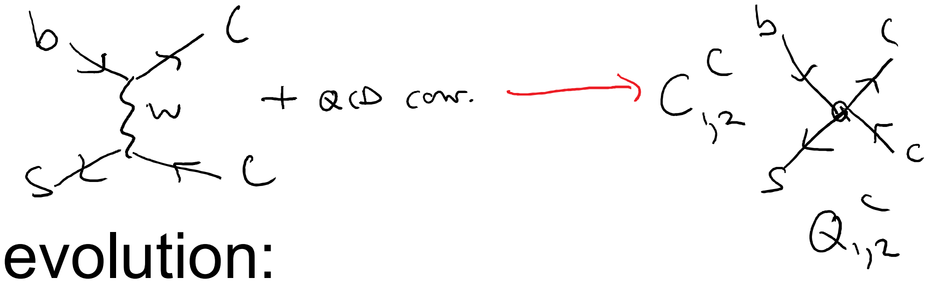
Lifetimes: experiment



$$\frac{\tau_{B_s}}{\tau_{B_d}} = 0.994 \pm 0.004$$ (HFLAV average)

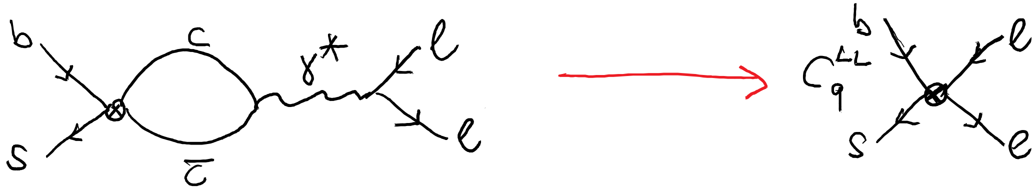
Rare & radiative decays

Standard Model: tree-level W exchange

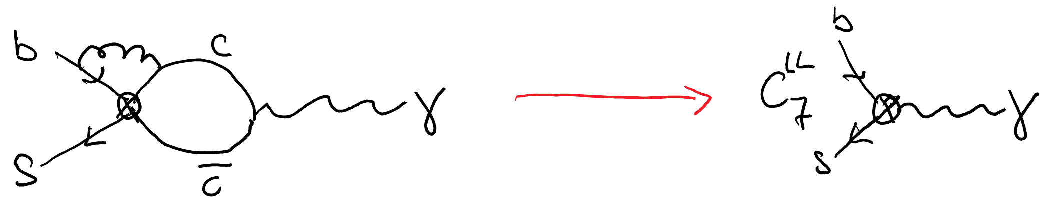


$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i)$$
$$Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j)$$

RG evolution:



$$Q_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$



$$Q_7 \propto (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$$

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

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

O(50%) in both cases comes from virtual charm

Rare & radiative decays: experiment

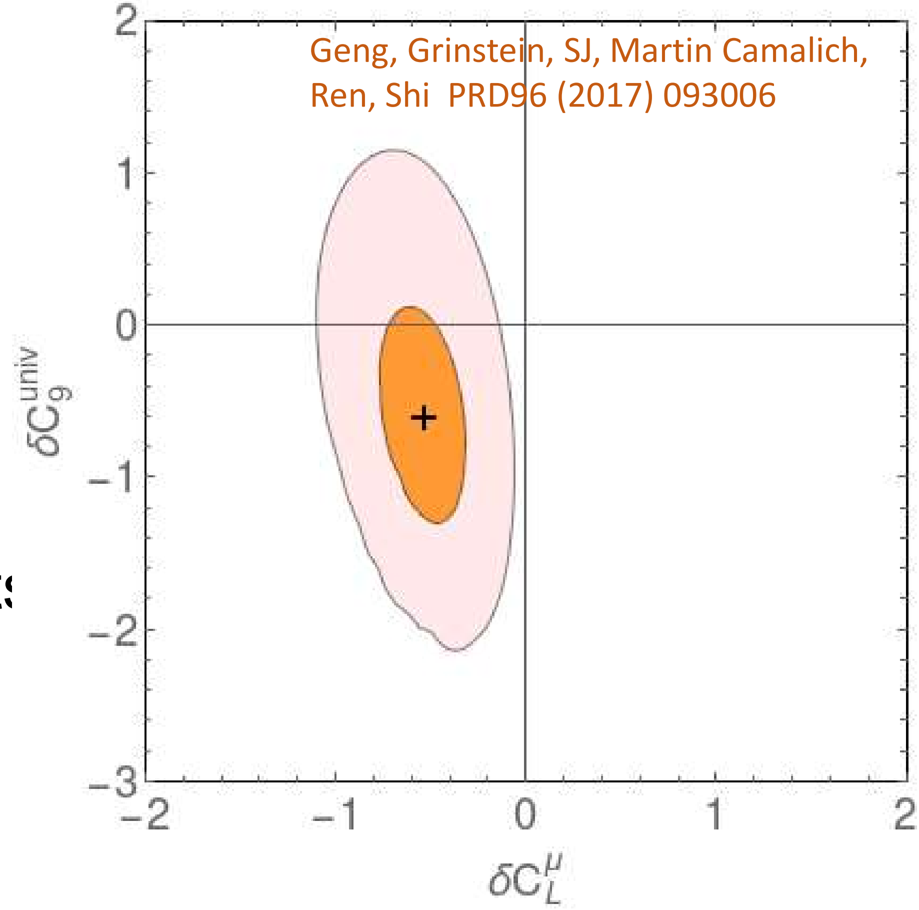
Rare B-decay data shows tensions with SM

1) Lepton-universality breaking (~ 4σ)

2) angular distribution (P_5')

O(1) BSM Wilson coefficients

1) requires lepton-flavour-specific BSM interaction



But global fit allows a sizable lepton- universal effect.

A UV model may well give both.

Charming BSM scenario

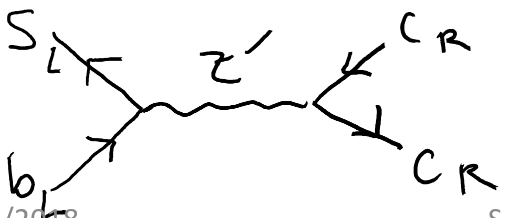
SJ, Kirk, Lenz, Leslie PRD97 (2018) 015021

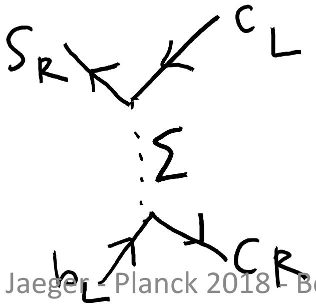
model-independent description by an effective Hamiltonian with 20 operators/Wilson coefficients

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

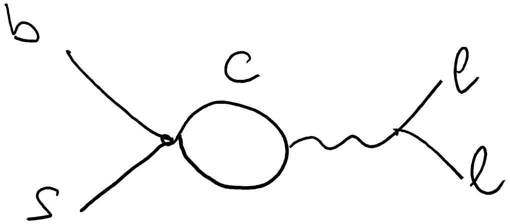
+ parity conjugates

Could arise from e.g.



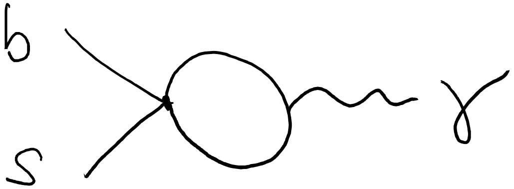


CBSM effects on observables



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

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

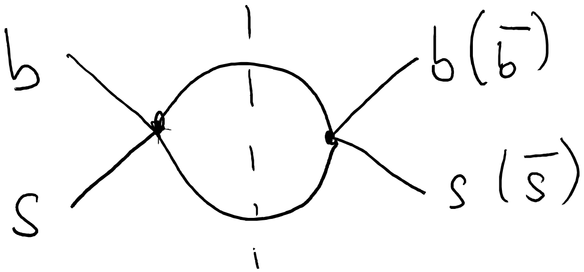


$$\Delta C_7^{\rm eff}(q^2) = \frac{m_c}{m_b}\left[(4C^c_{9,10} - C^c_{7,8}) y(q^2, m_c, \mu) + \frac{4\, C^c_{5,6} - C^c_{7,8}}{6}\right]$$

note that h and y dependent on photon virtuality

At one loop, radiative decay constrains $C_{5..10}$ but not $C_{1..4}$

Lifetime/mixing observables depend on all coefficients



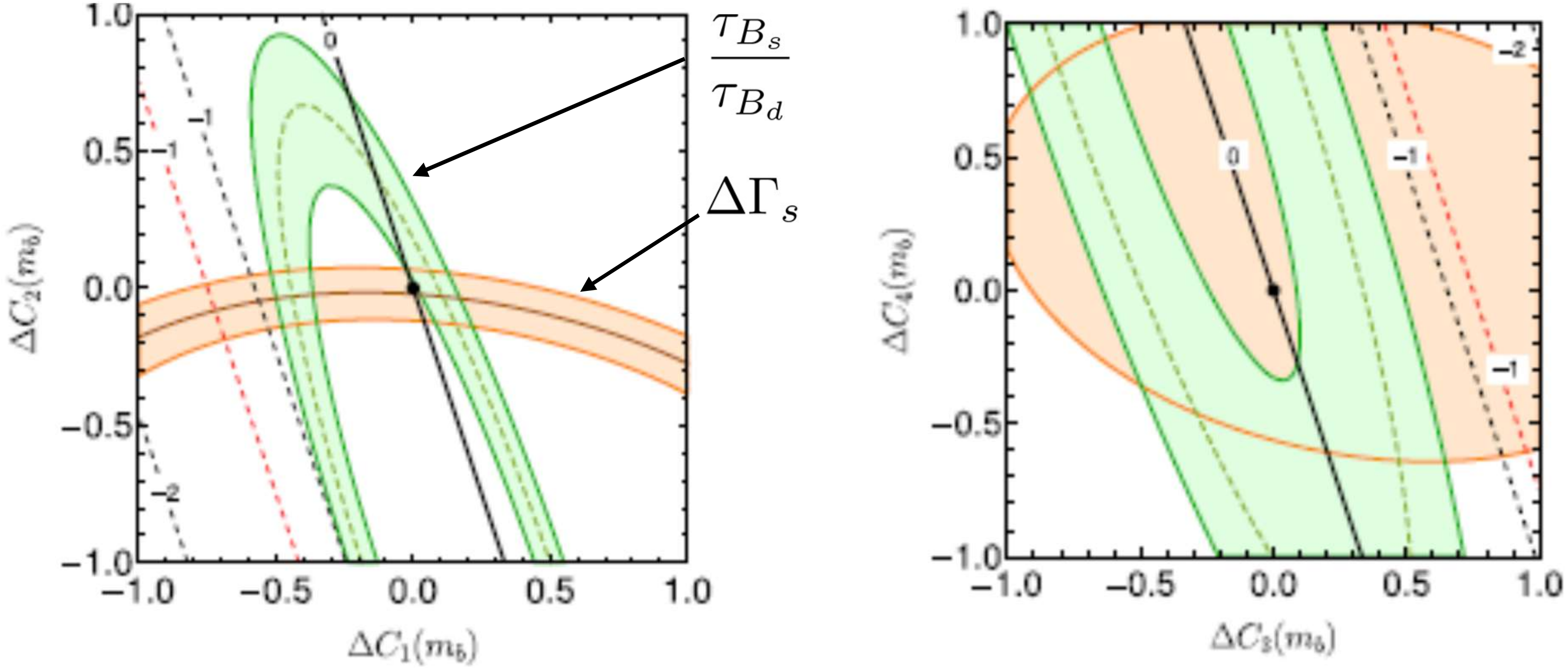
$\Delta\Gamma_s$

τ_{B_s}/τ_{B_d}

$C_{1..10}$, $C'_{1..10}$

Phenomenology – low NP scale

For NP below 10 GeV or so, could use directly for pheno (no large logs)



Straight lines: $\Delta C_9(q^2)$ contours (two q^2 values)

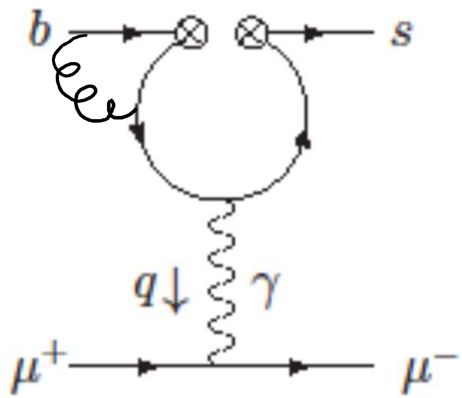
Can generate O(1) effect while satisfying mixing constraints

High new physics scale

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

If $\ln(M_{NP}/m_b) >> 1$ then should resum to all orders.

= RG evolution from M_{NP} to m_b



For C_1 .. C_6, leading order anomalous dimension **is 2-loop for b->sγ (C_7)**

(computed following method of Chetyrkin et al NPB 518,473)

q^2-dedependence now a *subleading* (NLL) effect.

C_7..C_{10} generated at one loop with large log, implying very stringent constraint from radiative decay

RGE evolution – results [$C_{1..4}$]

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

For evolution from M_W to 4.6 GeV

$$\Delta C_7^{\text{eff}} = 0.02\Delta C_1 - 0.19\Delta C_2 - 0.01\Delta C_3 - 0.13\Delta C_4$$
$$\Delta C_9^{\text{eff}} = 8.48\Delta C_1 + 1.96\Delta C_2 - 4.24\Delta C_3 - 1.91\Delta C_4$$

Setting Delta C_2 (M_W) to 1 and rest to zero, reproduce the (large) SM charm contribution to C_9(4.6 GeV).

But C_1 and C_3 are even more effective in generating C_9!

C_2 and C_4 feed strongly into C_7, hence $B \to X_s \gamma$.

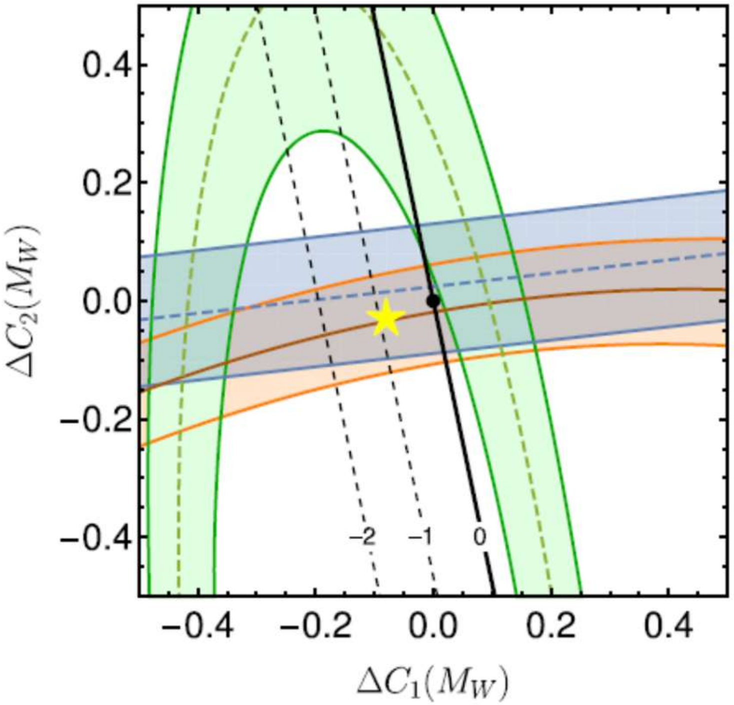
But C_1 and C_3 practically irrelevant for radiative decay!

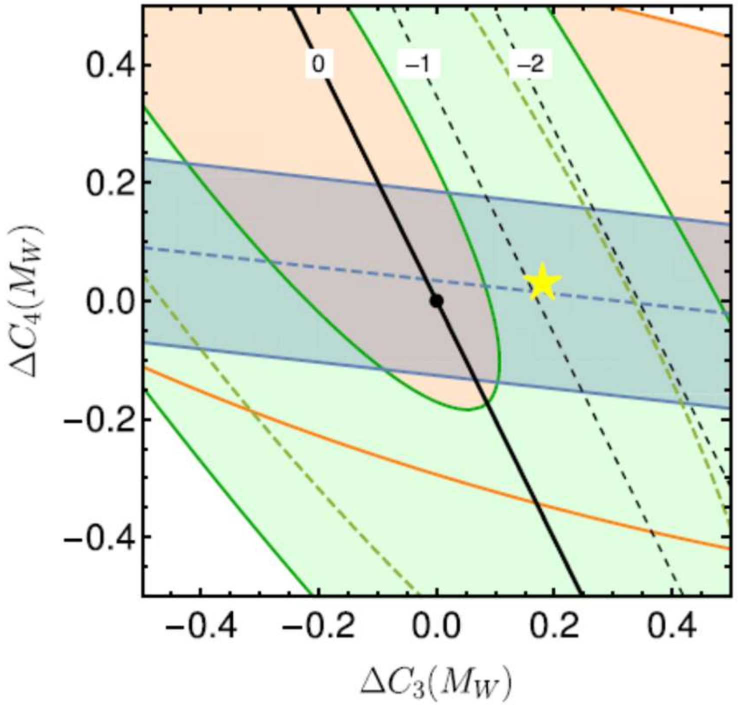
Four-quark Wilson coefficients also evolve, but comparatively mildly.

High NP scale – global analysis

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

Blue – $B \to X_s \gamma$ experiment

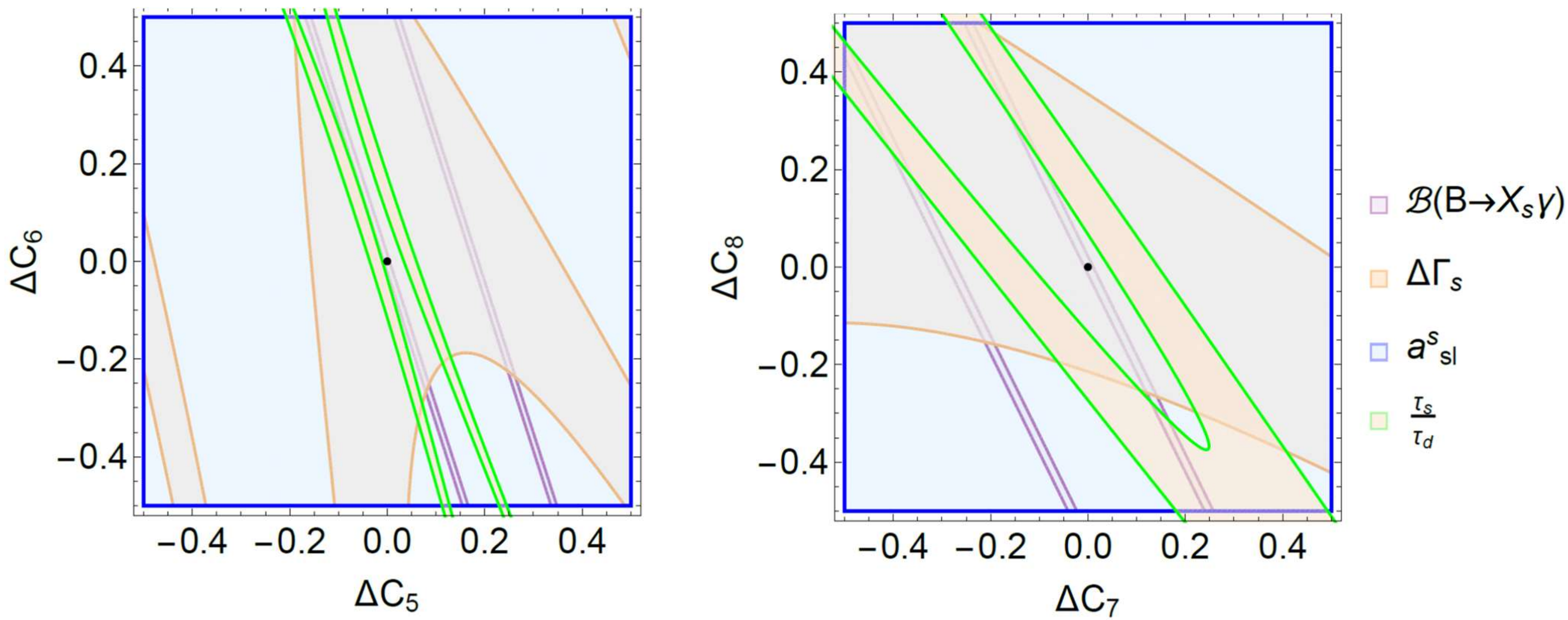




Sizable C_9 effects from small BSM C_1 or C_3

(more combinations in paper)

Constraints from $B \to X_s\gamma$

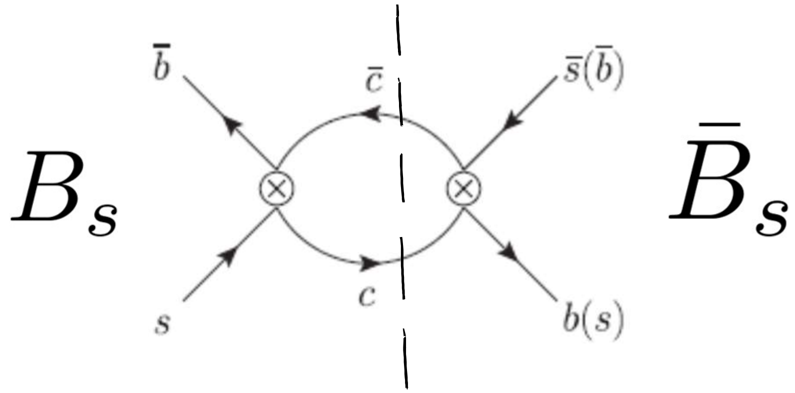


Barring cancellations, BSM coefficients $C_{5\ldots10} \lesssim 0.02$

CP violation

One more observable: semileptonic CP asymmetry

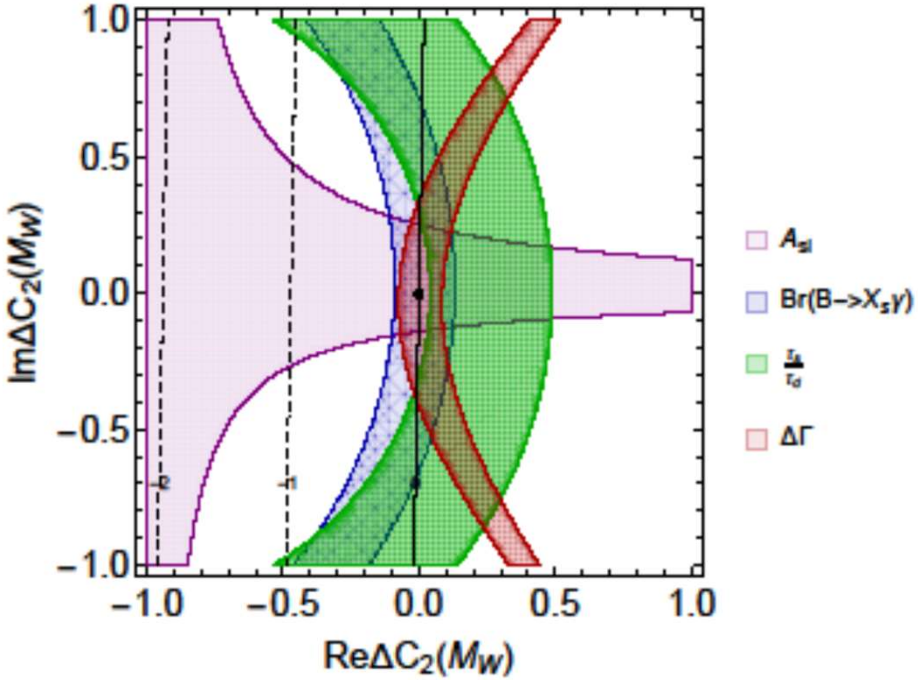
$$A_{\mathrm{SL}}^s = \frac{N(\bar{B}_s(t) \to \ell^+ \nu_e ll X) - N(B_s(t) \to \ell^- \bar{\nu}_e ll X)}{N(\bar{B}_s(t) \to \ell^+ \nu_e ll X) + N(B_s(t) \to \ell^- \bar{\nu}_e ll X)}$$

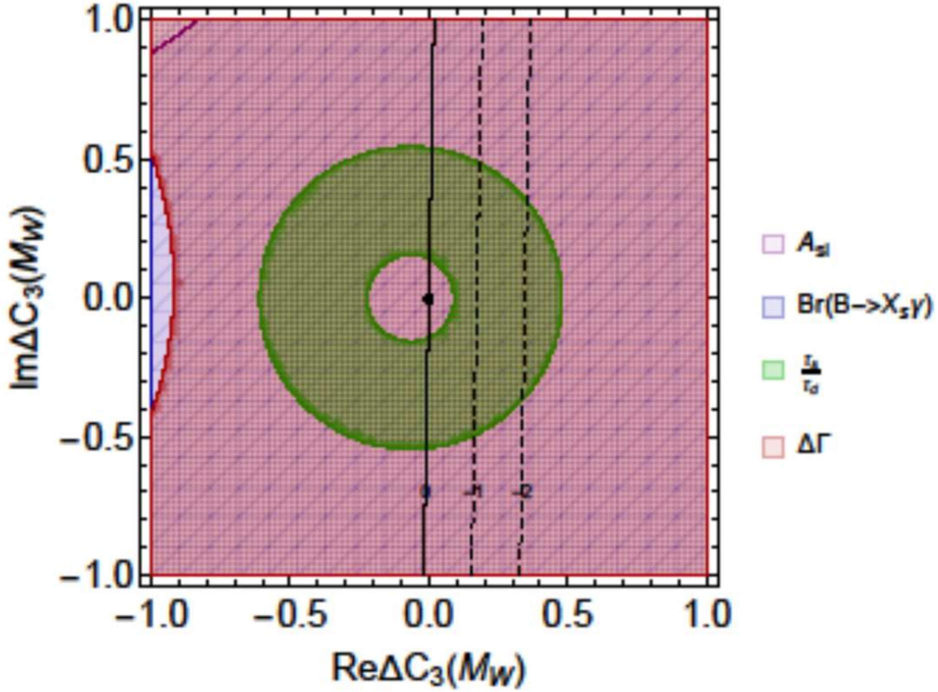


Sensitive to imaginary parts of Wilson coefficients.

$A_{\mathrm{SL}}^s = -0.0006 \pm 0.0028$ (HFLAV average)

Complex Wilson coefficients





C_3 weakly constrained and can contribute sizable C_9 ; even complex C_2 cannot accommodate C_9

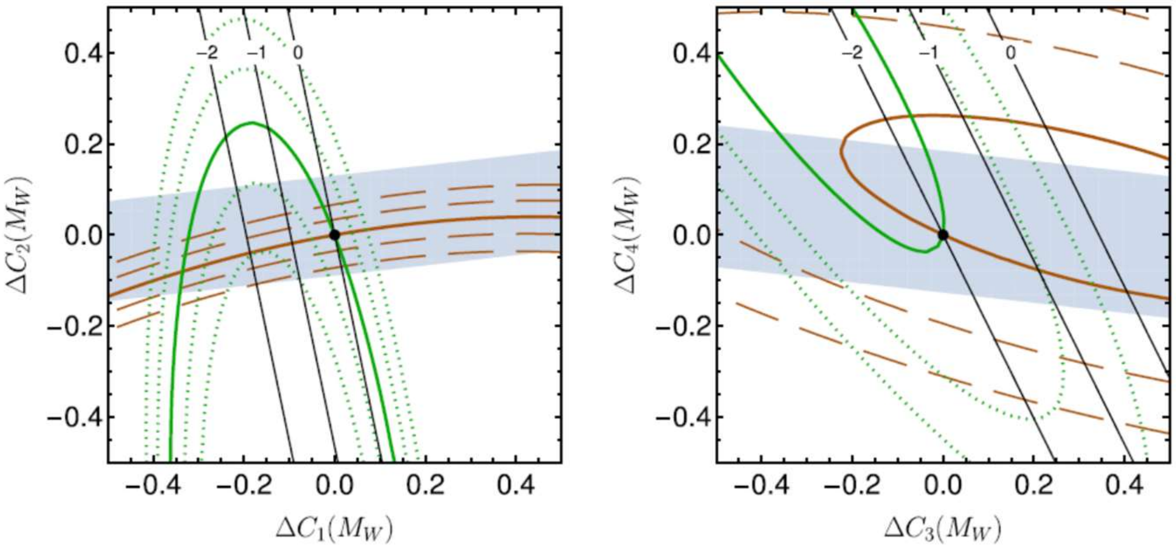
NB – impact on exclusive $B \to J/\psi K_S$ and related decays, but difficult to quantify.

Prospects

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

Width difference, lifetime ratio, and $B \to X_s\gamma$ will all be measured with increased precision at LHCb and Belle2.

May pin down allowed region in CBSM parameter space.



Bands between width difference/lifetime contours = projected future 1σ-sigma experimental error.
According theory progress would be required.

New physics scales

For an O(1) contribution to C_9, can use C_1 or C_3=O(0.1)

Naïve UV scale for this:

$$\Lambda \sim \left(\frac{4G_F}{\sqrt{2}} |V_{cb}^* V_{cb}| \times 0.1 \right)^{-1/2} \sim 3\,\mathrm{TeV}$$

Conversely $C_{5..10}$ must have scale at ~10 TeV or above

For strong coupling, the scales can be an order of magnitude higher.

Summary

New physics in the $b \to c\bar{c}s$ transition will affect well-measured lifetime/mixing observables and can give sizable, correlated effects in rare semileptonic decay.

Rich spin structure of the interaction (20 couplings). Radiative decay a powerful constraint on some contact interactions (implying lower bounds of order 10 TeV)

Effects of this kind should generically be present at some level in BSM models addressing e.g. B-physics anomalies.