Ode to charm

in rare B decays and lifetime observables

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Work with M Kirk, A Lenz, and K Leslie

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Outline and summary

1. O Freunde, nicht diese Töne!

   The case for BSM in $b \to c\bar{c}s$ *transitions is better than what the (scarce) attention in the literature might suggest*

2. Lasst uns angenehmere anstimmen und freudenvollere!

   A comprehensive, predictive, analysis of observables is possible. And it gives multiple viable scenarios, which can fit the b->s l l anomalies, too.

3. Alle Menschen werden Brüder.

   Rare semileptonic decay, radiative decay, and lifetime observables (lifetime difference and Bs/Bd lifetime ratio) are all affected in a correlated manner. In particular, the b->s l l anomaly could be corroborated (or not) in future lifetime measurements.

Charm and new physics

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

Discovery key to establishing SM (November revolution)

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

Large CKM factor, tree-level in weak interaction.

Usually one assumes BSM corrections to be negligible.

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

Digression on the SM

The SM is a scenario where charm effects are present and large.

The point is that this is not restricted to tree decays.

Charm is **leading** in both radiative and rare semileptonic decay, too!

$$BR(B \to X_s\gamma)_{\mathrm{charm,LL}} \approx 2 \times BR(B \to X_s\gamma)_{\mathrm{exp}}$$

Destructive interference with top-W loop & higher-order corrections reduce it to within 1 sigma of the experimental value.
If it had been measured early enough, there would have been an "anomaly" pointing to the top quark.

rare semileptonic decay: governed by Wilson coefficients $C_9,\ C_{10}$
$C_9^{\mathrm{charm,LL}} \approx 2$ (at 4.6 GeV), close to half of total SM value

Both cases suggest **huge** BSM charm effects are possible!

Hold on – there is an anomaly!
Values of $\Delta C_9 \sim -1$ would explain it

BSM in charm: state of the art

Assuming there was a BSM $b \to c\bar{c}s$ vertex. Where would it show up?

* Lifetime observables

These are really inclusive sums dominated by tree decays.
Calculable in an OPE in the heavy-quark expansion.

Some charming BSM effects considered by Bobeth et al 2014 (2x), Brod, Lenz, Tetlalmatzi-Xolocotzi, Wiebusch 2014, also Bauer and Dunn 2011

* Rare decays

He, Tandean, Valencia 2009 - BSM/charm-mediated $B_s \to \mu\mu$ and Bs mixing in a W' model (small effects in both cases). Rare semileptonic and radiative decay not considered.

Lyon, Zwicky 2014 - SM analysis of observed resonances in B->K mu mu.

Conclusion: QCD has difficulty explaining the size of the resonances; suggesting possible BSM effects. Qualitative discussion of decays to charmonia.

Note that these are tree-level, but theory at best O(1) accuracy.

Going forward, focus on all observables that are amenable to heavy-quark expansion.

Charming BSM scenario

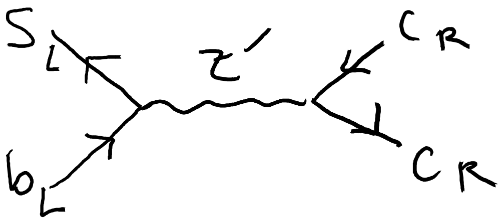
SJ, Kirk, Lenz, Leslie arxiv:1701.09183

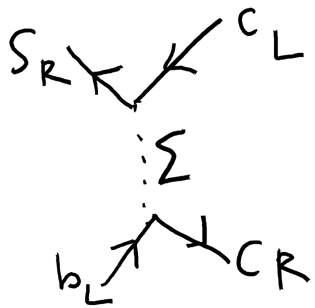
As long as NP mass scale M is >(>) , model-independently captured by an effective Hamiltonian with 20 operators/Wilson coefficients (including C1, C2 of SM)

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

+ parity conjugates

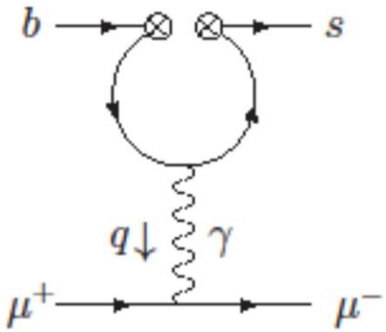
Could arise from e.g.

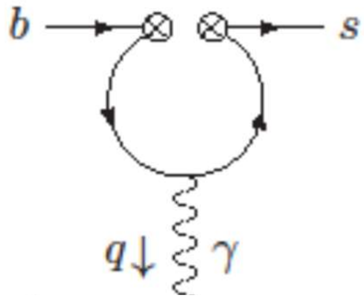




Rare semileptonic & radiative decay

SJ, Kirk, Lenz, Leslie arxiv:1701.09183





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

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

$$h(q^2, m_c, \mu) = -\frac{4}{9} \left[\ln \frac{m_c^2}{\mu^2} - \frac{2}{3} + (2+z)a(z) - z \right]$$

$$y(q^2, m_c, \mu) = -\frac{1}{3} \left[\ln \frac{m_c^2}{\mu^2} - \frac{3}{2} + 2a(z) \right] ,$$

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

Dependence on dilepton mass q2 ! (q2=0 for radiative decay)

If ln(M/m_B) = O(1) (still allows M = (few times m_B) !) directly useable for pheno. Radiative decay constrains C5..C10, but not C1..C4.

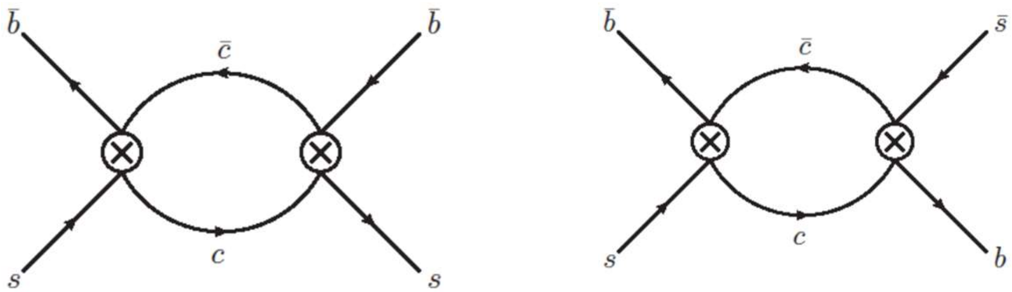
If ln(M/m_B) large needs to be resumed (RGE). Then radiative decay affected by C1..C4 (will show). But C9 strongly affected, too!

Lifetime observables

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

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

Leading effects:



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

In light of 1-loop contributions of C5..C10 to the precisely measured $B \to X_s\gamma$, consider only C1 .. C4.

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See paper for analytical expressions.

Phenomenology – low NP scale

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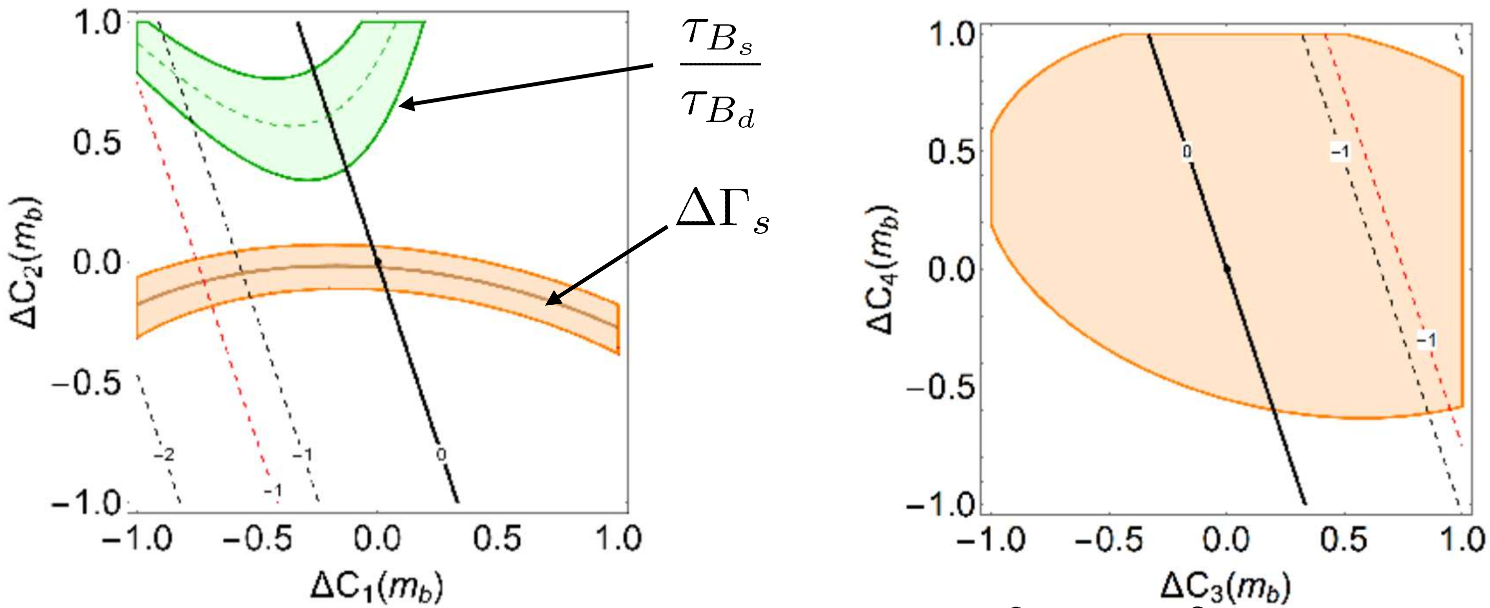
If ln(M/m_B) not large, higher-order corrections (including RGE effects) small.
Can set $\mu \sim m_B, m_b$ (we choose mu = 4.6 GeV).



Straight lines: $\Delta C_9(q^2)$ contours. Red dotted: q^2=2 GeV^2, black: 5 GeV^2.

Can easily accommodate P5' anomaly while satisfying width difference.

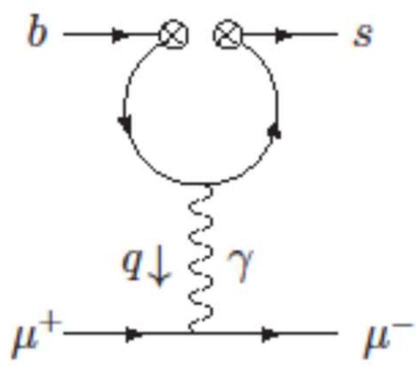
Note that the lifetime ratio is not well consistent with the SM. Could reconcile with CBSM physics, but never consistent with width difference.

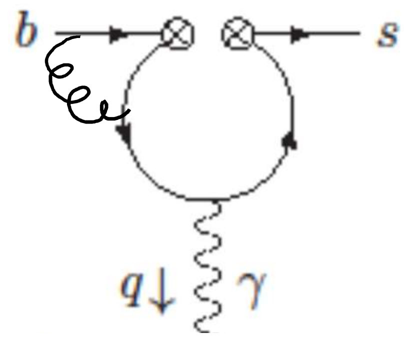
High new physics scale

If ln(M/m_B) >> 1 then need to resum to all orders.

Technically, the leading effects are then accounted for by RG-evolving the Wilson coefficients from μ ~M to μ~ m_B. q2 dependence now a subleading (NLL) effect.

For C1 .. C4, leading effect 1-loop for b->sll, **2-loop for b->s gamma**





Technically nontrivial (spurious IR divergences, scheme dependence of diagrams, spurious gauge-noninvariant terms, etc).

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End result gauge- and scheme-independent if expressed in terms of the scheme-independent coefficient C_7^{eff} (which enters the observables).

RGE evolution - numerical

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For evolution from MW to 4.6 GeV: (l.h.s. at 4.6 GeV, r.h.s. at MW)

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

Setting Delta C2 to 1 and rest to zero, reproduce the (large) SM charm contribution to C9(4.6 GeV).

But C1 and C3 are even (much) more effective in generating C9!

C2 and C4 feed strongly into C7eff, hence $B \to X_s\gamma$.

But C1 and C3 are practically irrelevant for radiative decay!

One can also have a 'pure C2-C4' scenario, where both contributions to C7eff cancel.

The four-quark Wilson coefficients also evolve, but comparatively mildly (see paper).

High NP scale – global analysis

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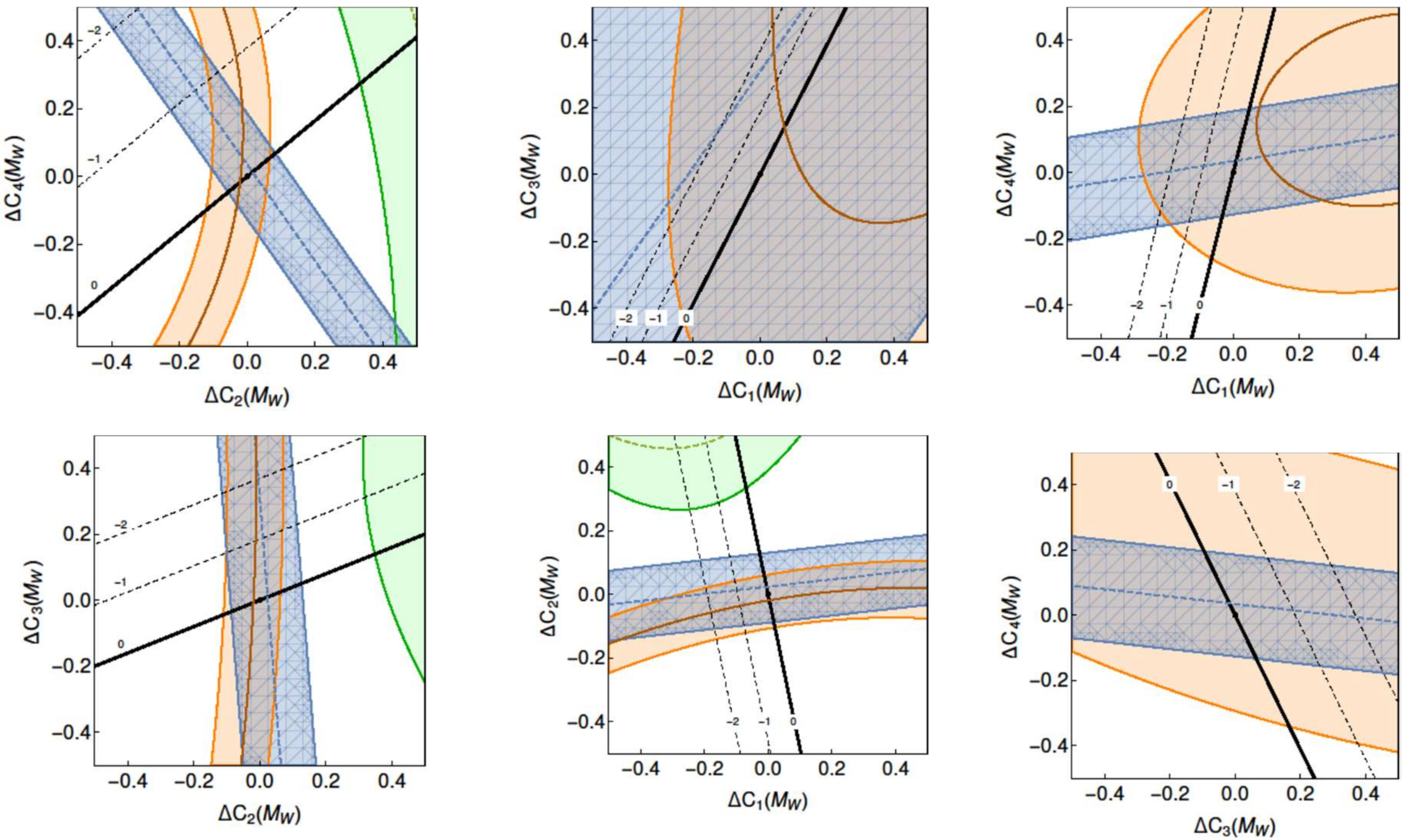
Blue – $B \to X_s\gamma$ experiment



Discussion

Low new physics scale: ΔC_9~ -1 requires sizable coefficients, but consistent with all other constraints, except lifetime ratio (or width difference). Likely consistent with exclusive B -> charm decays in light of uncontrolled theory errors.

High new physics scale: Very small coefficients suffice: RG evolution greatly enhances the effect in b->s l l. At the same time, radiative decay is very sensitive to colour structure.

One can, and probably should, consider all observables on an equal basis (as opposed to b->s l l as ‘signal’ and others as ‘constraints’). Could interpret e.g. the band between ΔC_9 = -2 and ΔC_9= 0 as the region allowed by b->s l l.

One could view this as ‘global fit’ to CBSM. Quantifying this however convolutes unambiguous BSM effects with necessary assumptions about uncontrolled theory errors in b->s l l exclusive observables, which we wish to avoid.

Prospects

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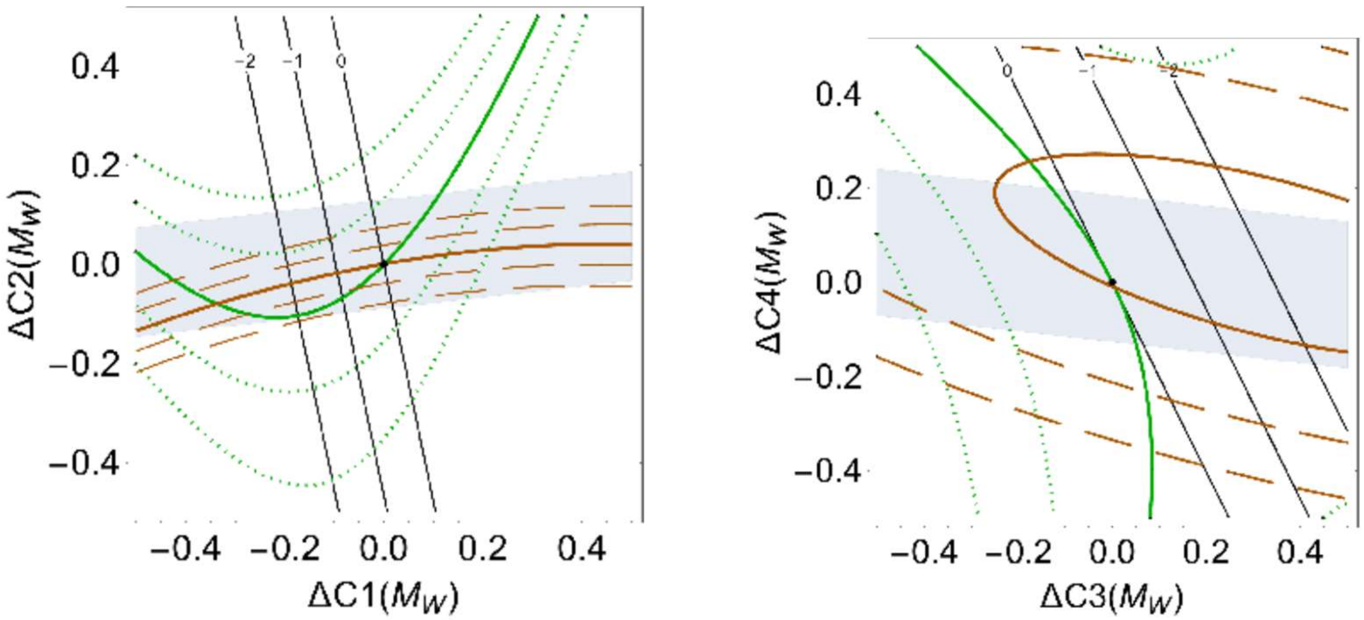
Width difference, lifetime ratio, and $B \to X_s\gamma$ will all be measured with increased precision at LHCb and Belle2.
May allow to pin down allowed region in CBSM parameter space quite precisely:



Bands between width difference/lifetime contours = projected furture 1-sigma experimental error. According theory progress required.

Lepton universality

Und wer’s nie gekonnt, der stehle weinend sich aus diesem Bund.

All CBSM effects are photon-mediated, and as such are lepton-flavour-universal (if the lepton mass is neglected).

As such, CBSM cannot accommodate the current central value of RK.

More properly put, **if the b->s l l anomalies are indeed due to (or dominated by) CBSM effects, then RK must revert to one (or close to it). Similarly, RK* etc should show an (approximate) null result.**

Note that this is a (near-term) **falsifiable prediction.**

(Even if RK stays, CBSM could still be relevant to lifetimes.)

Conclusions

There is a case for studying charming new physics in B decays.

A comprehensive, predictive, analysis of observables is possible.
Multiple viable scenarios.

Can fit the b->s l l anomalies.

For low new physics scale, the effect is (moderately) q^2-dependent.

For high new physic scale, very strong enhancement of b->s l l effect from radiative corrections. $B \to X_s \gamma$ easily decoupled. Negligible q^2-dependence.

CBSM can be tested with future lifetime and $B \to X_s \gamma$ measurements.

If CBSM is behind P5' anomaly etc, it predicts RK ~ 1