Charming new physics

Sebastian Jäger (University of Sussex)

Portoroz 2019: “Precision era in high-energy physics”

Portoroz, 17 April 2019

Work with M Kirk, A Lenz, K Leslie

Outline

How to observe new physics in $b \to c\bar{c}s$ transitions

Operators & RGE

Lifetime observables

Radiative & rare decay: P5' & null tests

$B \to J/\psi K_S$ & CP violation

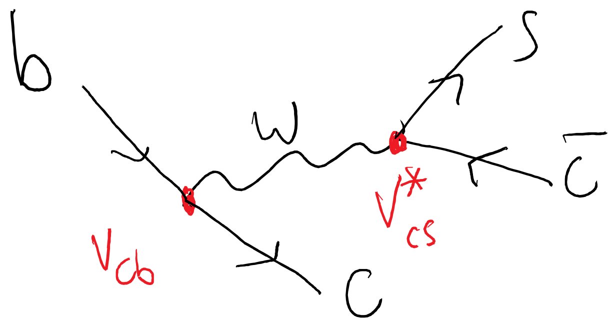
Wilson coefficient constraints & new physics scale

Charm and new physics

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

Discovery key to establishing SM

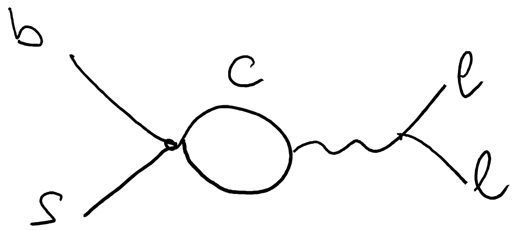
In B physics, charm appears in leading decays through a partonic $b \to c\bar{c}s$ transition. Large CKM factor.



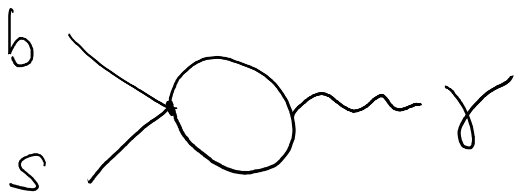
Usually one assumes BSM corrections to be negligible.

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

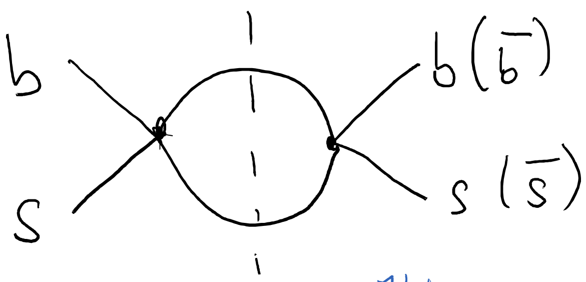
Observables



rare semileptonic (P5' etc)



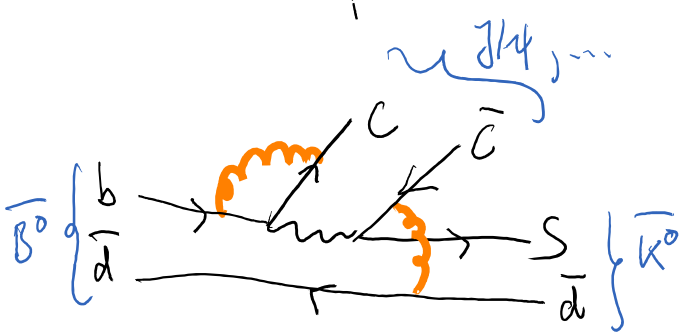
radiative (B->Xs gamma)



width/lifetime differences

$\Delta\Gamma_s \qquad \tau_{B_s}/\tau_{B_d}$

All calculable in heavy-quark expansion (1/mb)



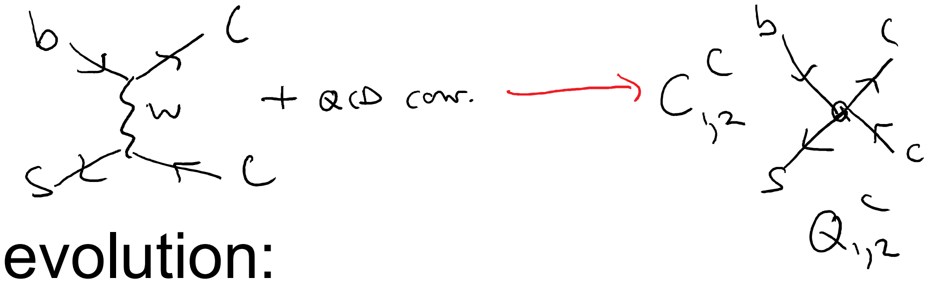
exclusive charmful: BR, A_CP, S_CP precisely measured

- not calculable (HQE is 1/(mc alpha_s)))

will show a data-driven method

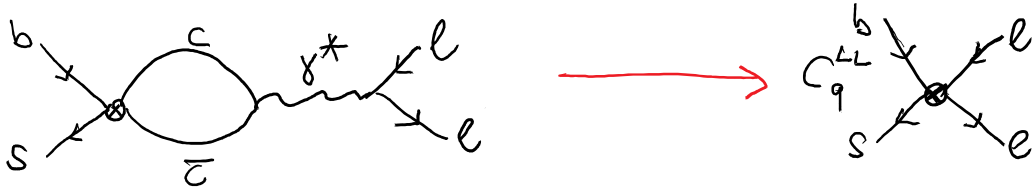
Rare & radiative decays

Standard Model: tree-level W exchange

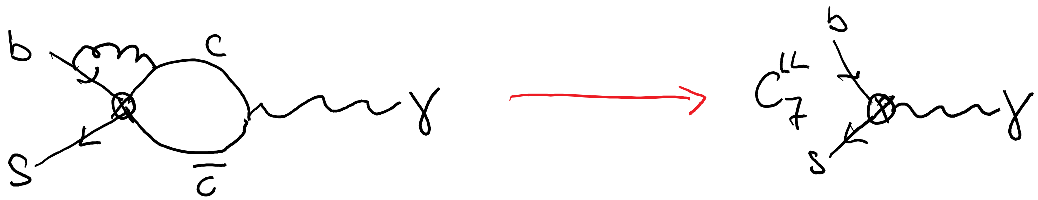


$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i)$$
$$Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j)$$

RG evolution:



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



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

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

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

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

Rare & radiative decays: experiment

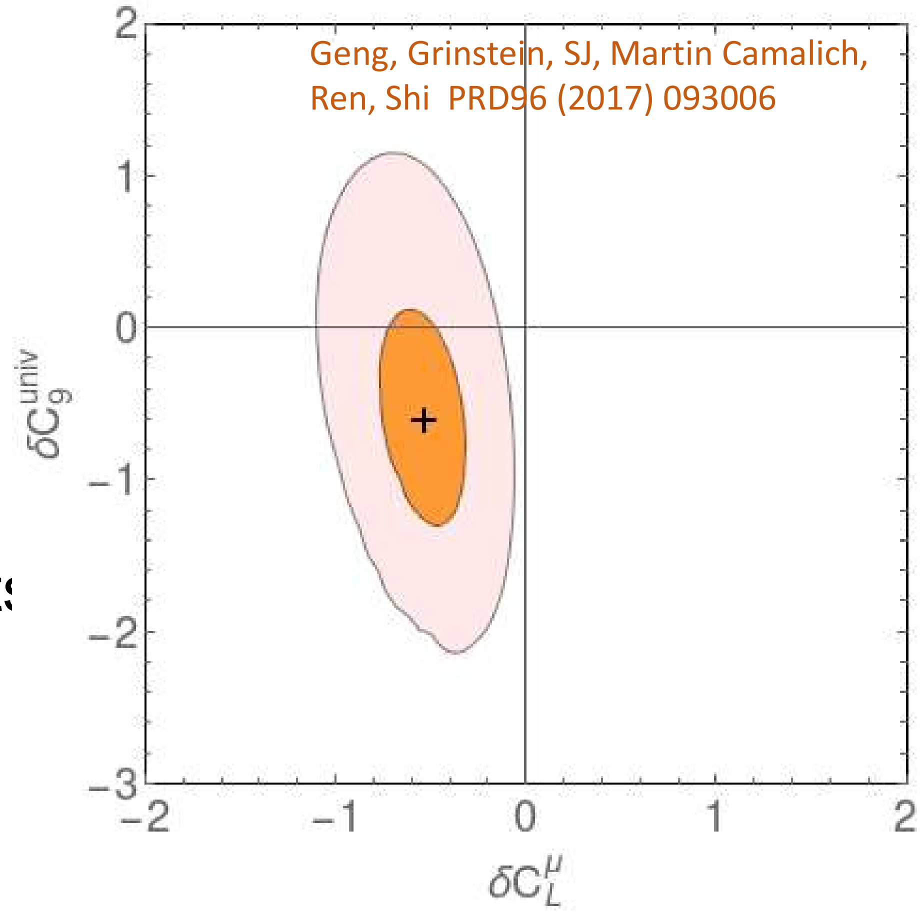
Rare B-decay data shows tensions with SM

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 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)

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

+ parity conjugates

RG evolution - numerical

SJ, Kirk, Lenz, Leslie arxiv:1701.09183, 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 - can accommodate P_5'

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

RH(primed) 4-quark ops constrained by both C_7' and C_9'

Observables/constraints

Lifetime ratio $\frac{\tau(B_s)}{\tau(B_d)} = 0.9994 \pm 0.0025$

Width difference $\Delta\Gamma_s^{\rm exp} = 0.088 \pm 0.006\,\mathrm{ps}^{-1}$

Inclusive radiative decay $\mathcal{B}(\bar{B} \to X_s\gamma)^{\rm exp} = (3.32 \pm 0.15) \times 10^{-4}$

'Pseudo-observables:' fitted Wilson coefficients from (mainly) exclusive radiative and semileptonic decay

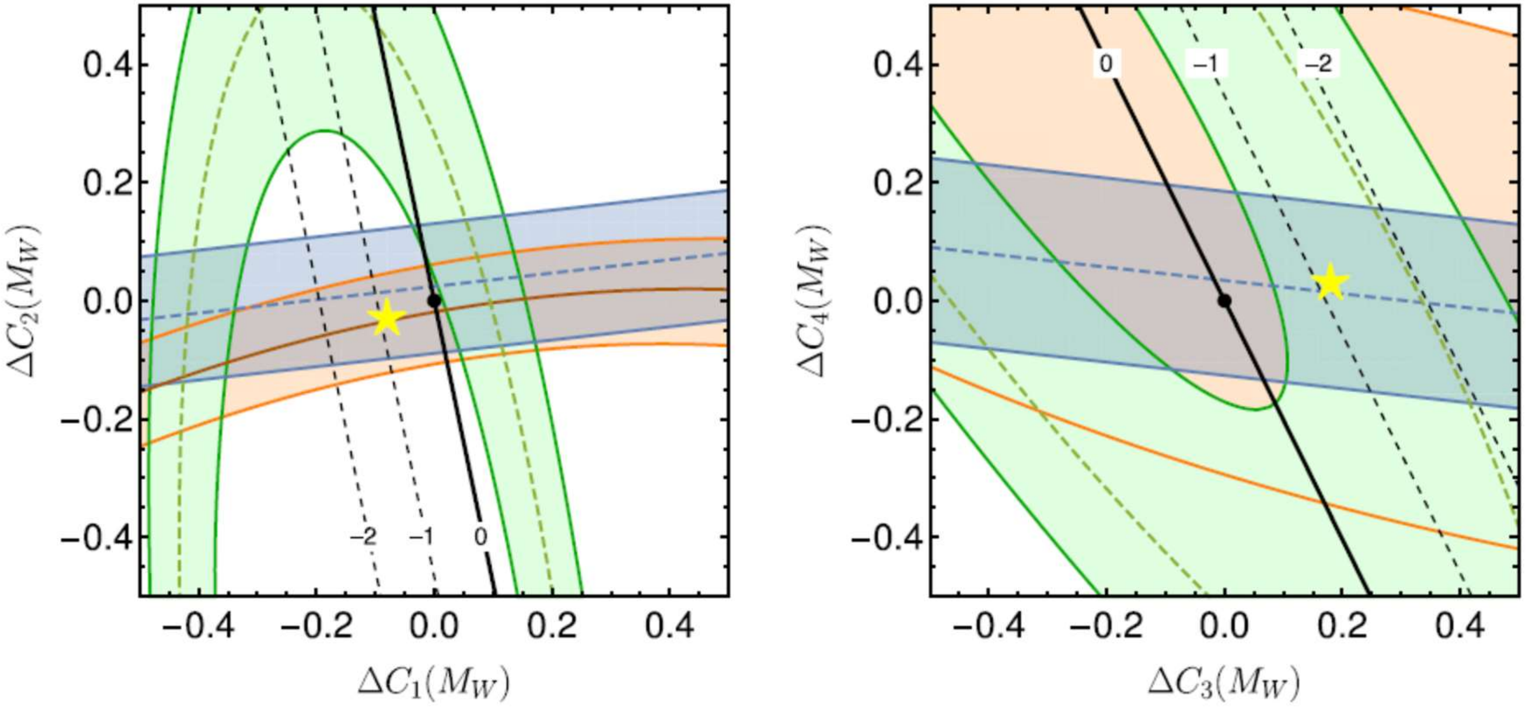
$C'_{7\gamma} = 0.018 \pm 0.037$ Aebischer et al arXiv:1903.10434

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

Global analysis

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

'LH currents' – strong mixing into C_9



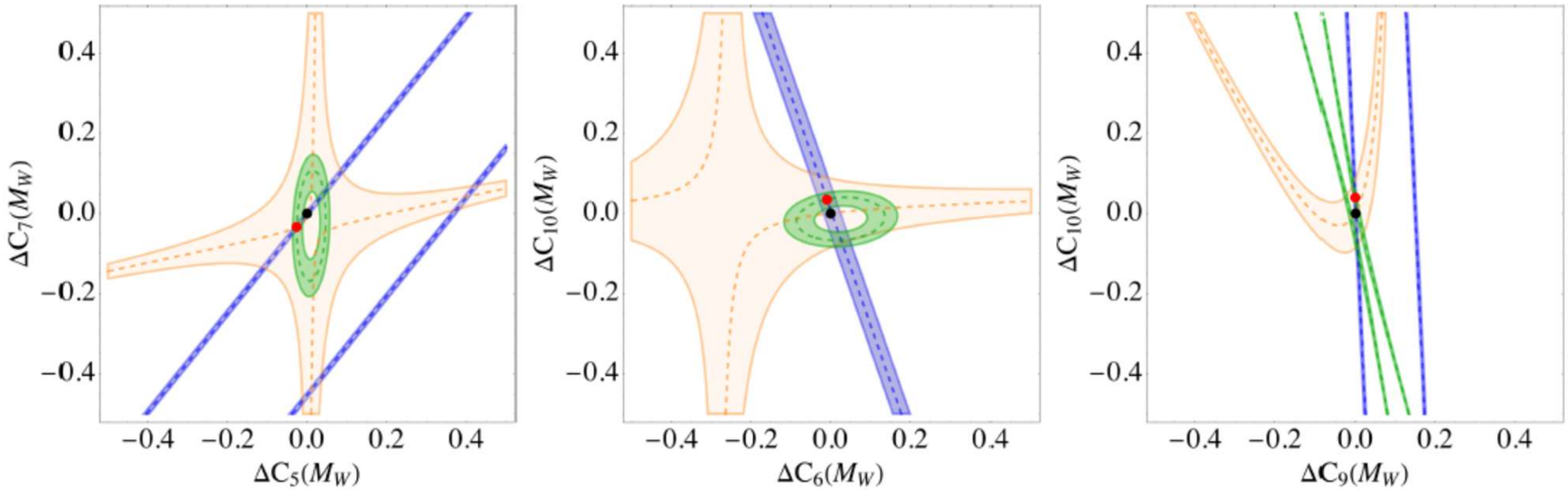
Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

Dashed/solid black: C9(BSM)

Global analysis

SJ, Kirk, Lenz, Leslie to appear

‘LH currents’ – strong mixing into dipole

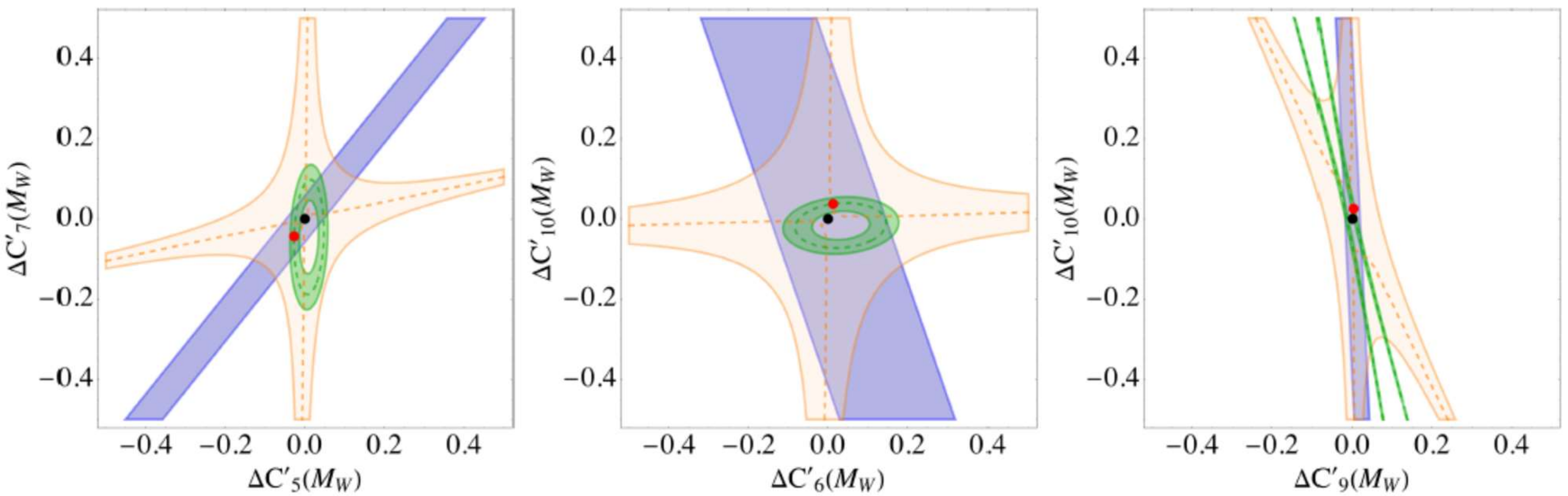


Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

Global analysis

SJ, Kirk, Lenz, Leslie   to appear

‘RH currents’ – strong mixing into dipole



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

Lower bounds on NP scale

SJ, Kirk, Lenz, Leslie, to appear

Delta C<0

Delta C>0

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

$B \to J/\psi\ K_S$ & CP violation

If new physics in $b \to c\bar{c}s$ is CP-violating, it will impact on the precisely measured exclusive $B \to J/\psi\ K_S$ decays.

Three precisely observables:

$$S_{J/\psi K_S} = 0.699 \pm 0.017$$

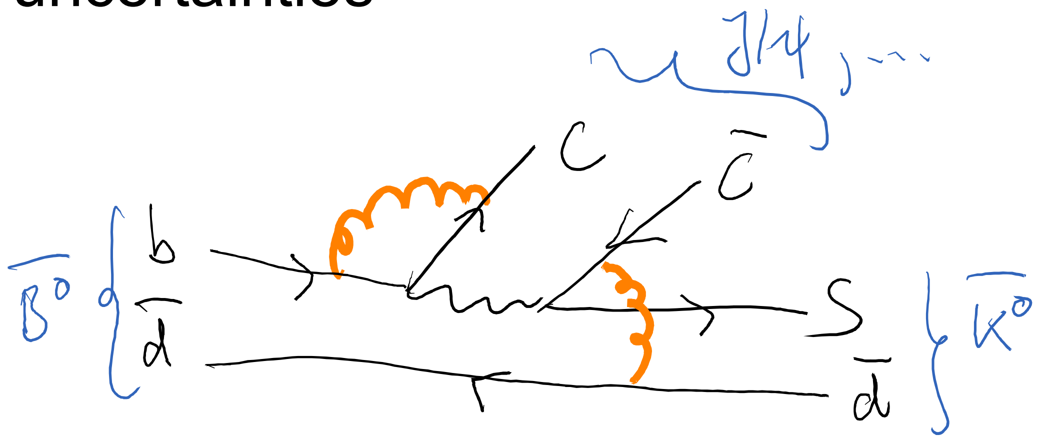
$$C_{J/\psi K_S} = -0.005 \pm 0.015$$

$$\mathcal{B}(B_d \to J/\psi K_S) = (8.73 \pm 0.32) \times 10^{-4}$$

Note: The impact on the semileptonic asymmetry turns out to be comparably small (will show).

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

B→J/ψ K_S : theory

Problem: hadronic matrix elements $\langle J/\psi K_S|Q_i|B\rangle$

Heavy-quark expansion uncontrolled

expansion parameter is $\Lambda_{\rm QCD}/(\alpha_s m_c)$

But $$\langle J/\psi K_S|Q_1|B\rangle = \frac{M_B p_c}{2} f_{J/\psi} F^{B\to K}\left(1+\frac{1}{N_c^2}\right)$$

factorizes naively, up to colour-suppressed corrections.

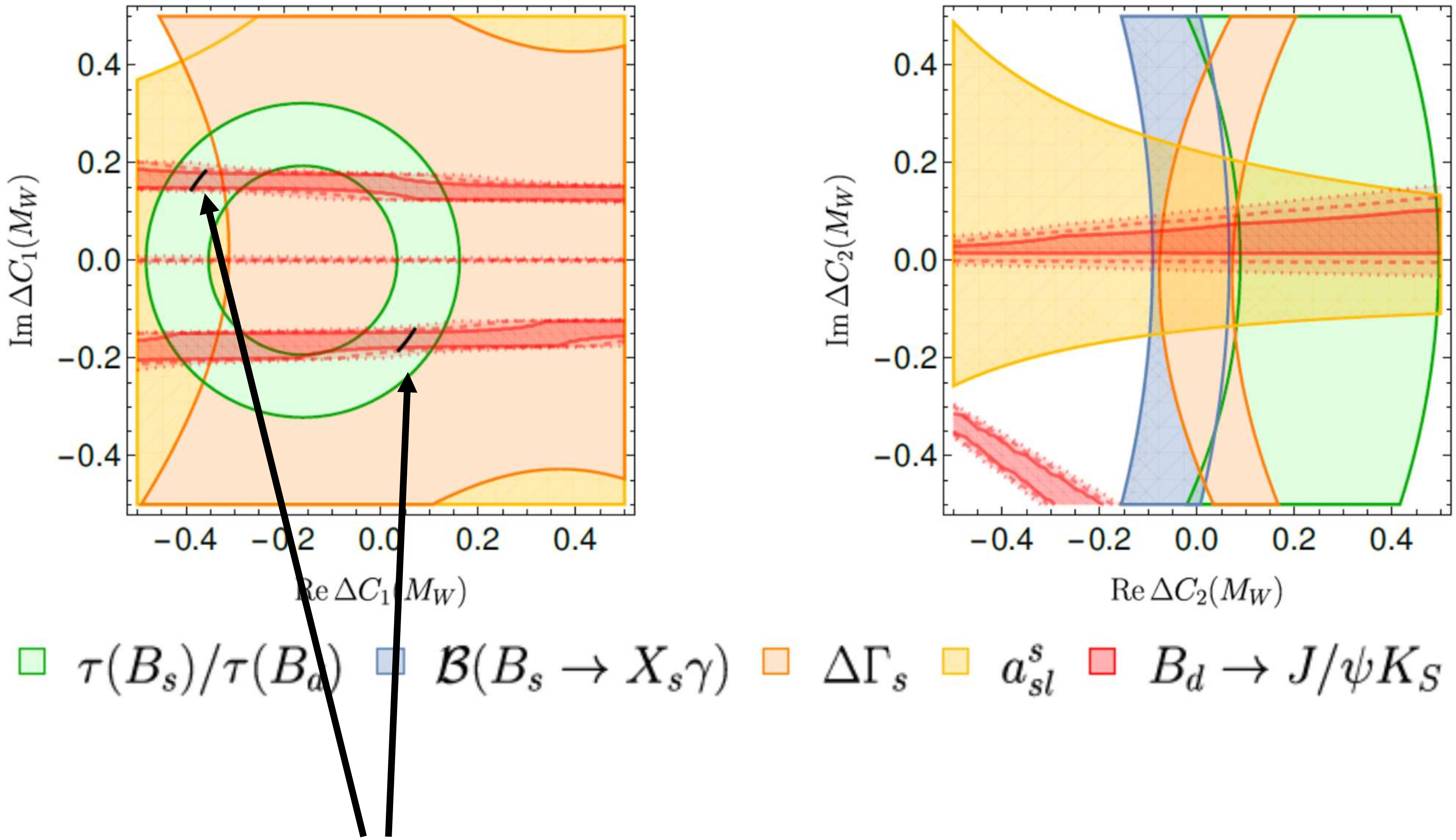
If new physics only affects C_1 or C_2, the incalculable hadronic dynamics is largely contained in a single complex ratio $r_{21} = \langle Q_2\rangle/\langle Q_1\rangle$

e.g. $$\lambda_{J/\psi K_S} = \frac{q}{p}\frac{\bar{A}}{A} \propto \frac{C_1^* + r_{21} C_2^*}{C_1 + r_{21} C_2}$$

4 unknowns (Re C, Im C, Re r_{21}, Im r_{21}) : fit to data !

Global analysis: CP-violating case

SJ, Kirk, Lenz, Leslie, to appear



Fitted r_{21} agrees with naïve (!) factorisation

Conclusions

New physics should affect the $b \to c\bar{c}s$ transitions

Large RG mixing into dipoles and semileptonic operators

Complementary sensitivity from radiative decay, B->K*l l angular, B lifetime differences, $B \to J/\psi\ K_S$.

Simultaneous fit to NP and $B \to J/\psi\ K_S$ hadronic matrix elements possible (for restricted operator basis). Data can accommodate ‘unexpected’ hadronic matrix element values - including naïve-factorization ones!

Bounds on new physics scales range from few TeV to >10 TeV depending on the vertex.

Backup

Def. new physics scale

$$\Lambda_{NP}^2 \geq \frac{\sqrt{2}}{4G_F}\frac{1}{V_{cb}V_{cs}^*}\frac{1}{|\Delta C_i(M_W)|}$$