Charming new physics

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Durham IPPP b->s l l workshop
22 April 2021

Work with M Kirk, A Lenz, K Leslie:

arXiv:1701.09183, PRD 97 (2018) 1
arXiv:1910.12924, JHEP 03 (2020) 122

Outline

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

Operators & RGE

Lifetime observables

Radiative & rare decay: P_5' & null tests

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

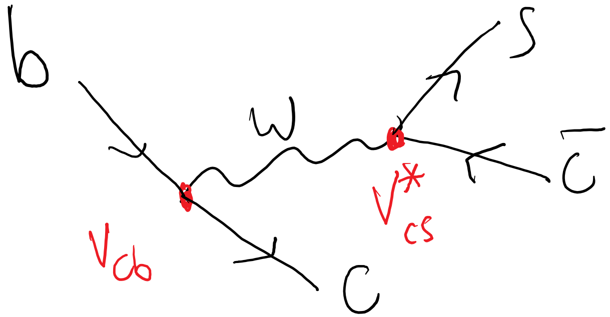
Wilson coefficient constraints & new physics scale

Charm and new physics

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

Discovery key to establishing SM

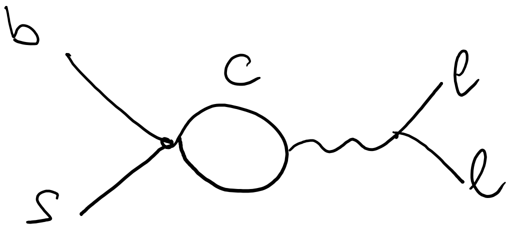
In B physics, charm appears in leading decays through a partonic $b \to c\bar{c}s$ transition. Large CKM factor.



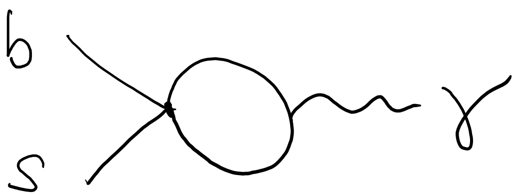
Usually one assumes BSM corrections to be negligible.

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

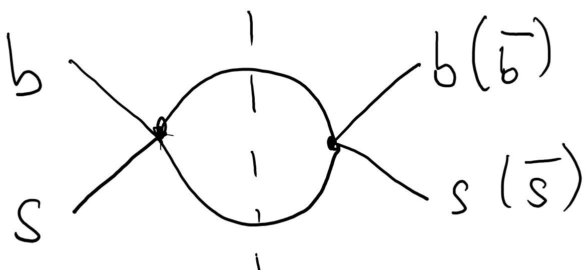
Observables



rare semileptonic (P5' etc)



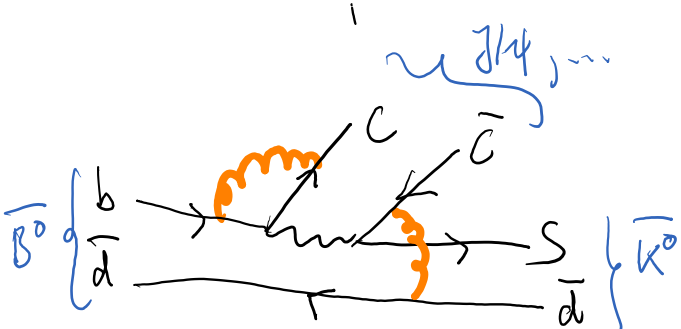
radiative ($B \to X_s \gamma$)



width/lifetime differences

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

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



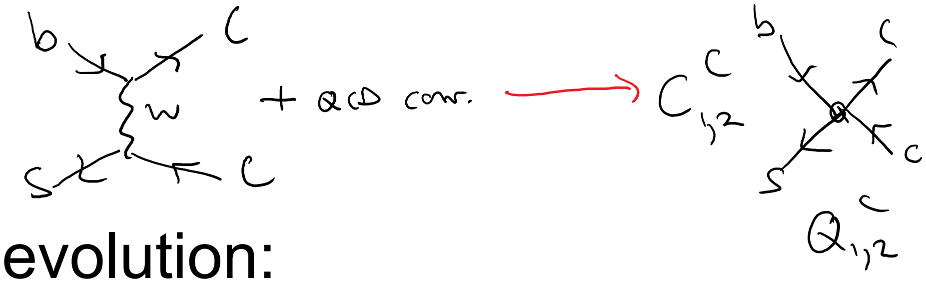
exclusive charmful: BR, A_{CP}, S_{CP} precisely measured

- not calculable (HQE is $1/(m_c\ \text{alpha}_s)$))

will show a data-driven method

Rare & radiative decays

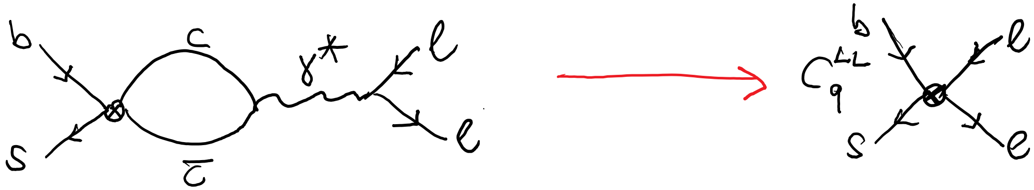
Standard Model: tree-level W exchange



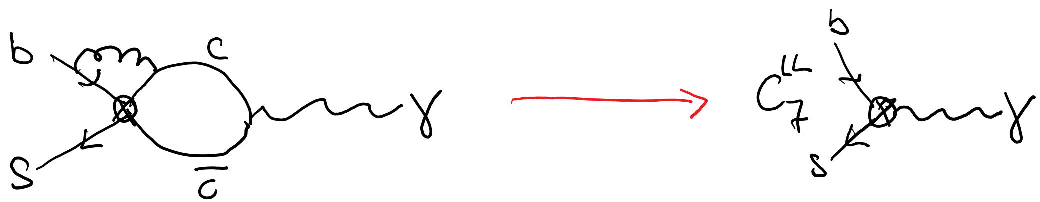
$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i)$$

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

RG evolution:



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



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

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

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

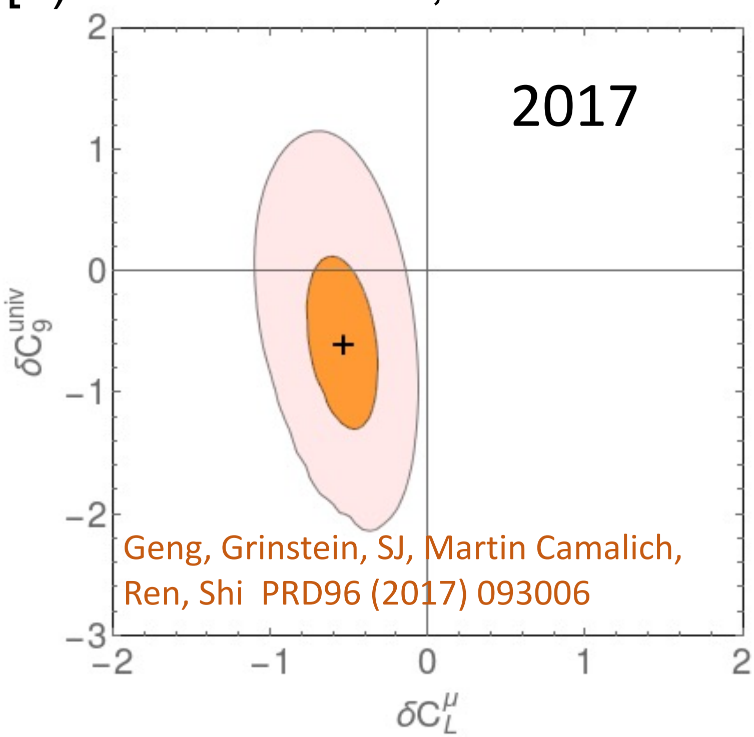
In SM: O(50%) in both cases comes from virtual charm

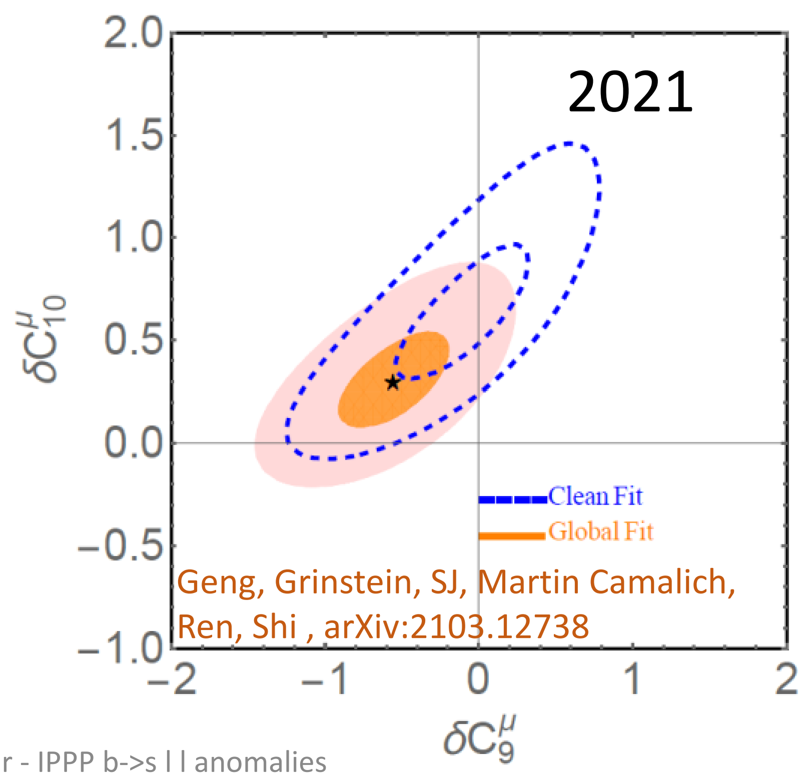
Rare & radiative decays: experiment

Rare B-decay data shows tensions with SM

1) Lepton-universality breaking - needs lepton-flavour specific effect
2) $B_s \to \mu\mu$
3) angular distribution (P_5') - could be lepton-universal C_9-type effect

[2) could be either, but not via C_9]





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)

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

$$Q_3^c = (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i), \qquad Q_4^c = (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j),$$

$$Q_5^c = (\bar{c}_R^i \gamma_\mu b_R^j)(\bar{s}_L^j \gamma^\mu c_L^i), \qquad Q_6^c = (\bar{c}_R^i \gamma_\mu b_R^i)(\bar{s}_L^j \gamma^\mu c_L^j),$$

$$Q_7^c = (\bar{c}_L^i b_R^j)(\bar{s}_L^j c_R^i), \qquad Q_8^c = (\bar{c}_L^i b_R^i)(\bar{s}_L^j c_R^j),$$

$$Q_9^c = (\bar{c}_L^i \sigma_{\mu\nu} b_R^j)(\bar{s}_L^j \sigma^{\mu\nu} c_R^i), \qquad Q_{10}^c = (\bar{c}_L^i \sigma_{\mu\nu} b_R^i)(\bar{s}_L^j \sigma^{\mu\nu} c_R^j),$$

+ parity conjugates

RG evolution - numerical

SJ, Kirk, Lenz, Leslie, arxiv:1701.09183 and arXiv:1910.12924,

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

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

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

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

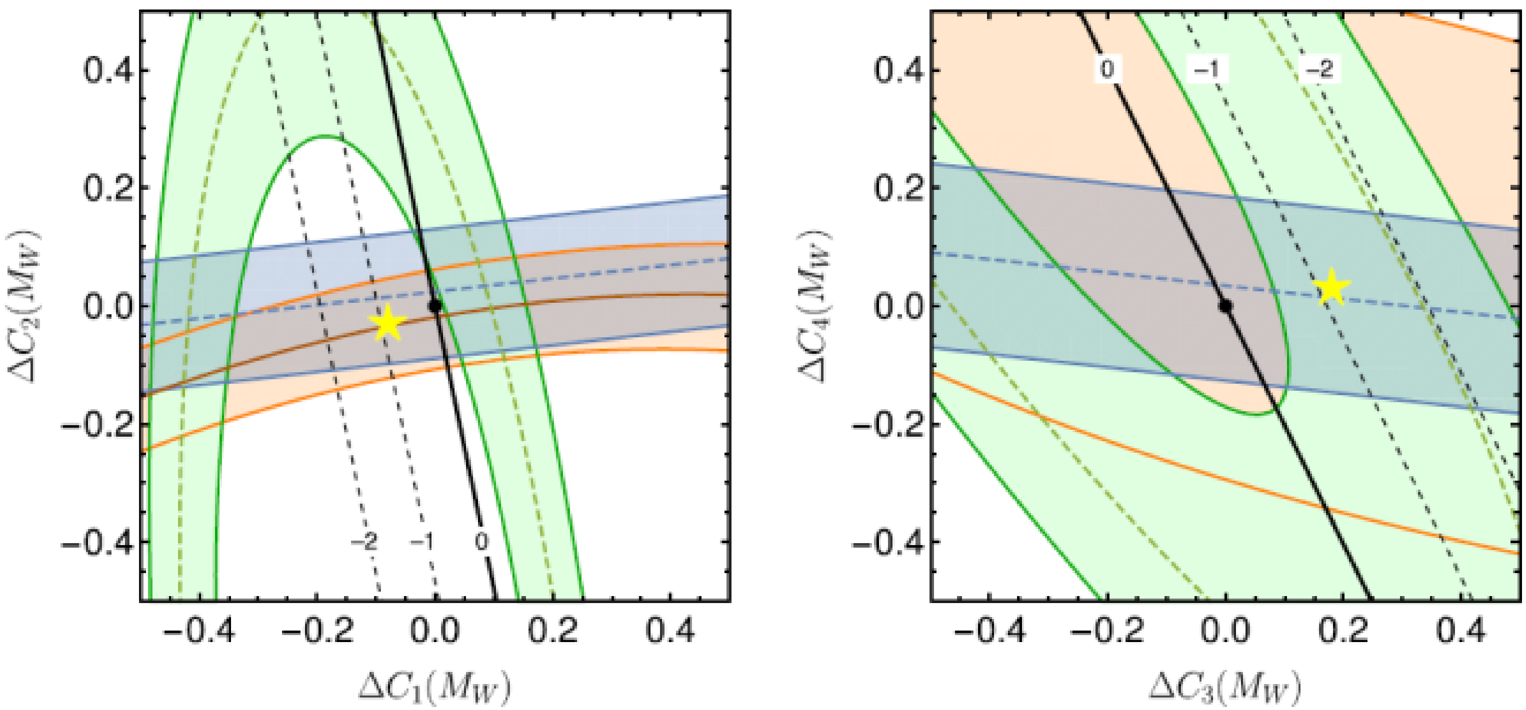
$C'_{7\gamma} = 0.018 \pm 0.037$ Aebischer et al arXiv:1903.10434

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

Global analysis

SJ, Kirk, Lenz, Leslie, arXiv:1910.12924

'LH currents' – strong mixing into C_9



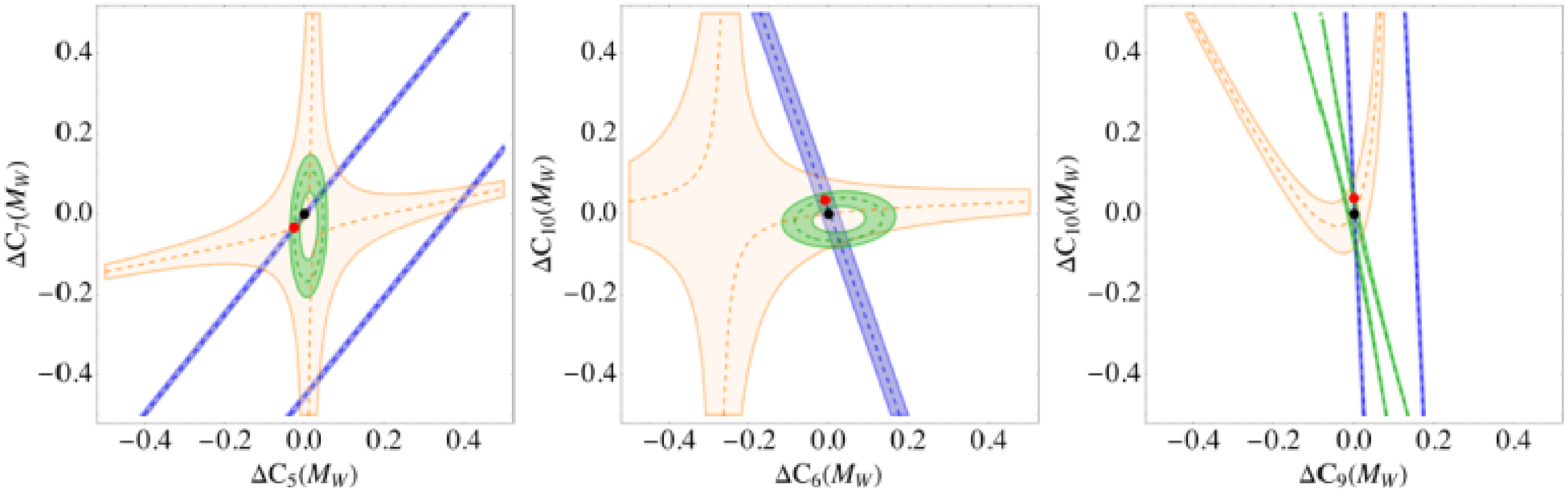
Blue – radiative decay, green – lifetime ratio, brown – width difference

Dashed/solid black: C9(BSM)

Global analysis

SJ, Kirk, Lenz, Leslie, arXiv:1910.12924

‘LH currents’ – strong mixing into dipole



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Global analysis

SJ, Kirk, Lenz, Leslie, arXiv:1910.12924

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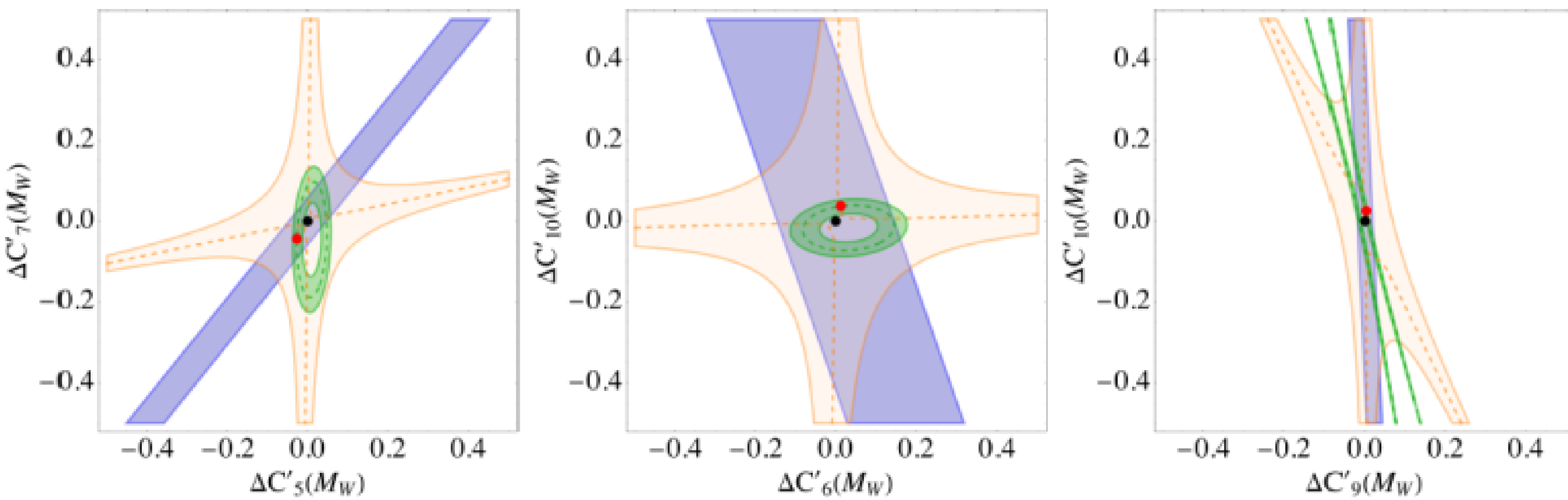


Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

Lower bounds on NP scale

SJ, Kirk, Lenz, Leslie, arXiv:1910.12924

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:

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

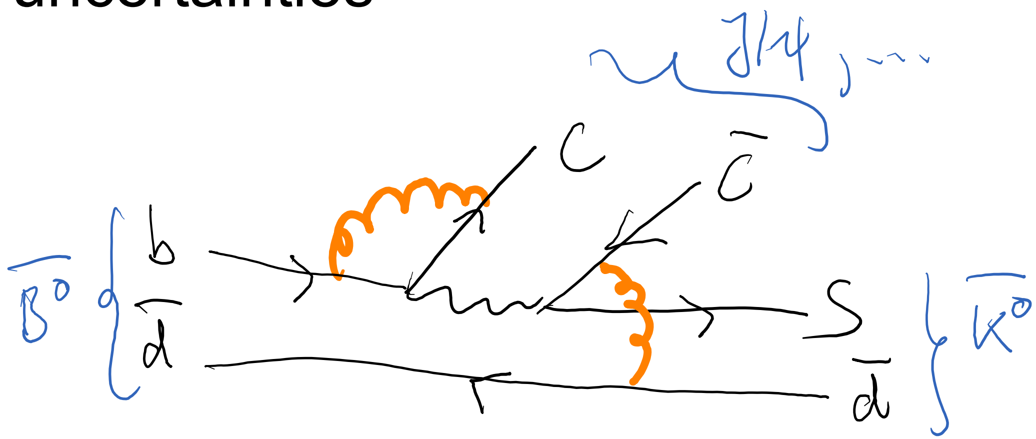
$$C_{J/\psi K_S} = -0.005 \pm 0.015$$

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

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.

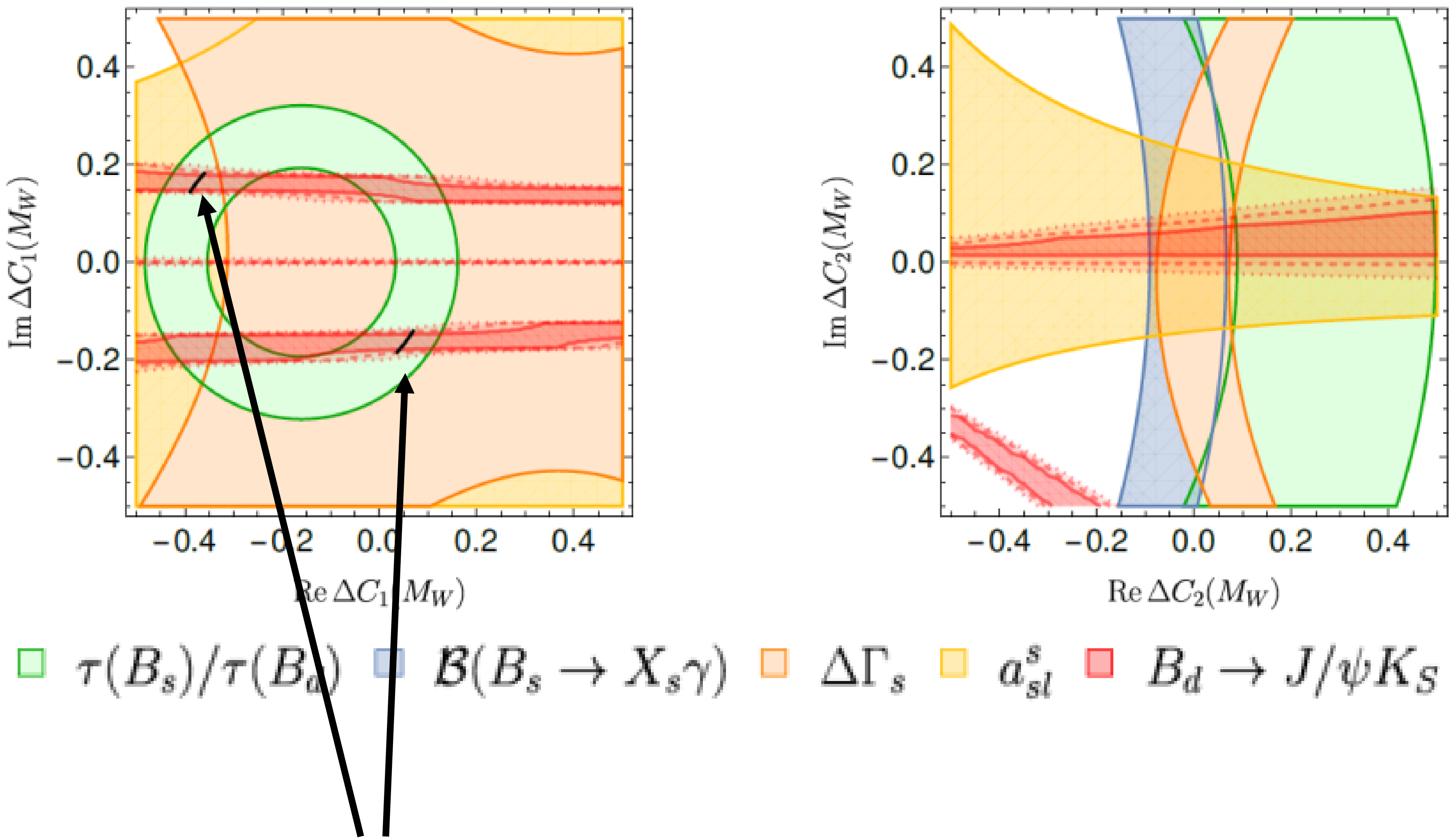
If new physics only affects C_1 or C_2, the incalculable hadronic dynamics is largely contained in a single complex ratio $r_{21} = \langle Q_2 \rangle / \langle Q_1 \rangle$

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

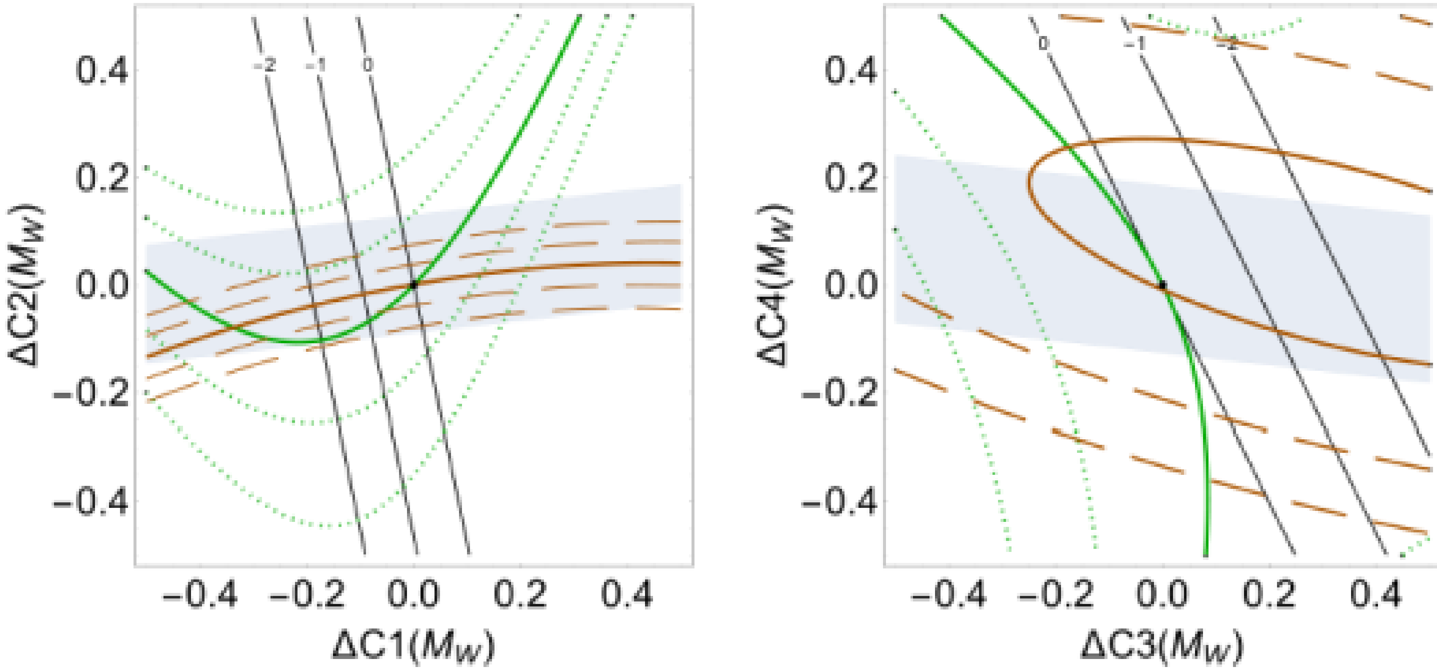
SJ, Kirk, Lenz, Leslie, arXiv:1910.12924



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

Future prospects for mixing

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



Brown – width difference, green -- lifetime ratio

solid – SM central value

spacing of contours – projected half-width of a 1-σ band

Grey – current BR($B \to X_s \gamma$)

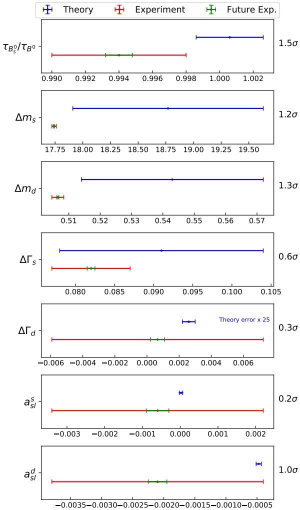
Assumptions: 5% combined (th/exp) error on width difference

0.001 combined error on lifetime ratio

What measurements are these?

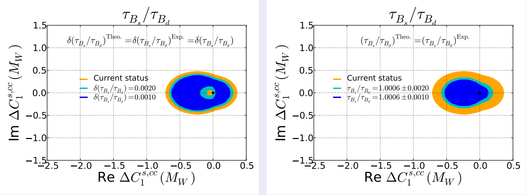
- Observables relevant for tree-level WCs in $b \to c$ (and $b \to u$) transitions
  - Lifetime ratio, $\tau_{B_s^0}/\tau_{B^0}$
  - Mass and width differences, Δm_s, Δm_d, $\Delta\Gamma_s$, $\Delta\Gamma_d$
  - Semileptonic asymmetries, a_{sl}^s, a_{sl}^d
  - Time dependent CPV in $B^0 \to hh$ (α), $B^0 \to J/\psi K_S^0$ (β) and $B_s^0 \to J/\psi\phi$ (β_s) and similar
  - Time integrated CPV in $B^\pm \to D\, h^\pm$ (γ)
  - Probably others I've forgotten
- I don't have time to cover all so will just talk about a couple
- A few general points to bare in mind:
  - Belle-II cannot do much with the B_s^0
  - CMS / ATLAS are competitive with LHCb in decays with J/ψ
  - For most CPV measurements the LHCb upgrade(s) designs strive to ensure measurements do not become systematically saturated
    - This is easy to say now, in practise will be very difficult for some measurements at 300 fb^{-1}
    - Understanding time-acceptance is vital
    - Projections are very reliant on maintaining / improving flavour tagging performance

B^0 and B_s^0 mixing

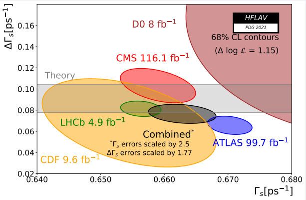


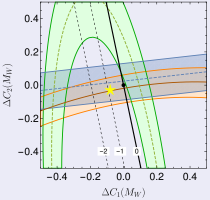
Theory [arXiv:1912.07621]
Experiment [arXiv:1909.12524]
Future [arXiv:1808.08865]
[arXiv:1808.10567]

Lifetime ratios - [arXiv:1912.07621]



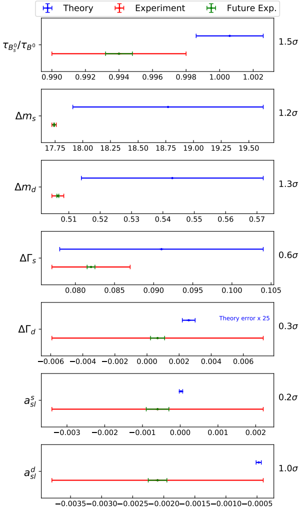
Tension in $\Delta\Gamma_s$ world average - [arXiv:1909.12524] [arXiv:1701.09183]





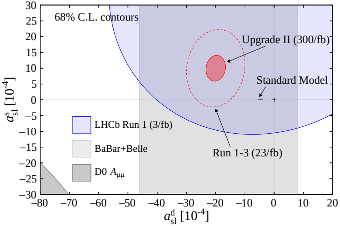
- Eventually (LHCb+Belle-II) $\Delta\Gamma_d \neq 0$ may be observable
- LHCb measurement is at $1\,\text{fb}^{-1}$- how desirable is an update?

Semileptonic asymmetries

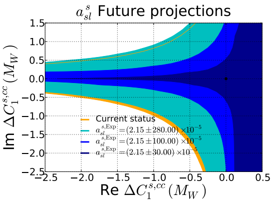


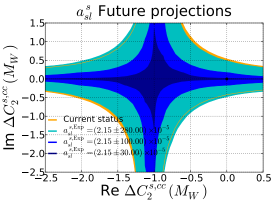
Theory [arXiv:1912.07621]
Experiment [arXiv:1909.12524]
Future [arXiv:1808.08865]
[arXiv:1808.10567]

- Powerful constraints from semileptonic asymmetries



[arXiv:1808.08865]

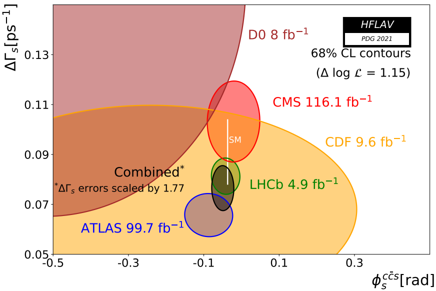


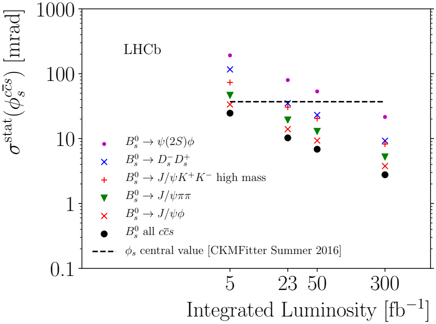


[arXiv:1912.07621]

Time-dependent CPV - ϕ_s

- Understanding of penguin pollution important as precision approaches SM prediction
- Exploitation of SU(3) partner modes, *e.g.* $B^0 \to J/\psi\rho$, $B_s^0 \to J/\psi\overline{K}^{*0}$
- Measurements of γ get so good that measurement of ϕ_s in $B_s^0 \to D_s^- K^+$ gets to $\sim$0.019 rad (current WA precision)
  - γ at 300 fb^{-1} $\sim$0.4°, $(\gamma - \phi_s) \sim 1°$

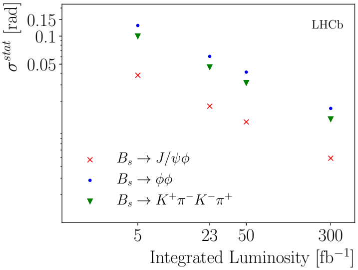


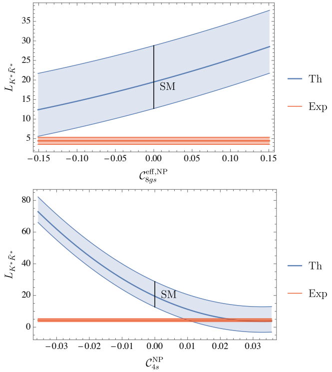


- Long term goal for *sin*(2β) precision is $\sim$0.002 (LHCb+Belle-II)

$B^0_{(s)} \to K^{*0}\overline{K}^{*0}$- going slightly off topic

- If there is NP in $b \to s\ell^+\ell^-$ transitions then reasonable to expect something in hadronic $b \to sq\overline{q}$
- Decays like $B^0_s \to K^{*0}\overline{K}^{*0}$ and $B^0_s \to \phi\phi$ also provide *loop-only* access to ϕ_s
- $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ almost unique in that the U-spin transformation leaves the final state unchanged
- Gives access to relatively clean observables like $L_{K^{*0}\overline{K}^{*0}}$ equivalent to R_K
  - Decay rate ratio of $B^0_s \to K^{*0}\overline{K}^{*0}$ and $B^0 \to K^{*0}\overline{K}^{*0}$

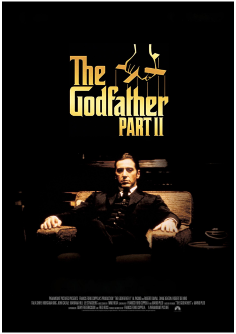




[arXiv:2011.07867]

Sequels that are better than the original?

The Godfather Part II



The Empire Strikes Back

Aliens

Beyond the Flavour Anomalies?

Beyond the Flavour Anomalies II

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, $B \to K^* l\, l$ 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.

More precise results on lifetime observables would be useful

Backup

Def. new physics scale

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