Model Independent Study of CP Conserving and CP Violating BSM Effects in $b \to c\bar{c}s$ Couplings

MITP Workshop on "Future Challenges in Non-Leptonic B Decays"

Kirsten Leslie

S.Jäger, M.Kirk, A.Lenz

University of Sussex

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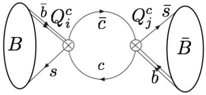
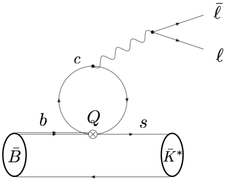
Outline

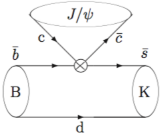
- Description of set up
- Motivation - anomalies in rare decay, consistency in mixing
- Constraints from radiative decay, mixing and lifetimes - BSM in rare decay
- CP Asymmetries - BSM in complex couplings
- Non leptonic decay - hadronic parameter fitting technique
- Conclusions

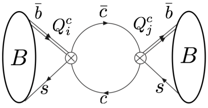
Set up

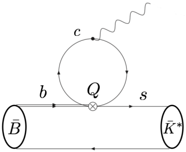
- $b \to c\bar{c}s$ four quark operators contribute to $B_s^{(0)} - \bar{B}_s^{(0)}$ mixing, $B_s^{(0)}$ lifetime, rare and radiative B decay at loop level and to $B \to J/\psi K_S$ at tree level





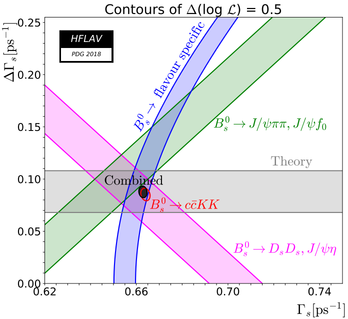




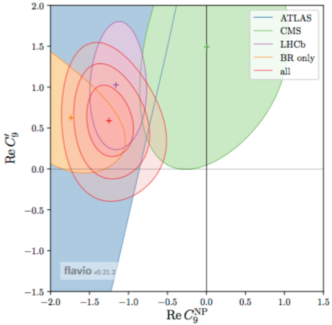


Schematically

- $Q = \hat{V}(\bar{c}\Gamma_X b)(\bar{s}\Gamma_Y c)$



Eur.Phys.J.C77(2017)895,http://www.slac.stanford.edu/xorg/hfag



Altmannshofer, Niehoff, Stangl, Straub, 1703.09189

- SM predictions consistent with measurement in mixing observables
- Anomalies in rare decay are reported in LHCb analysis, indicating a possible shift to Wilson coefficient C_9

Operator Basis

$$\mathcal{H}^{\text{eff}} = \frac{4G_F}{\sqrt{2}}\left[\lambda_c \sum_{i=1}^{10} C_i^c Q_i^c - \lambda_t (C_{7\gamma} Q_{7\gamma} + C_{9V} Q_{9V}) + Primed + \text{h.c}\right]$$

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

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

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

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

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

$$Q_{7\gamma} = \frac{e m_b}{16\pi^2}(\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}, \qquad Q_{9V} = \frac{\alpha}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

- Plus 12 more primed operators obtained by letting $P_{L(R)} \to P_{R(L)}$ in the above

$$C_i^c(\mu) = \begin{cases} C_i^{SM}(\mu) + \Delta C_i(\mu), & i = 1,2 \\ \Delta C_i(\mu), & i = 3,..,10 \end{cases}$$

$$C_i^{\prime c}(\mu) = \Delta C_i^{\prime}(\mu) \qquad i = 1,\ldots,10$$

$$C_i^{\prime}(\mu) = C_i^{\prime}(\mu) \qquad i = 7\gamma, 9V$$

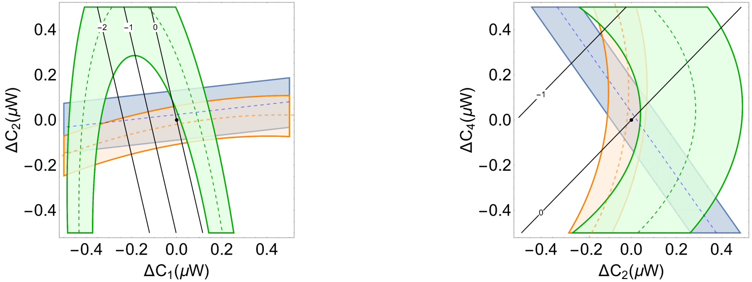
Case I: Rare decay anomalies $C_1^c - C_4^c$ in C_{9V} from previous publication

Strategy

- Consider shift to C_9 induced by Operators $Q_1^c - Q_4^c$ in $b \to s\ell\ell$ amplitude
- constrain with BSM predictions for mixing, lifetime and radiative decay using Operators $Q_1^c - Q_4^c$

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

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



$C_9^{SM} = 4.27$, shift to C_9 of $\Delta C_9 = -1$ could explain anomaly in rare decay

[Jäger,Kirk,Leslie,Lenz 1701.09183]

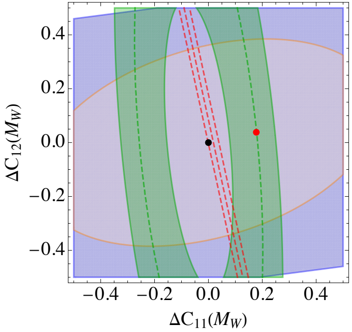
Case II: Right handed currents analysis (New work)

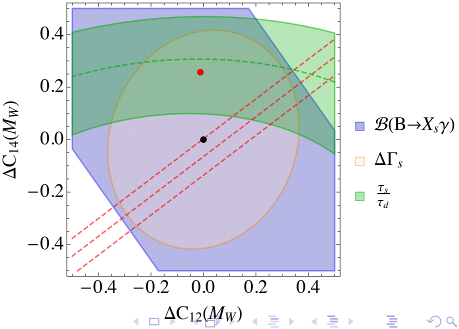
Strategy

- C_9' here constrains general BSM contributions from Operators $Q_1'^c - Q_4'^c$.
  $C_9' = 0.2 \pm 0.2$ [Altmannshofer, Niehoff,Stangl,Straub 1703:09189]
- Can again constrain size of $\Delta C_1'^c - \Delta C_4'^c$ with BSM predictions for mixing, lifetime and radiative decay inserting Operators $Q_1'^c - Q_4'^c$

$$Q_1'^c = (\bar{c}^i_R \gamma_\mu b^j_R)(\bar{s}^j_R \gamma^\mu c^i_R), \qquad Q_2'^c = (\bar{c}^i_R \gamma_\mu b^i_R)(\bar{s}^j_R \gamma^\mu c^j_R),$$

$$Q_3'^c = (\bar{c}^i_L b^j_R)(\bar{s}^j_R c^i_L), \qquad Q_4'^c = (\bar{c}^i_L b^i_R)(\bar{s}^j_R c^j_L),$$





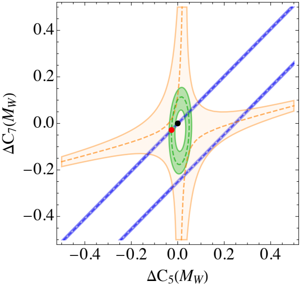
Case III: New operators $Q_5^c - Q_{10}^c$ (New work)

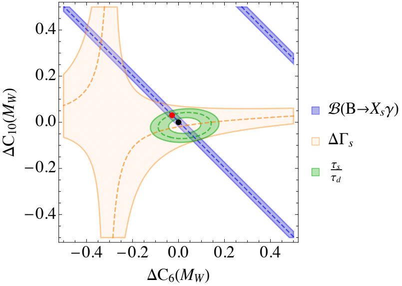
- Can only constrain size of $\Delta C_5 - \Delta C_{10}$ with BSM predictions for mixing, lifetime and radiative decay
- Dominant constraint is from $\mathcal{B}(B \to X_s\gamma)$ and rules out many scenarios involving pairs of these coefficients

$$Q_5^c = (\bar{c}^i_R\gamma_\mu b^j_R)(\bar{s}^j_L\gamma^\mu c^i_L), \qquad Q_6^c = (\bar{c}^i_R\gamma_\mu b^i_R)(\bar{s}^j_L\gamma^\mu c^j_L),$$

$$Q_7^c = (\bar{c}^i_L b^j_R)(\bar{s}^j_L c^i_R), \qquad Q_8^c = (\bar{c}^i_L b^i_R)(\bar{s}^j_L c^j_R),$$

$$Q_9^c = (\bar{c}^i_L\sigma_{\mu\nu} b^j_R)(\bar{s}^j_L\sigma^{\mu\nu} c^i_R), \qquad Q_{10}^c = (\bar{c}^i_L\sigma_{\mu\nu} b^i_R)(\bar{s}^j_L\sigma^{\mu\nu} c^j_R),$$

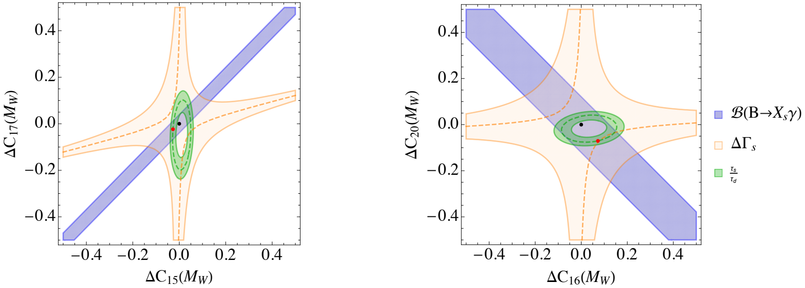




Case IV: New operators $Q'^{c}_5 - Q'^{c}_{10}$ (New work)

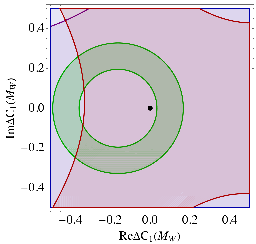
- Can only constrain size of $\Delta C'_5 - \Delta C'_{10}$ with BSM predictions for mixing, lifetime and radiative decay
- Dominant constraint is again from $\mathcal{B}(B \to X_s\gamma)$ and is less constraining dues to quadratic dependence of ratio upon $\Delta C'_{7\gamma}$

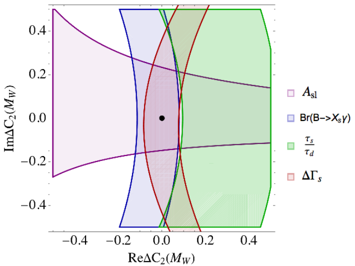
$$
\begin{aligned}
Q'^{c}_5 &= (\bar{c}^i_L \gamma_\mu b^j_L)(\bar{s}^j_R \gamma^\mu c^i_R), & Q'^{c}_6 &= (\bar{c}^i_L \gamma_\mu b^i_L)(\bar{s}^j_R \gamma^\mu c^j_R), \\
Q'^{c}_7 &= (\bar{c}^i_R b^j_L)(\bar{s}^j_R c^i_L), & Q'^{c}_8 &= (\bar{c}^i_R b^i_L)(\bar{s}^j_R c^j_L), \\
Q'^{c}_9 &= (\bar{c}^i_R \sigma_{\mu\nu} b^j_L)(\bar{s}^j_R \sigma^{\mu\nu} c^i_L), & Q'^{c}_{10} &= (\bar{c}^i_R \sigma_{\mu\nu} b^i_L)(\bar{s}^j_R \sigma^{\mu\nu} c^j_L),
\end{aligned}
$$



CP Asymmetries - New Weak Phases from SM Wilson coefficients

$$C_i^c = C_i^{\mathrm{SM}} + \mathrm{Re}(\Delta C_i) + \mathrm{Im}(\Delta C_i) \qquad i = 1, 2$$





$$A_{sl}^s = \frac{\Gamma(\bar{B}_s^0(t) \to f) - \Gamma(B_s^0(t) \to \bar{f})}{\Gamma(\bar{B}_s^0(t) \to f) + \Gamma(B_s^0(t) \to \bar{f})}$$

- Introduce new source of CP violation by allowing Wilson coefficients to be complex
- Any deviation of A_{sl} from zero signals CP violation

CP Asymmetries II: Further constraints from $B \to J/\psi K_S$?

Time Dependent CP Asymmetry

$$A_{CP}(t) = S_{J/\psi K} \sin(\Delta M t) - C_{J/\psi K} \cos(\Delta M t)$$

$$S_{J/\psi K} = \frac{2\mathrm{Im}(\lambda_{J/\psi K})}{\left(1+|\lambda_{J/\psi K}|^2\right)}$$

$$C_{J/\psi K} = \frac{\left(1-|\lambda_{J/\psi K}|^2\right)}{\left(1+|\lambda_{J/\psi K}|^2\right)}$$

$$\lambda_{J/\psi K} = e^{2i\beta} \frac{((C_1^c)^* + (C_2^c)^* r_{21})}{(C_1^c + C_2^c r_{21} +)} \qquad r_{21} = \frac{\langle J/\psi K_d^0 | O_2 | B_d^0 \rangle}{\langle J/\psi K_d^0 | O_1 | B_d^0 \rangle} \qquad r_{21} \in \mathbb{C}$$

Branching ratio

$$\mathcal{B}(B \to J/\psi K) = \frac{\tau_B |\vec{p}_c| G_F^2 |\lambda_c|^2}{M_B^2 \pi} |\langle \mathcal{O}_1 \rangle|^2 |(C_1^c + C_2^c r_{21})|^2$$

- Theoretically challenging to compute the hadronic matrix elements

Fit of hadronic parameters

- $\langle\mathcal{O}_1\rangle$ factorizes in the naive sense with correction in the large N limit of $\mathcal{O}\left(\frac{1}{N^2}\right)$ relative to NF
- $\langle\mathcal{O}_2\rangle$ color fierzes into a color singlet and color octet and is $\frac{1}{N}$ suppressed in Naive factorization

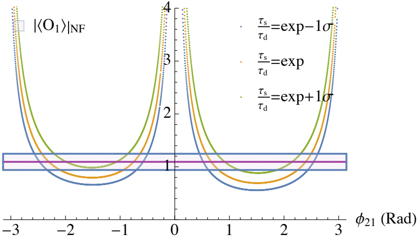
$$\langle\mathcal{O}_1\rangle = \langle\mathcal{O}_1\rangle_{NF}(1+\mathcal{O}\left(\frac{1}{N^2}\right))$$

$$\langle\mathcal{O}_2\rangle = \frac{1}{N}\langle\mathcal{O}_1\rangle + \langle T_1\rangle$$

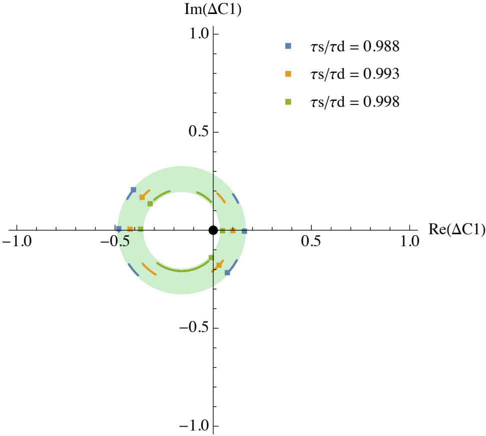
Strategy

- Keep $r_{21}, \langle\mathcal{O}_1\rangle$ exact
- 3 observables, 3 predictions, 3 hadronic parameters
- Fit hadronic parameters $Re(r_{21}), Im(r_{21}), |\langle\mathcal{O}_1\rangle|$ to experimental data
- Compare with theoretical estimate of $|\langle\mathcal{O}_1\rangle|_{NF}$

Fit of hadronic parameters II



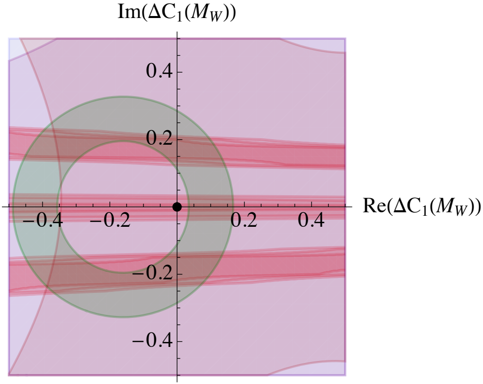
$$|\langle \mathcal{O}_1 \rangle|_{NF} = (1.094 \pm 0.106)\mathrm{GeV}^3$$



- Fitted hadronic parameters agree with Naive factorization and with lifetime ratio constraint at distinct points

Full constraint from $B \to J/\psi K_S$ on complex C_1^c

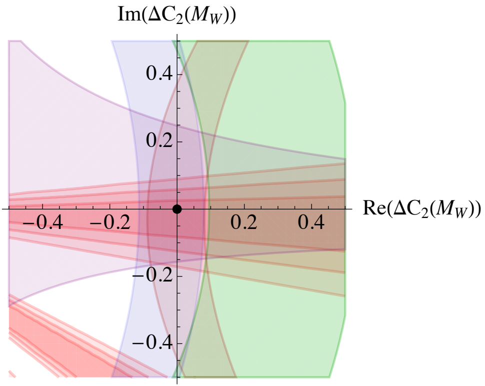
$$\Delta C_1 = \mathrm{Re}(\Delta C_1) + i\mathrm{Im}(\Delta C_1)$$



- discrete points become bands when requiring $|\langle \mathcal{O}_1 \rangle|$ is within theoretical error for NF prediction (quite good) and r_{21} left free
- CP violation with imaginary shift to C_1^c of around ± 0.2
- With very little theoretical input it is possible to obtain a further constraint in the complex C_1^c plane

Full constraint from $B \to J/\psi K_S$ on C_2^c

$$\Delta C_2 = \text{Re}(\Delta C_2) + i\text{Im}(\Delta C_2)$$



- Still possible to constrain further using fitted parameters but less clear outcome in C_2^c
- No region where all observables agree to a particular value for $\Delta C_2 \in \mathbb{C}$ but real axis in agreement with NF estimate

Conclusions

- BSM physics in rare decays can be connected to radiative decays, mixing and lifetimes using charmed four quark operators
- Explanation to rare decay anomalies in shift to C_{9V} from $C_1^c - C_4^c$ is possible
- $C_5^c - C_{10}^c$ are strongly constrained by radiative decay but $C_5'^c - C_{10}'^c$ less stringently so due to quadratic dependence of branching ratio upon $\Delta C'_{7\gamma}$
- $C_1'^c - C_4'^c$ constrained by mixing, lifetimes, radiative and rare decay
- we looked at CPV and used "novel " method to consider BSM effects vs NF
- $\mathcal{O}_1$ is quite well approximated by NF ; distinct regions in the complex ΔC_1 plane for which theory prediction agrees with $B \to J/\psi K_S$
- $\mathcal{O}_2$ is not so trustworthy and regions agreeing with NF in complex ΔC_2 plane are not so useful

Backup

- The color octet operator contains $SU(3)$ color generators
  $T_1 = (\bar{c}\gamma_\mu T^A P_L c)(\bar{s}\gamma^\mu T^A P_L b)$
- In naive factorization the operator matrix element of $\mathcal{O}_1$ factorizes as
  $\langle \mathcal{O}_1 \rangle_{NF} = \langle J/\psi|\bar{c}\gamma_\mu c|0\rangle\langle K|\bar{s}\gamma^\mu b|B\rangle$

$\Delta B = 0, 2$ Basis

$\Delta B = 0$: SM

$$Q_1^s = \bar{b}\gamma_\mu(1-\gamma^5)s\bar{s}\gamma^\mu(1-\gamma^5)b$$

$$Q_2^s = \bar{b}(1-\gamma^5)s\bar{s}(1+\gamma^5)b$$

$$T_1^s = \bar{b}\gamma_\mu(1-\gamma^5)T^A s\bar{s}\gamma^\mu(1-\gamma^5)T^A b$$

$$T_2^s = \bar{b}(1-\gamma^5)T^A s\bar{s}(1+\gamma^5)T^A b$$

M.Kirk, A.Lenz,T.Rauh, 1711.02100

$\Delta B = 0$: New Operators

$$Q_3^s = \bar{b}\gamma_\mu(1-\gamma^5)s\bar{s}\gamma^\mu(1+\gamma^5)b$$

$$Q_4^s = \bar{b}(1-\gamma^5)s\bar{s}(1-\gamma^5)b$$

$$T_3^s = \bar{b}\gamma_\mu(1-\gamma^5)T^A s\bar{s}\gamma^\mu(1+\gamma^5)T^A b$$

$$T_4^s = \bar{b}(1-\gamma^5)T^A s\bar{s}(1-\gamma^5)T^A b$$

$\Delta B = 2$

$$Q = (\bar{s}^\alpha\gamma_\mu(1-\gamma_5)b^\alpha)(\bar{s}^\beta\gamma^\mu(1-\gamma_5)b^\beta) \quad Q_S = (\bar{s}^\alpha(1+\gamma_5)b^\alpha)\times(\bar{s}^\beta(1+\gamma_5)b^\beta)$$

$$\tilde{Q}_S = (\bar{s}^\alpha(1+\gamma_5)b^\beta)\times(\bar{s}^\beta(1+\gamma_5)b^\alpha) \quad R_1 = \frac{m_s}{m_b}(\bar{s}^\alpha(1+\gamma^5)b^\alpha)\times(\bar{s}^\beta(1-\gamma^5)b^\beta)$$

$$\tilde{R}_1 = \frac{m_s}{m_b}(\bar{s}^\alpha(1+\gamma^5)b^\beta)\times(\bar{s}^\beta(1-\gamma^5)b^\alpha)$$

α, β Colour indices, T^A are $SU(3)$ Colour generators