New Physics In $b \to c\bar{c}s$ Couplings? A Model Independent Study

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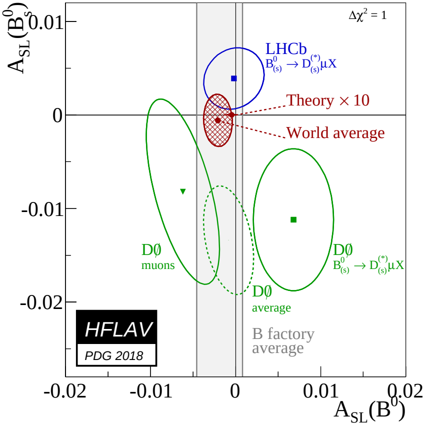
Outline

- Motivation
- Set up
- Constraints on NP in rare decay from mixing, lifetimes and radiative decay
- Model independent constraints on different NP scenarios
- $b \to c\bar{c}s$ in CP Asymmetries
- Conclusions

$b \to c\bar{c}s$ in Mixing and Lifetimes



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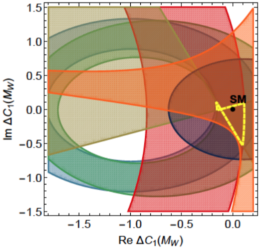
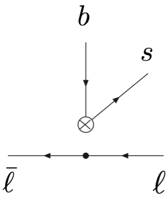
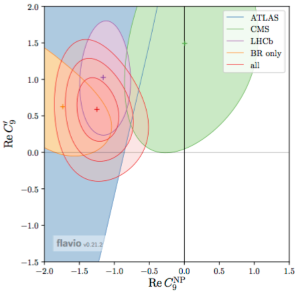


Brod, Lenz, Tetlalmatzi-Xolocotzi,Wiebusch 1412.1446v1

$b \to c\bar{c}s$ in Rare Decay



$$Q_9^l = \frac{\alpha}{4\pi}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell)$$

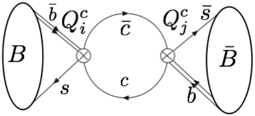


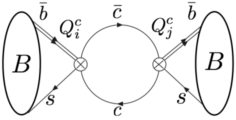
Altmannshofer, Niehoff, Stangl, Straub, 1703.09189

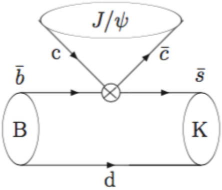
- Anomalies in rare decay are reported in LHCb analysis, indicating a possible shift to Wilson coefficient C_9

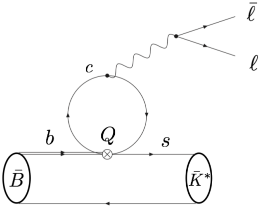
Set Up

- $b \to c\bar{c}s$ operators contribute to mixing, lifetime, rare decay at loop level and to $B \to J/\psi K$ at tree level









$\Delta B = 1$ Operator Basis

$$\mathcal{H}^{\text{eff}} = \frac{4G_F}{\sqrt{2}}\left[\lambda_c \sum_{i=1}^{10} C_i^c Q_i^c - \lambda_t \left(\sum_{i=3}^{6} C_i^p \mathcal{P}_i + C_7 Q_{7\gamma} + C_9 Q_{9V}\right) + \text{Primed} + \text{h.c}\right]$$

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

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

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

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

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

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

Constraints on New Physics at lower scales

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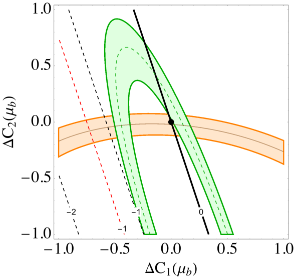
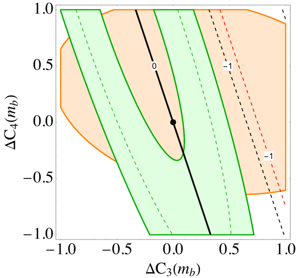
$$\Delta C_9^{\text{eff}}(q^2,\mu,m_c) = \left(C_{1,2}^c - \frac{C_{3,4}^c}{2}\right) h - \frac{2}{9} C_{3,4}^c\,,$$

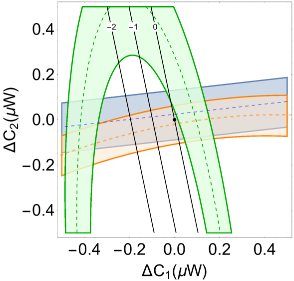
$$\Delta C_7^{\text{eff}}(q^2,\mu,m_c) = \frac{m_c}{m_b}\left[\left(4C_{9,10}^c - C_{7,8}^c\right) y + \frac{4C_{5,6}^c - C_{7,8}^c}{6}\right]$$

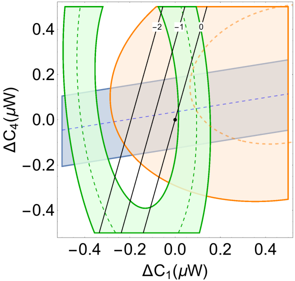




- q^2 is the dilepton invariant mass squared in $b \to s\ell\ell$
- At the lower scale $\mu \approx 4.6 GeV$ there is a mild q^2 dependence
- greater sensitivity at higher $q^2 = 5GeV^2$ (black) than $q^2 = 2GeV^2$ (red)

Constraints on New Physics at higher scales



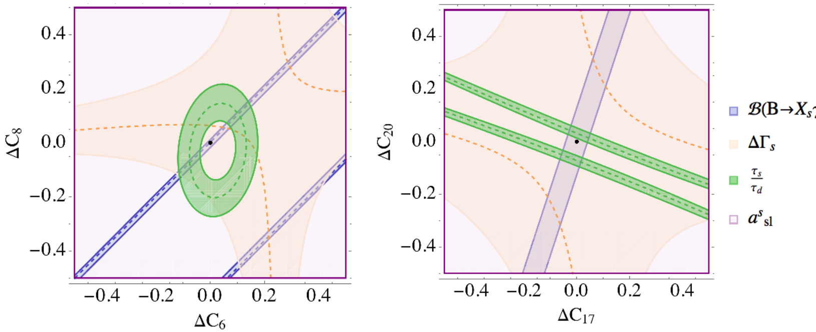


$$\Delta C_7^{\mathrm{eff}}(m_b) = 0.02\Delta C_1(M_W) - 0.19\Delta C_2(M_W) - 0.01\Delta C_3(M_W) - 0.13\Delta C_4(M_W) + 1.01\Delta C_5(M_W) + 0.30\Delta C_6(M_W) - 1.83\Delta C_7(M_W) - 0.85\Delta C_8(M_W) + 7.21\Delta C_9(M_W) + 1.26\Delta C_{10}(M_W)$$

$$\Delta C_9^{\mathrm{eff}}(m_b) = 8.48\Delta C_1(M_W) + 1.96\Delta C_2(M_W) - 4.24\Delta C_3(M_W) - 1.91\Delta C_4(M_W)$$

[Chetyrkin, Misiak, Munz arXiv:hep-ph/9612313]
[Jäger,Kirk,Leslie,Lenz 1701.09183]

Constraints on New Physics at higher scales



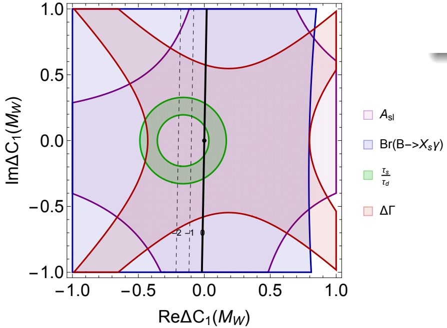
- Unprimed coefficients are suppressed by radiative decay due to RG enhancements
- Primed coefficients are enhanced by radiative decay due to RG enhancements and no SM contribution

[Jäger,Kirk,Leslie,Lenz in preparation] $\Delta C_{17} = \Delta C_7'$, $\Delta C_{20} = \Delta C_{10}'$

CP Violation - New Weak Phases $\Delta C_j(\mu) = |\Delta C_j(\mu)|e^{i\phi_j}$

- Allowing the Wilson coefficients to be complex introduces new weak CP violating phases

$$C_1^c(\mu) = C_1^{SM}(\mu) + Re(\Delta C_1(\mu)) + Im(\Delta C_1(\mu))$$



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

- Any deviation of A_{sl} from zero signals CP violation
- $\Delta C_9 = -1$ achievable in the complex ΔC_1 plane
- Real and imaginary part of $\Delta C_1(\mu)$ constrained by B_s^0 to B^0 lifetime ratio

CP Violation and $b \to c\bar{c}s$ in $B \to J/\psi K$

Time Dependent CP Asymmetry

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

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

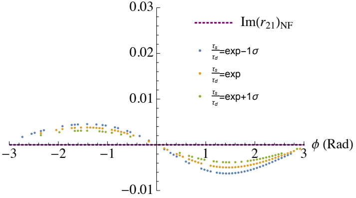
$$C_{J/\psi K} = \frac{\left(1-|\lambda_{J/\psi K}|^2\right)}{\left(1+|\lambda_{J/\psi K}|^2\right)}$$

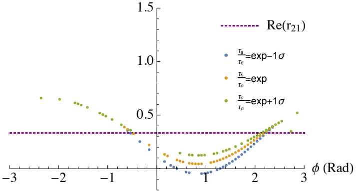
$$\lambda_{J/\psi K} = e^{2i\beta} \frac{((C_1^c)^* + (C_2^c)^* r_{21} + (C_3^c)^* r_{31} + (C_4^c)^* r_{41})}{(C_1^c + C_2^c r_{21} + C_3^c r_{31} + C_4^c r_{41})}, \qquad r_{ij} = \frac{\langle O_i \rangle}{\langle O_j \rangle}$$

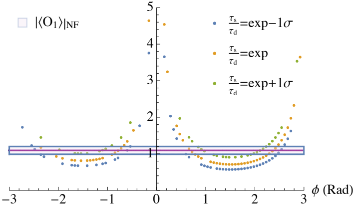
- Theoretically challenging to compute the hadronic matrix elements
- Strategy: Minimize the χ^2 and find the best fit solutions for hadronic parameters $Im(r_{12}), Re(r_{12}), |\langle O_1 \rangle|$ allowed by lifetime ratio

$$\chi^2 = \chi^2(S_{J/\psi K}) + \chi^2(C_{J/\psi K}) + \chi^2(\mathcal{B}(B \to J/\psi K))$$

Fits for hadronic paramaters







$\phi \in [-2.6, -0.5]$rad

$\phi \in [0.6, 1.1]$rad

$\phi \in [1.8, 2.6]$rad

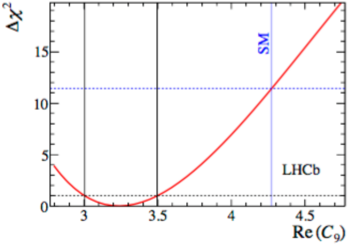
$$\phi = Arg\left(\frac{Im(\Delta C_1)}{Re((\Delta C_1 + \delta)}\right)$$

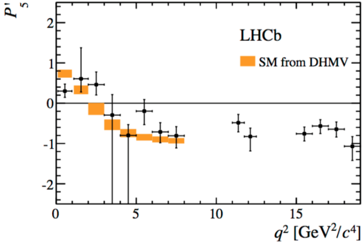
Summary

- Mild q^2 dependence in ΔC_9 for lower scale NP and modified SM coefficients
- For Weak scale Wilson coefficients, negative ΔC_9 shift enhanced by RG effects - not ruled out by mixing, lifetimes and radiative decay
- Wilson coefficients of full basis are suppressed or enhanced by RG effects due to ΔC_7^{eff} in radiative decay
- A constraint from A_{sl}^s is possible in the complex case. Measurement of non zero A_{sl}^s could imply a small imaginary part in ΔC_1.
- CP Violation in $B- \to J/\psi K$ is studied through fitting hadronic parameters and implying discrete ranges of Wilson coefficient allowed in NFA
- Further work: Include $\frac{1}{N^2}$, $\mathcal{O}(\alpha_s)$ and $\frac{\Lambda}{m_b}$, $\frac{\Lambda}{\alpha_s m_b}$ corrections to Naive Factorization in $B \to J/\psi K$
- Further work - extend hadronic fitting parameter analysis to further pairs of coefficients

Back up Slides

B decay anomalies





JHEP 02 (2016) 104

- LHCb analysis implies a negative shift to Wilson coefficient C_9
- $Re(C_9) = 4.27$ [arXiv:1310.2478]
- $\Delta Re(C_9) = -1.04 \pm 0.25$

$\Delta B = 0, 2$ 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

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

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

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

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

$\Delta B = 2$

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

$$Q_S = (\bar{s}^\alpha(1+\gamma_5)b^\alpha)\times(\bar{s}^\beta(1+\gamma_5)b^\beta)$$

$$\tilde{Q}_S = (\bar{s}^\alpha(1+\gamma_5)b^\beta)\times(\bar{s}^\beta(1+\gamma_5)b^\alpha)$$

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

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

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