# Charming new physics in rare $B$ decays and mixing

SEPTA Meeting at University of Sussex

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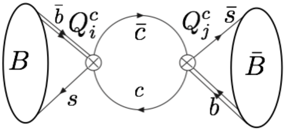
# Outline

- Motivation
- Methodology
- Preliminary results
- Conclusions

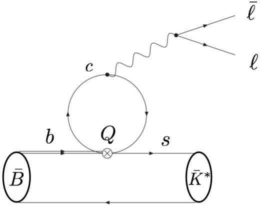
# Central idea

Both $B_s$ meson mixing and rare $B$ decays receive contributions from charmed operators at 1-loop



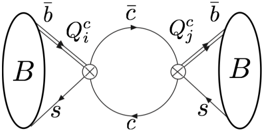

**$B_s$-$B_d$ Lifetime ratio**

$$\left(\frac{\tau_{B_s}}{\tau_{B_d}}\right)$$




**Width/Mass differentce**

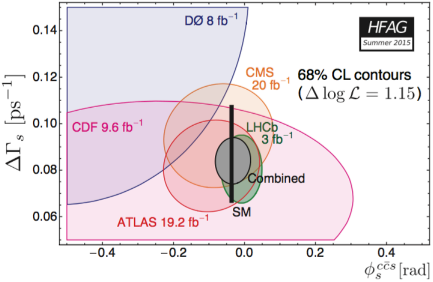
$$\frac{\Delta\Gamma}{\Delta M}, a_{sl}^s$$



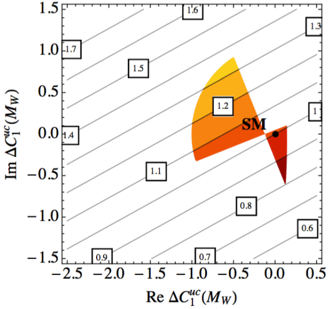

**Rare decay observables**

$$A_{FB}, P_5'$$

# Motivation: Mixing observables



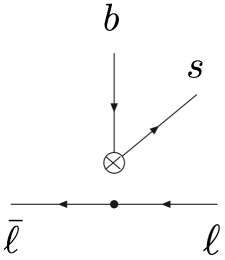

http://www.slac.stanford.edu/xorg/hfag/osc/spring_2016

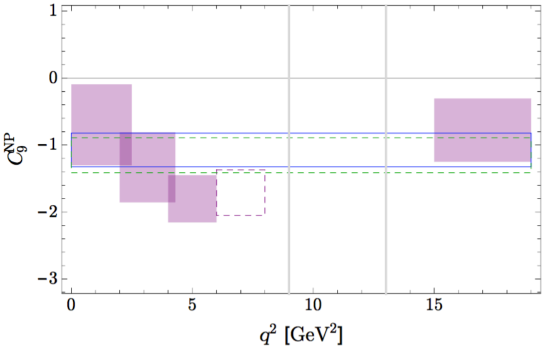



Brod, Lenz, Tetlalmatzi-Xolocotzi, Wiebusch, 1412.1446v1

- Mixing observables such as the decay rate difference and semileptonic assymmetry show consistency with the SM
- Another important observable to considershowing a slight deviation from the SM is the $B_s$-$B_d$ lifetime ratio
- If sizable NP contributions to $b \to c\bar{c}s$ couplings are present in mixing, they could also effect and constrain $b \to s\ell\bar{\ell}$

# Motivation: Rare decay anomalies




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

Altmannshofer, Straub, 1503:06199, (see also Descotes,Hofer,Matias,Virto 1605:06059)

- Recent analysis of LHCb data suggests a negative contribution to the Wilson coefficient $C_9$
- Possible explanation for tensions in rare decays such as $B \to K^* \mu\mu$
- Assume a negative shift to $C_9$ and ask if there are viable charming BSM scenarios which reproduce this effect

# Weak Effective Hamiltonian

## $\Delta B = 1$ Hamiltonian

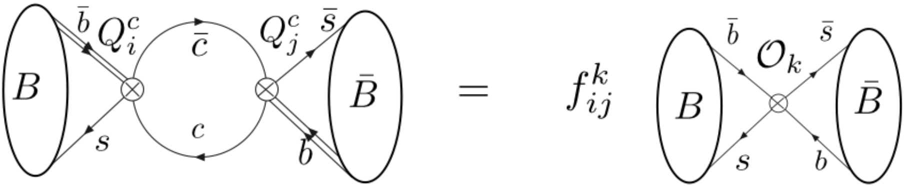
$$\mathcal{H}_{eff}^{c\bar{c}} = \frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \left[ \Sigma_{i=1}^{10} \left( C_i^c Q_i^c + C_i^{c\prime} Q_i^{c\prime} \right) + h.c \right]$$

## SM

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

## BSM

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



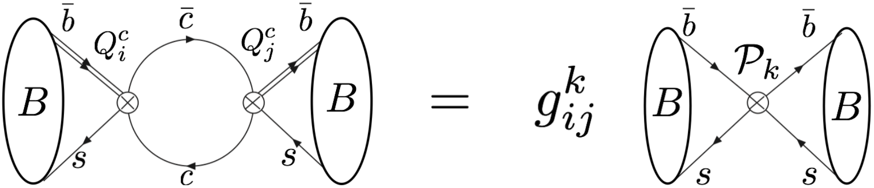

- Heavy Quark Expansion reduces original $\Delta B = 1$ basis to standard $\Delta B = 2$ basis

$$\Gamma_{12}^{cc} \sim \Sigma_{ijk} C_i^c C_j^c f_{ij}^k \frac{\langle B_s^0 | \mathcal{O}_k | \bar{B}_s^0 \rangle}{2M_B}$$

### Width difference / mass difference

$$\frac{\Delta\Gamma}{\Delta M} = -Re\left(\frac{\Gamma_{12}}{M_{12}}\right)$$

# $B_s$-$B_d$ Lifetime ratio : $\left(\frac{\tau_{B_s}}{\tau_{B_d}}\right)$

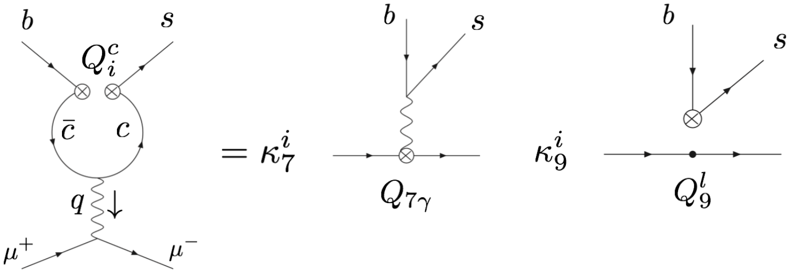


- Heavy Quark Expansion reduces original $\Delta B = 1$ basis to standard $\Delta B = 0$ basis

$$\Gamma^{cc} \sim \Sigma_{ijk} C_i^c C_j^c g_{ij}^k \frac{\langle B_s^0 | \mathcal{P}_k | B_s^0 \rangle}{2M_B}$$

The new physics part of lifetime ratio $r = \left(\frac{\tau_{B_s}}{\tau_{B_d}}\right)$ is constructed from $\Gamma^{cc}$

# Rare Decay: Short distance effects

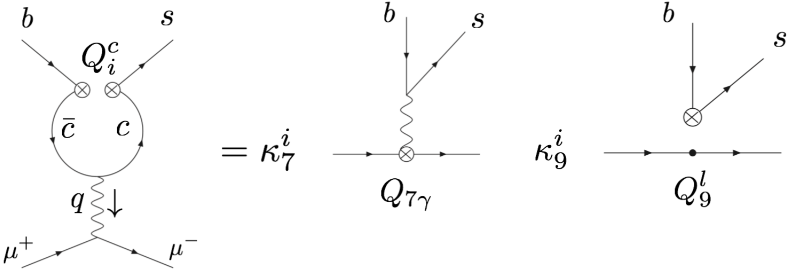



$$\langle \mu^+ \mu^- s | \mathcal{H}_{eff}^{cc} | b \rangle^{(1)} = \Delta C_{eff}^7(q^2) \langle Q_{7\gamma} \rangle^{tree} + \Delta C_{eff}^9(q^2) \langle Q_9^l \rangle^{tree} + \mathcal{O}(\alpha \alpha_s)$$

$$\Delta C_9^{eff}(q^2) = C_i \kappa_9^i$$

$$\Delta C_7^{eff}(q^2) = C_i \kappa_7^i$$

# Rare Decay: Short distance effects



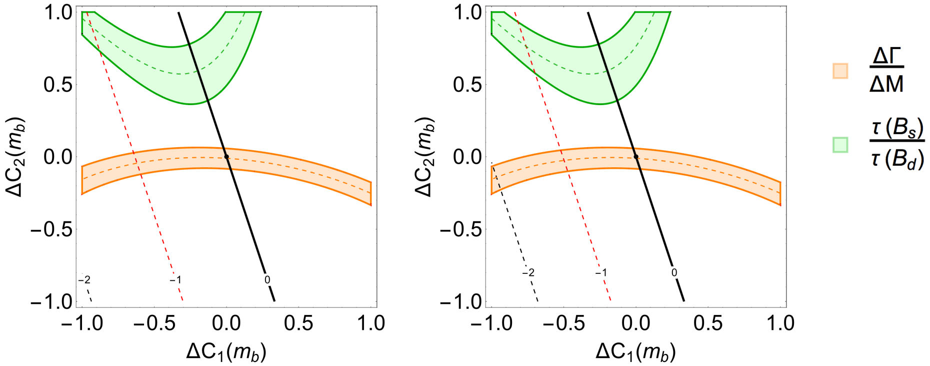

$$\langle \mu^+ \mu^- s | \mathcal{H}_{eff}^{cc} | b \rangle^{(1)} = \Delta C_{eff}^7(q^2) \langle Q_{7\gamma} \rangle^{tree} + \Delta C_{eff}^9(q^2) \langle Q_9^l \rangle^{tree} + \mathcal{O}(\alpha \alpha_s)$$

$$\Delta C_9^{eff}(q^2) = C_i \kappa_9^i$$

$$\Delta C_7^{eff}(q^2) = C_i \kappa_7^i$$

$$\Delta C_{\rm eff}^9 = \left[ \left( (3\Delta C_1 + \Delta C_2) - \tfrac{1}{2}(3\Delta C_3 + \Delta C_4) \right) h(q^2) - \tfrac{2}{9}(3\Delta C_3 + \Delta C_4) \right]$$

# Results I: Low Scale Constraints on $\Delta C^9_{eff}(q^2)$




$$\Delta C^9_{eff}(q^2 = 2GeV^2)$$

$$\Delta C^9_{eff}(q^2 = 5GeV^2)$$

- $q^2$ dependence of $\Delta C^9_{eff}$ is more sensitive to NP at higher values of $q^2$
- Negative shift of $\Delta C^9_{eff} = -1$ can be accomodated by $\frac{\Delta\Gamma}{\Delta M}$

# Renormalization Group Evolution

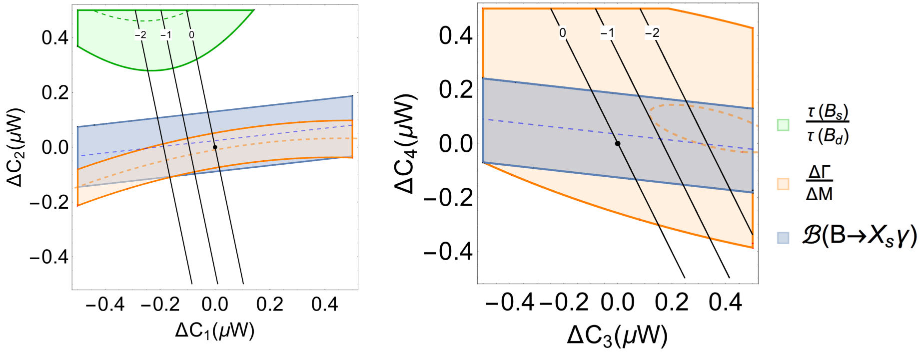
- When NP enters at the high scale $\mu \approx M_W$ Renormalization Group effects become important

$$\Delta C^7_{eff}(\mu_b) = 0.02 C^c_1(M_W) - 0.19 C^c_2(M_W) - 0.01 C^c_3(M_W) - 0.13 C^c_4(M_W)$$

$$\Delta C^9_{eff}(\mu_b) = 8.65 C^c_1(M_W) + 2.00 C^c_2(M_W) - 4.33 C^c_3(M_W) - 1.95 C^c_4(M_W)$$

- $\Delta C^7_{eff}$ generates $B \to X_s\gamma$ constraint
- $C^c_3(M_W)$and $C^c_4(M_W)$ are new in $\Delta C^7_{eff}$ and only appear at 2-loop

# Results II: High Scale Constraints on $\Delta C^{9}_{eff}(5GeV^2)$

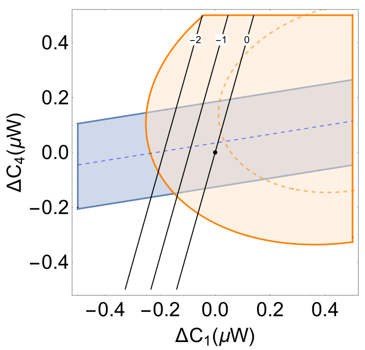


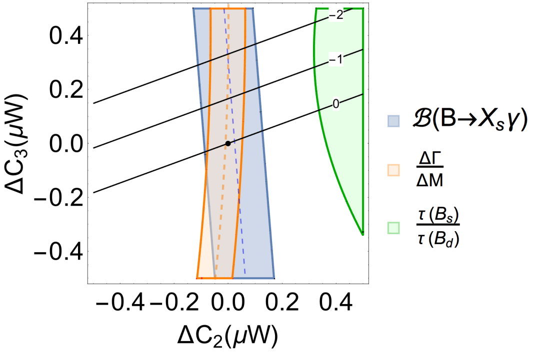

NP in $C_1$-$C_2$ scenario

NP in $C_3$-$C_4$ scenario

- In the $C_1$-$C_4$ and $C_3$-$C_4$ scenario, $B \to X_s\gamma$ and mixing constraints allows a negative shift to $C_9^{eff}$

# Results III: Constraints on $\Delta C^9_{eff}(5GeV^2)$




**NP in $C_1$-$C_4$ scenario**

**NP in $C_2$-$C_3$ scenario**

- Lifetime ratio $r = \left(\frac{\tau_{B_s}}{\tau_{B_d}}\right)$ could discriminate between different scenarios - all 6 combinations of Wilson coefficients under investigation

# Conclusions

- Deviations of SM theory predictions from experimental data could be explained by a negative shift in $C_9$
- Charmed new physics in $b \to c\bar{c}s$ transitions could provide an explanation, but will affect mixing
- A feature of the low scale scenario where NP enters at $\mu \approx 4.6$ is the $q^2$ dependence of $\Delta C_9^{eff}$
- Bounds from mixing observables $\frac{\Delta\Gamma}{\Delta M}$ and from inclusive $\mathcal{B}r(B \to X_s\gamma)$ allow a negative shift to $C_9$ in NP high scales BSM scenarios for both SM and BSM Wilson coefficients
- Lifetime ratio $r = \left(\frac{\tau_{B_s}}{\tau_{B_d}}\right)$ may be able to discriminate between different scenarios - currently under investigation

# Back up slides

# $\Delta C_7(q^2)$ and Loop functions

- The coefficients $\Delta C_9$ and $\Delta C_7$ are

$$\Delta C_{\text{eff}}^7 = \frac{m_c}{m_b}\left[(4(3C_9 + C_{10}) - (3C_7 + C_8))\, y + \frac{(4(3C_5+C_6)-(3C_7+C_8))}{6}\right]$$

$$\Delta C_{\text{eff}}^9 = \left[\left((3C_1 + C_2) - \frac{1}{2}(3C_3 + C_4)\right) h - \frac{2}{9}(3C_3 + C_4)\right]$$

- The loop functions are

$$h(q^2, m_c, \mu) = -\frac{4}{9}\left(\ln\left(\frac{m_c^2}{\mu^2}\right) - \frac{2}{3} - z + (z+2)\sqrt{|z-1|}\arctan\left(\frac{1}{\sqrt{z-1}}\right)\right)$$

$$y(q^2, m_c, \mu) = -\frac{1}{3}\left(\ln\left(\frac{m_c^2}{\mu^2}\right) - \frac{3}{2} + 2\sqrt{|z-1|}\arctan\left(\frac{1}{\sqrt{z-1}}\right)\right)$$

- $z = \frac{4m_c^2}{q^2}$, $z < 1$