Charming new physics in b(eautiful) processes?

(based on 1701.09183)

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What hints are there of the Standard Model breaking down?

In the flavour sector, over the last couple of years a few anomalies have appeared . . .
Di-muon final states easy to measure experimentally, but branching ratio $\sim 10^{-7}$

First hint of anomaly in August 2013

“Confirmed” / still present in March 2015 using full run 1 data set
Di-muon final states are easy to measure experimentally, but the branching ratio is approximately $10^{-7}$. First hint of an anomaly in August 2013. "Confirmed" and still present in March 2015 using full run 1 data set.
\[ B \to K^* \mu \mu \]

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\[
\frac{1}{\Gamma} \frac{d^3(G + \bar{G})}{d \cos \theta_{\ell} d \cos \theta_K d \phi} = \frac{9}{32 \pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_{\ell} \right. \\
- F_L \cos^2 \theta_K \cos 2\theta_{\ell} + \\
S_3 \sin^2 \theta_K \sin^2 \theta_{\ell} \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_{\ell} \cos \phi + \\
S_5 \sin 2\theta_K \sin \theta_{\ell} \cos \phi + S_6^g \sin^2 \theta_K \cos \theta_{\ell} + \\
S_7 \sin 2\theta_K \sin \theta_{\ell} \sin \phi + \\
S_8 \sin 2\theta_K \sin 2\theta_{\ell} \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_{\ell} \sin 2\phi \left. \right]
\]
$P_5'$ – combination of angular observables in $B \rightarrow K^* \mu \mu$ that is theoretically clean

$\sim 3\sigma$ deviations
Compare branching ratio of $B \to K^* \mu\mu$ to $B \to K^*ee$

SM: $R_K(1 < q^2 < 6 \text{ GeV}^2) = 1.0003 \pm 0.0001 \quad ^1$

LHCb Run 1:
$R_K(1 < q^2 < 6 \text{ GeV}^2) = 0.745^{+0.09}_{-0.074} \pm 0.036 \quad ^2$

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^1 arXiv:0709.4174

^2 arXiv:1406.6482
Compare branching ratio of $B \rightarrow D_{\tau \nu}$ to $B \rightarrow D_{\mu \nu}$

Interesting as this is a tree level decay
Good / Boring Flavour Measurements

\[ \Delta \Gamma_s : \frac{\text{Experiment}}{\text{SM}} = \frac{(0.086 \pm 0.006) \text{ ps}^{-1}}{(0.088 \pm 0.020) \text{ ps}^{-1}} = 0.98 \pm 0.23 \]

\[ B(B \to X_s \gamma) : \frac{\text{Experiment}}{\text{SM}} = \frac{(3.32 \pm 0.16) \times 10^{-4}}{(3.36 \pm 0.23) \times 10^{-4}} = 0.99 \pm 0.08 \]

\[ \frac{\tau(B_s)}{\tau(B_d)} : \frac{\text{Experiment}}{\text{SM}} = \frac{0.990 \pm 0.004}{1.0005 \pm 0.0011} = 0.990 \pm 0.004 \]
Lifetime ratio – side note

- Looks like lifetime ratio has $\sim 2.5\sigma$ deviation from SM
- So why is this not talked about as an anomaly?
- Look at history . . .
Since we have several anomalies, we pick our favourite – it seems unlikely all will survive more data

$P'_5$ – lots of global fits $^1$, result is a shift in $C_9 \sim -1$

What kind of NP can explain the effect, while also being testable in other observables?

$^1$arXiv:1310.2478, 1411.3161, 1510.04239, 1603.00865
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- $P'_5$ – lots of global fits\(^1\), result is a shift in $C_9 \sim -1$

- What kind of NP can explain the effect, while also being testable in other observables?

- ($\bar{s}b$) ($\bar{c}c$) operators contribute to rare B-decays and B-mixing – model independent approach, but giving correlated effects in several places

\(^1\text{arXiv:1310.2478, 1411.3161, 1510.04239, 1603.00865}\)
In the SM, around half of the contribution to $b \to s\mu\mu$ transitions comes from virtual charm quark loops. Seems like a reasonable place to start. Constraints on these kind of operators from tree-level decays are not as tight as might be expected (see e.g. Tetlalmatzi-Xolocotzi, Lenz, et al.\textsuperscript{1} – 10% effects still allowed).

\textsuperscript{1}arXiv:1412.1446
Basis of Operators

- We take the most general set of \((\bar{s}^{\alpha} \Gamma b^\beta) (\bar{c}^{\gamma} \Gamma' c^\delta)\) operators as our basis
- Two colour structures
- Five Dirac matrix combinations – two scalar, two vector, one tensor
- Plus a chirality flip
- Gives 20 possible operators
### Basis of Operators

| \( Q_c^1 \) | \( = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i) \) | \( Q_c^2 \) | \( = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j) \) |
| \( Q_c^3 \) | \( = (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i) \) | \( Q_c^4 \) | \( = (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j) \) |
| \( Q_c^5 \) | \( = (\bar{c}_R^i \gamma_\mu b_R^j)(\bar{s}_L^j \gamma^\mu c_L^i) \) | \( Q_c^6 \) | \( = (\bar{c}_R^i \gamma_\mu b_R^i)(\bar{s}_L^j \gamma^\mu c_L^j) \) |
| \( Q_c^7 \) | \( = (\bar{c}_L^i b_R^j)(\bar{s}_L^j c_R^i) \) | \( Q_c^8 \) | \( = (\bar{c}_L^i b_R^i)(\bar{s}_L^j c_R^j) \) |
| \( Q_c^9 \) | \( = (\bar{c}_L^i \sigma_{\mu\nu} b_R^j)(\bar{s}_L^j \sigma^{\mu\nu} c_R^i) \) | \( Q_c^{10} \) | \( = (\bar{c}_L^i \sigma_{\mu\nu} b_R^i)(\bar{s}_L^j \sigma^{\mu\nu} c_R^j) \) |
### Basis of Operators

\[
\begin{align*}
Q_1^c &= (\bar{c}_i^L \gamma_\mu b^j_L)(\bar{s}_j^L \gamma_\mu c^i_L) & Q_2^c &= (\bar{c}_i^L \gamma_\mu b^i_L)(\bar{s}_j^L \gamma_\mu c^j_L) \\
Q_3^c &= (\bar{c}_i^R b^j_R)(\bar{s}_j^L c^i_R) & Q_4^c &= (\bar{c}_i^R b^i_R)(\bar{s}_j^L c^j_R) \\
Q_5^c &= (\bar{c}_i^R \gamma_\mu b^j_R)(\bar{s}_j^L \gamma_\mu c^i_L) & Q_6^c &= (\bar{c}_i^R \gamma_\mu b^i_R)(\bar{s}_j^L \gamma_\mu c^j_L) \\
Q_7^c &= (\bar{c}_i^L b^j_R)(\bar{s}_j^L c^i_R) & Q_8^c &= (\bar{c}_i^L b^i_R)(\bar{s}_j^L c^j_R) \\
Q_9^c &= (\bar{c}_i^L \sigma_{\mu\nu} b^j_R)(\bar{s}_j^L \sigma_{\mu\nu} c^i_R) & Q_{10}^c &= (\bar{c}_i^L \sigma_{\mu\nu} b^i_R)(\bar{s}_j^L \sigma_{\mu\nu} c^j_R)
\end{align*}
\]

\[\mathcal{H}_{\text{eff}} = \frac{4 G_F}{\sqrt{2}} V_{cb} V_{cs}^* \sum_{i=1}^{20} (C_i^c Q_i^c + C_i^{c'} Q_i^{c'})\]

Since \( Q_{1,2} \) appears in the SM, we split up the Wilson coefficients as \( C_i^c = C_i^{\text{SM}} + \Delta C_i \), with \( C_{1,2}^{\text{SM}} \neq 0 \)
Calculating the NP contributions

- We focused on the new contributions to 3 observables

\[ \Delta \Gamma_s, \quad \frac{\tau(B_s)}{\tau(B_d)}, \quad B(B \rightarrow X_s \gamma) \]

- We calculated at leading order in our NP coefficients, but didn’t include any \( \mathcal{O}(\alpha_s) \) corrections to those
$B \rightarrow X_s \gamma$ results
B $\rightarrow X_s \gamma$ results
\[ B \to X_s \gamma \] results

- \( Q_9 \) is leptonic penguin: \((\bar{s}\gamma^\mu P_L b) (\bar{\ell}\gamma_\mu \ell)\)
- \( Q_{7\gamma} \) is photon penguin: \((\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}\)

\[
Q_{1-4}^c \sim \left( \ln \frac{m_c^2}{\mu^2} + \text{const.} + q^2\text{-dependent terms} \right) Q_9 \\
Q_{5,6}^c \sim (q^2\text{-dependent terms}) Q_{7\gamma} \\
Q_{7-10}^c \sim \left( \ln \frac{m_c^2}{\mu^2} + \text{const.} + q^2\text{-dependent terms} \right) Q_{7\gamma}
\]
B → X_sγ results

\[
Q_{1-4}^c \sim (\ln m_c^2/\mu^2 + \text{const.} + q^2\text{-dependent terms})Q_9
\]
\[
Q_{5,6}^c \sim (q^2\text{-dependent terms})Q_{7\gamma}
\]
\[
Q_{7-10}^c \sim (\ln m_c^2/\mu^2 + \text{const.} + q^2\text{-dependent terms})Q_{7\gamma}
\]

We focus for now only on \(C_{1-4}^c\) for two reasons:

- The coefficient \(C_{7\gamma}\) is strongly constrained, even at leading order \(\Delta C_{5-10}\) will be forced to be small
- \(\Delta C_{1-4}\) generate shift in \(C_9\) at leading order, which we want, and (spoilers) small effect on \(C_{7\gamma}\) from RG mixing
$\Delta \Gamma_s$ results

Width difference can be calculated from this diagram
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Width difference can be calculated from this diagram

\[
\Gamma_{12}^{cc} = -G_F^2 (V_{cs}^* V_{cb})^2 m_b^2 M_{Bs} f_{Bs}^2 \frac{\sqrt{1-4z}}{576\pi} \times \\
\left\{ 16(1-z)(4(C_2^c)^2 + (C_4^c)^2) + 8(1-4z) \times (12(C_1^c)^2 + 8C_1^c C_2^c + 2C_3^c C_4^c + 3(C_3^c)^2) \\
- 192z \times (3C_1^c C_3^c + C_1^c C_4^c + C_2^c C_3^c + C_2^c C_4^c) \right\} B \\
+ 2(1+2z) \times [4(C_2^c)^2 - 8C_1^c C_2^c - 12(C_1^c)^2 \\
- 3(C_3^c)^2 - 2C_3^c C_4^c + (C_4^c)^2] \tilde{B}_S' \right\}
\]
$\tau(B_s)/\tau(B_d)$ results

- There are 3 components of the SM calculation of the lifetime

- We use optical theorem to relate these to imaginary parts of loop diagrams
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$\tau(B_s)/\tau(B_d)$ results

- There are 3 components of the SM calculation of the lifetime
  - Free b-quark decay
  - QCD corrections to free b-quark decay
  - Weak annihilation diagrams

- We use optical theorem to relate these to imaginary parts of loop diagrams
\[ \frac{\tau(B_s)}{\tau(B_d)} \text{ results} \]

\[
\left( \frac{\tau_{B_s}}{\tau_{B_d}} \right)_{NP} = G_F^2 |V_{cb} V_{cs}|^2 m_b^2 M_{B_s} f_{B_s}^2 \tau_{B_s} \frac{\sqrt{1-4z}}{144\pi} \times \]

\[
\begin{cases}
(1 - z) \left[ (4(3C_1^c + C_2^c)^2 + (3C_3^c + C_4^c)^2)B_1 \\
+ 6(4C_2^{c,2} + C_4^{c,2})\epsilon_1 \right] \\
- 12z \left[ (3C_1^c + C_2^c)(3C_3^c + C_4^c)B_1 + 6C_2^c C_4^c \epsilon_1 \right] \\
- (1 + 2z) \left[ (4(3C_1^c + C_2^c)^2 + (3C_3^c + C_4^c)^2)B_2 \\
+ 6(4C_2^{c,2} + C_4^{c,2})\epsilon_2 \right]
\end{cases}
\]
Using the results described above, we can see what kind of shifts are allowed at low scales
Low scale Wilson coefficient shifts

Very interesting feature is the non-negligible \( q^2 \) dependence. In other BSM models (e.g. leptoquarks or \( Z' \)), this does not appear. "The NP hypothesis requires a \( q^2 \) independent shift in \( C_9 \)" (1503.06199, Altmannshofer & Straub).
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“The NP hypothesis requires a $q^2$ independent shift in $C_9$” (1503.06199, Altmannshofer & Straub)
Looking at constraints on low scale Wilson coefficients not a particularly realistic scenario

Expect our effective operators to be generated at the weak scale or above by some new physics

Have to include the effect of RG running ...
In order to compute RG effects, need a set of operators closed under RG mixing.

Starting with $Q_{1-4}^c, Q_{7\gamma}, Q_9$ we have to add 4 QCD penguins and chromodipole operator $Q_{8g} \sim (\bar{s}\sigma^{\mu\nu}T^aP_Rb)G^a_{\mu\nu}$.

Get an $11 \times 11$ anomalous dimension matrix – many components already known, but mixing of $Q_{3,4}^c$ into $Q_9$ and $Q_{7\gamma}$ are new.
Operator Mixing

- In order to compute RG effects, need a set of operators closed under RG mixing.
- Starting with $Q_{c1}^2 - 4$, $Q_7^\gamma$, and $Q_9^\gamma$, we have to add 4 QCD penguins and chromodipole operator $Q_{8g} \sim (s\sigma^{\mu\nu}T^aPR^b)G_a^{\mu\nu}$.
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$$Q_{8g} \sim (\bar{s}\sigma^{\mu\nu}T^aP_Rb)G_{\mu\nu}^a$$

Get an $11 \times 11$ anomalous dimension matrix – many components already known, but mixing of $Q_{3,4}^c$ into $Q_9$ and $Q_{7\gamma}$ are new.
Operator Mixing – new results

- Mixing into $Q_9$ can be read off from logarithmic terms in our result for $B \rightarrow X_s \gamma$ results
- Mixing into $Q_7 \gamma$ arises at two loops
Wilson Coefficients RG Running

\[
\begin{pmatrix}
\Delta C_1(\mu) \\
\Delta C_2(\mu) \\
\Delta C_3(\mu) \\
\Delta C_4(\mu) \\
\Delta C_7(\mu) \\
\Delta C_9(\mu)
\end{pmatrix} =
\begin{pmatrix}
1.12 & -0.27 & 0 & 0 \\
-0.27 & 1.12 & 0 & 0 \\
0 & 0 & 0.92 & 0 \\
0 & 0 & 0.33 & 1.91 \\
0.02 & -0.19 & -0.01 & -0.13 \\
8.48 & 1.96 & -4.24 & -1.91
\end{pmatrix}
\begin{pmatrix}
\Delta C_1(\mu_0) \\
\Delta C_2(\mu_0) \\
\Delta C_3(\mu_0) \\
\Delta C_4(\mu_0)
\end{pmatrix}
\]
High scale NP

- With the RG running calculated, we can see how much the Wilson coefficients would need to shift at the weak scale to explain the $P'_5$ anomaly.
- This is a more realistic scenario, as some high scale NP would alter the Wilson coefficients at that high scale.
NP in $C_1^c, C_2^c$
NP in $C_1^c$, $C_2^c$
NP in $C_1^c, C_2^c$
NP in $C_1^c, C_3^c$
NP in $C_1^c, C_4^c$
NP in $C^c_2$, $C^c_3$
NP in $C_2^c, C_4^c$
NP in $C_3^c$, $C_4^c$
Future Prospects

- How can we tell if this is the right approach, and distinguish between NP in the different Wilson coefficients?
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- $\Delta \Gamma_s$ error dominated by theory – use QCD sum rules / pray to the lattice gods
- Lifetime ratio – error quite small, depends on how future experimental averages evolve
- Also issue of scheme dependence of charm mass – effect on our leading order calculation quite strong
Our model only involves NP in the quark sector $\Rightarrow$ other lepton-flavour violating anomalies should revert to SM with more data

Should $(P'_5/R_K/R_D)$ stay or should $(P'_5/R_K/R_D)$ go . . .
Work in progress

- Work so far covers just 4 possible operators
- Give the most “obvious” solutions ...
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- We looked only at real shifts in the Wilson coefficients
- Had we chosen imaginary shifts, the constraints from $\Delta \Gamma$ get worse, while those from semi-leptonic asymmetry get a lot stronger
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- Give the most “obvious” solutions . . .
- We looked only at real shifts in the Wilson coefficients
- Had we chosen imaginary shifts, the constraints from $\Delta \Gamma$ get worse, while those from semi-leptonic asymmetry get a lot stronger
- Could also look at shifts in more than 2 Wilson coefficients simultaneously, and/or NP Wilson coefficients as arbitrary complex numbers
Summary

- Tried to explain the $P'_5$ anomaly in a model independent way
- Renormalisation group running effects are very important – rather than a shift $\Delta C_1 \sim -0.5$ at the B meson scale, only a shift of $\Delta C_1 \sim -0.1$ at the weak scale
- As such small shifts can fit the anomaly, improved bounds are needed if the anomaly persists and we want to distinguish different scenarios
Backup
Definition of $P'_5$

$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

$$\frac{1}{\Gamma} \frac{d^3(\Gamma + \Gamma)}{d \cos \theta_\ell d \cos \theta_K d \phi} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$
Definition of $\Delta \Gamma$, $a_{sl}$

$$
\Delta \Gamma = -2|\Gamma_{12}| \cos \left( \arg \left( \frac{\Gamma_{12}}{M_{12}} \right) \right)
$$

$$
a_{sl} = \left| \frac{\Gamma_{12}}{M_{12}} \right| \sin \left( \arg \left( \frac{\Gamma_{12}}{M_{12}} \right) \right)
$$