Charming new physics in b(eautiful) processes?

(based on 1701.09183)

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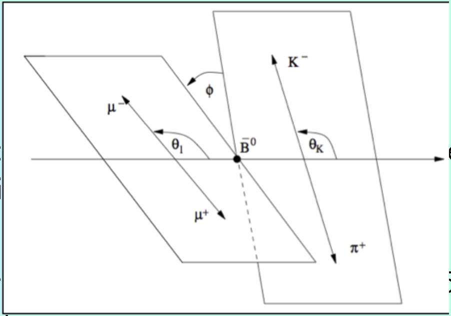
Background

- 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 ...

$\mathrm{B} \to \mathrm{K}^*\mu\mu$

- 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

B → $K^*\mu\mu$



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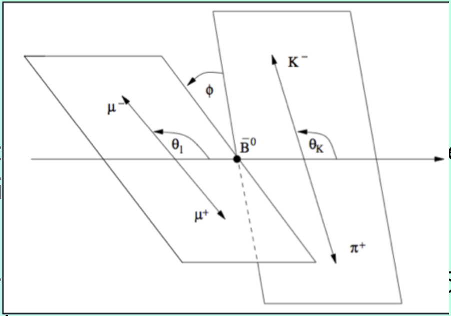
$B \to K^* \mu\mu$



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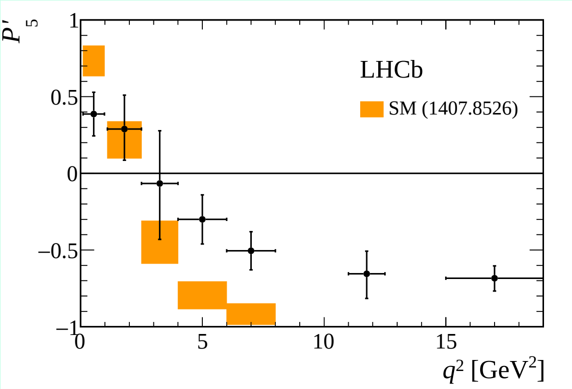
$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

P_5'

P_5' – combination of angular observables in $B \to K^*\mu\mu$ that is theoretically clean



$\sim 3\sigma$ deviations

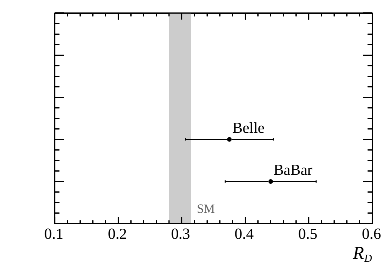
R_K

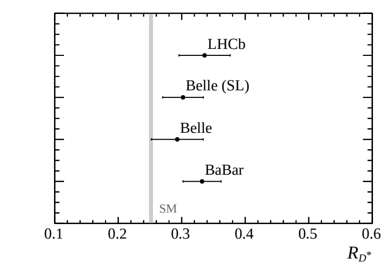
- Compare branching ratio of $B \to K^*\mu\mu$ to $B \to K^*ee$
- SM: $R_K(1 < q^2 < 6\,\text{GeV}^2) = 1.0003 \pm 0.0001$ [1]
- LHCb Run 1:
  $R_K(1 < q^2 < 6\,\text{GeV}^2) = 0.745^{+0.09}_{-0.074} \pm 0.036$ [2]

[1] arXiv:0709.4174
[2] arXiv:1406.6482

R_D

- Compare branching ratio of $B \to D\tau\nu$ to $B \to D\mu\nu$
- Interesting as this is a tree level decay





Good / Boring Flavour Measurements

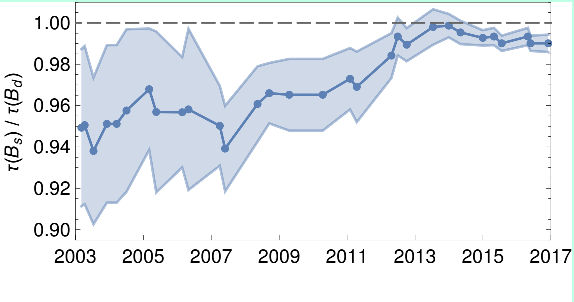
$$\Delta\Gamma_s : \frac{\text{Experiment}}{\text{SM}} = \frac{(0.086 \pm 0.006)\,\text{ps}^{-1}}{(0.088 \pm 0.020)\,\text{ps}^{-1}} = 0.98 \pm 0.23$$

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

$$\frac{\tau(B_s)}{\tau(B_d)} : \frac{\text{Experiment}}{\text{SM}} = \frac{0.990 \pm 0.004}{1.0005 \pm 0.0011} = 0.990 \pm 0.004$$

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 ...



Charming New Physics

- 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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- 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] arXiv:1310.2478, 1411.3161, 1510.04239, 1603.00865

Charming New Physics

- In the SM, around half of the contribution to b $\rightarrow$ 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.[1] – 10% effects still allowed)

[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

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

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

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

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

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

Basis of Operators

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\end{aligned}
$$

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

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 $C_{1,2}^{\text{SM}} \neq 0$

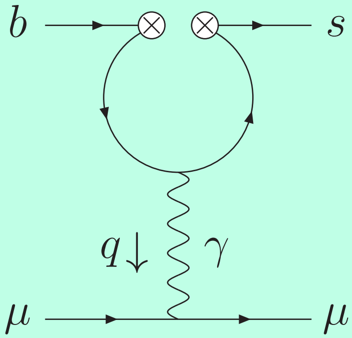
Calculating the NP contributions

- We focused on the new contributions to 3 observables

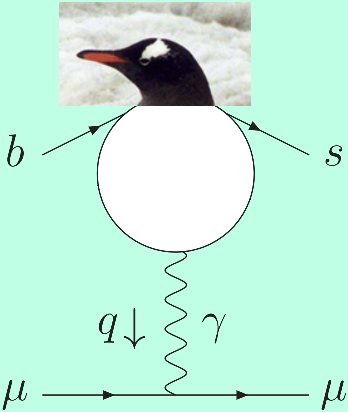
$$\Delta\Gamma_s \qquad \frac{\tau(B_s)}{\tau(B_d)} \qquad \mathcal{B}(B \to X_s\gamma)$$

- We calculated at leading order in our NP coefficients, but didn't include any $\mathcal{O}(\alpha_s)$ corrections to those

B $\to X_s\gamma$ results



$B \to X_s\gamma$ 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: $(\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}$

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

$\mathrm{B} \to X_s\gamma$ results

$$Q^c_{1-4} \sim (\ln m_c^2/\mu^2 + \text{const.} + q^2\text{-dependent terms})Q_9$$
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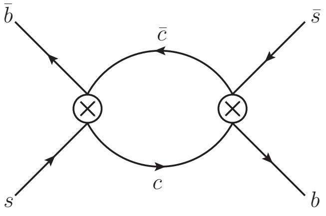
$$Q^c_{7-10} \sim (\ln m_c^2/\mu^2 + \text{const.} + q^2\text{-dependent terms})Q_{7\gamma}$$

- We focus for now only on C^c_{1-4} for two reasons:
  - The coefficient $C_{7\gamma}$ is strongly constrained, even at leading order ΔC_{5-10} will be forced to be small
  - ΔC_{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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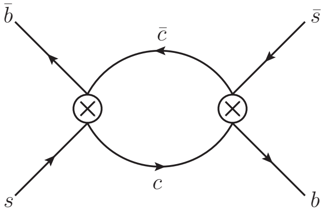

$$\Gamma_{12}^{cc} = -G_F^2 (V_{\rm cs}^* V_{\rm cb})^2 m_b^2 M_{B_s} f_{B_s}^2 \frac{\sqrt{1-4z}}{576\pi} \times$$

$$\Big\{ \Big[16(1-z)(4(C_2^c)^2 + (C_4^c)^2)$$

$$+ 8(1-4z) \times (12(C_1^c)^2 + 8C_1^c C_2^c + 2C_3^c C_4^c + 3(C_3^c)^2)$$

$$- 192z \times (3C_1^c C_3^c + C_1^c C_4^c + C_2^c C_3^c + C_2^c C_4^c) \Big] B$$

$$+ 2(1+2z) \times [4(C_2^c)^2 - 8C_1^c C_2^c - 12(C_1^c)^2$$

$$- 3(C_3^c)^2 - 2C_3^c C_4^c + (C_4^c)^2] \tilde{B}_S' \Big\}$$

$\tau(B_s)/\tau(B_d)$ 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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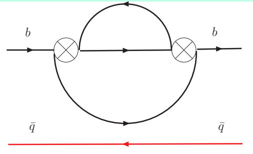

$\tau(B_s)/\tau(B_d)$ results

- There are 3 components of the SM calculation of the lifetime
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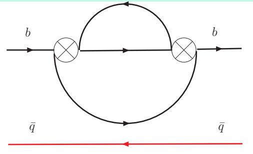
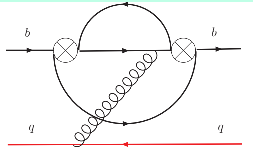
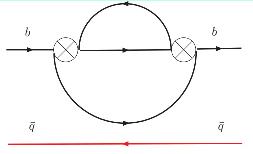
  - QCD corrections to free b-quark decay
- We use optical theorem to relate these to imaginary parts of loop diagrams

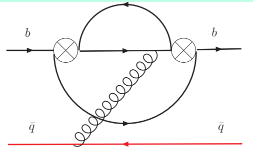


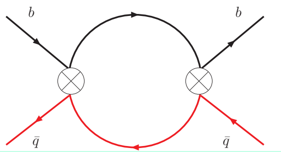


$\tau(B_s)/\tau(B_d)$ results

- 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







$\tau(\mathrm{B_s})/\tau(\mathrm{B_d})$ results

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

$$\Big\{ (1-z)\Big[(4(3C_1^c + C_2^c)^2 + (3C_3^c + C_4^c)^2) B_1$$

$$+ 6(4C_2^{c,2} + C_4^{c,2})\epsilon_1 \Big]$$

$$- 12z\Big[(3C_1^c + C_2^c)(3C_3^c + C_4^c) B_1 + 6C_2^c C_4^c \epsilon_1 \Big]$$

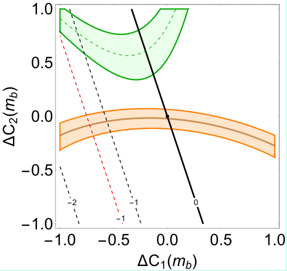
$$- (1+2z)\Big[(4(3C_1^c + C_2^c)^2 + (3C_3^c + C_4^c)^2) B_2$$

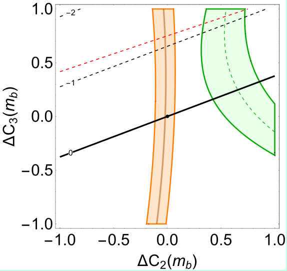
$$+ 6(4C_2^{c,2} + C_4^{c,2})\epsilon_2 \Big] \Big\}$$

Low scale Wilson coefficient shifts

- Using the results described above, we can see what kind of shifts are allowed at low scales

Low scale Wilson coefficient shifts





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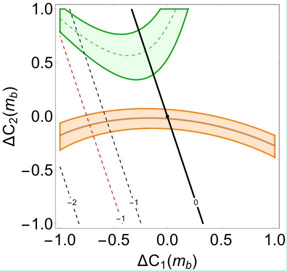
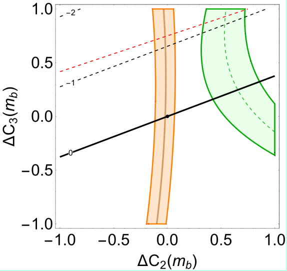
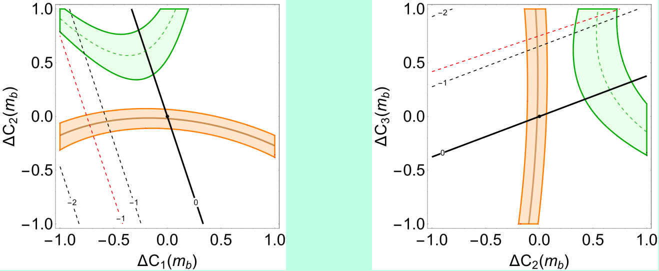




- Very interesting feature is the non-negligible q^2 dependence
- In other BSM models (e.g. leptoquarks or Z'), this does not appear

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)

Renormalisation Group Running

- 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 . . .

Operator Mixing

- In order to compute RG effects, need a set of operators closed under RG mixing
- Starting with $Q^c_{1-4}, Q_{7\gamma}, Q_9$ we have to add 4 QCD penguins and chromodipole operator $Q_{8\text{g}} \sim (\bar{\text{s}}\sigma^{\mu\nu} T^a P_R \text{b}) G^a_{\mu\nu}$
- Get an 11×11 anomalous dimension matrix – many components already known, but mixing of $Q^c_{3,4}$ into Q_9 and $Q_{7\gamma}$ are new

Operator Mixing

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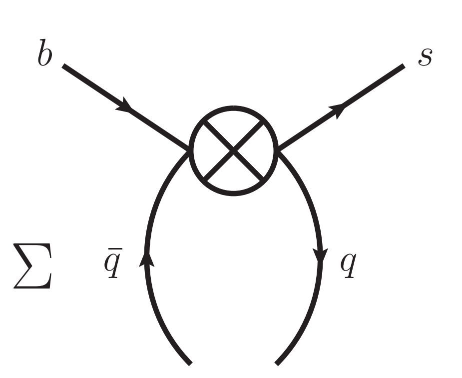
- Startin d 4 QCD pengui $Q_{8g} \sim$
- Get an rix – many compo $Q^c_{3,4}$ into Q_9 and Q_7



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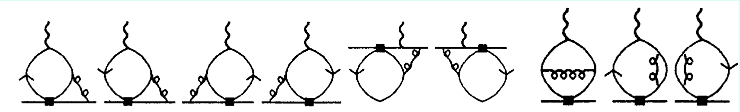
Operator Mixing – new results

- Mixing into Q_9 can be read off from logarithmic terms in our result for $\mathrm{B} \to X_s\gamma$ results
- Mixing into $Q_{7\gamma}$ arises at two loops



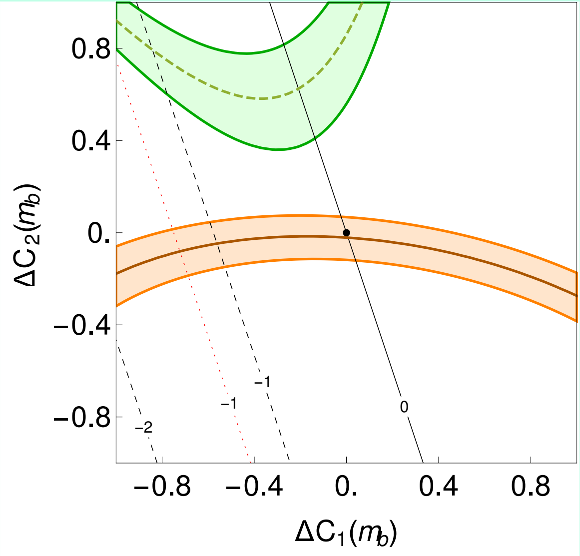
Wilson Coefficients RG Running

$$\begin{pmatrix} \Delta C_1(\mu) \\ \Delta C_2(\mu) \\ \Delta C_3(\mu) \\ \Delta C_4(\mu) \\ \Delta C_{7\gamma}(\mu) \\ \Delta C_9(\mu) \end{pmatrix} = \begin{pmatrix} 1.12 & -0.27 & 0 & 0 \\ -0.27 & 1.12 & 0 & 0 \\ 0 & 0 & 0.92 & 0 \\ 0 & 0 & 0.33 & 1.91 \\ 0.02 & -0.19 & -0.01 & -0.13 \\ 8.48 & 1.96 & -4.24 & -1.91 \end{pmatrix} \begin{pmatrix} \Delta C_1(\mu_0) \\ \Delta C_2(\mu_0) \\ \Delta C_3(\mu_0) \\ \Delta C_4(\mu_0) \end{pmatrix}$$

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



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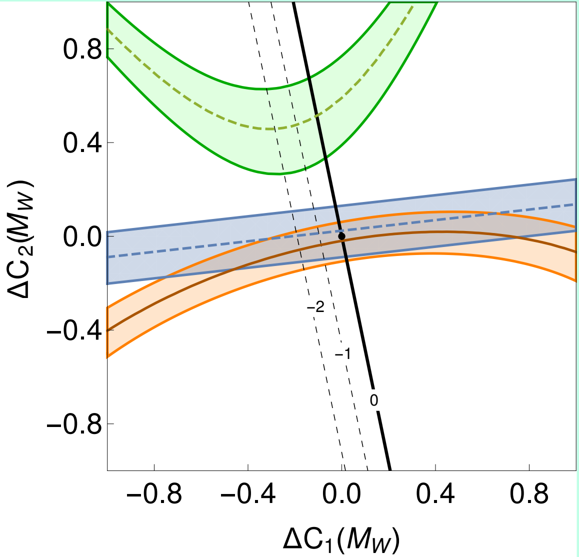

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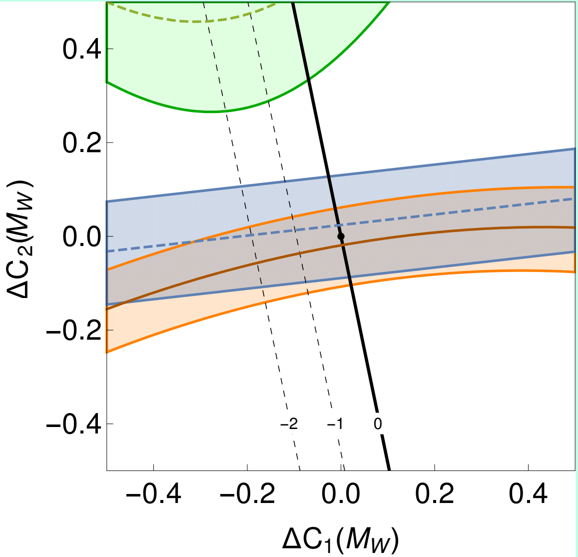
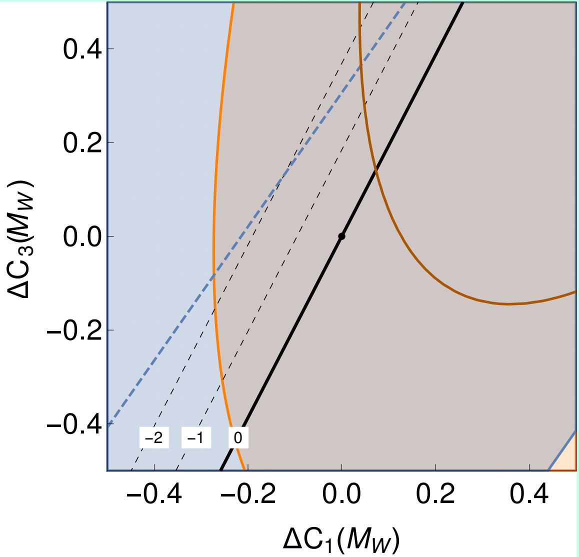
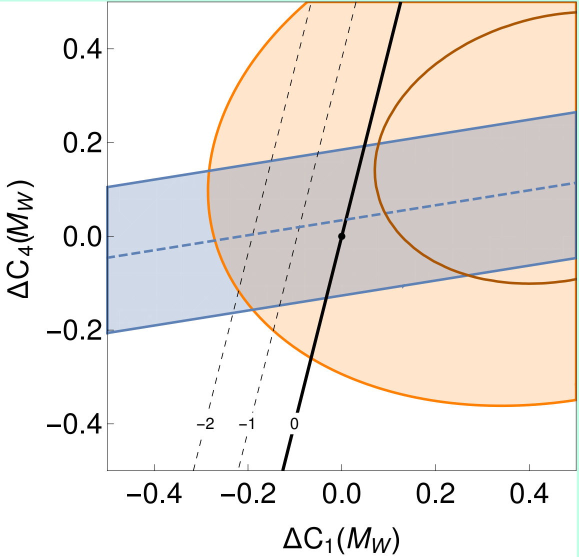


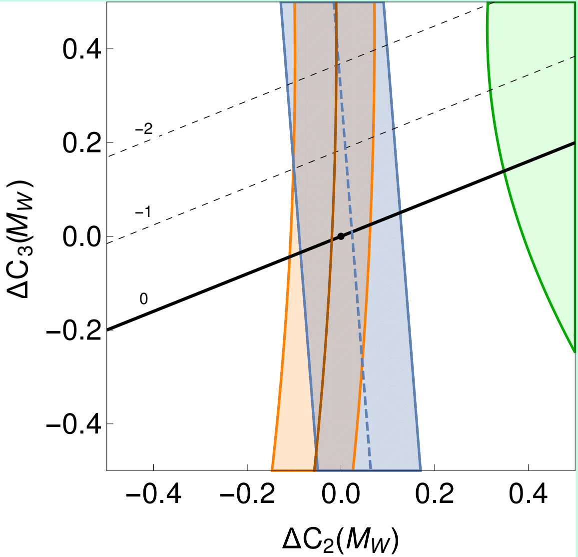
NP in C_1^c, C_3^c



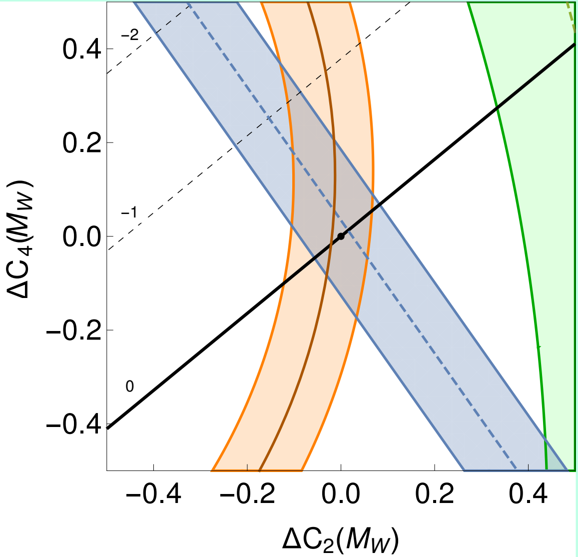
NP in C_1^c, C_4^c



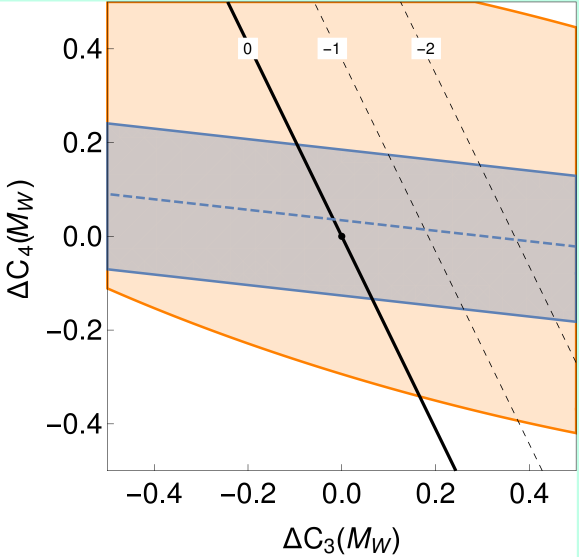
NP in C_2^c, C_3^c



NP in C_2^c, C_4^c



NP in C_3^c, C_4^c



Future Prospects

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- Also issue of scheme dependence of charm mass – effect on our leading order calculation quite strong

Future Prospects

- Our model only involves NP in the quark sector $\implies$ 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 ...

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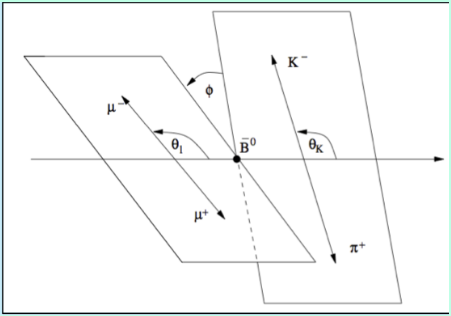
- We looked only at real shifts in the Wilson coefficients
- Had we chosen imaginary shifts, the constraints from $\Delta\Gamma$ get worse, while those from semi-leptonic asymmetry get a lot stronger
- Could also look at shifts in more than 2 Wilson coefficients simultaneously, and/or NP Wilson coefficients 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'



$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

$$\begin{aligned}\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\ &- F_L\cos^2\theta_K\cos 2\theta_\ell + \\ &S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \\ &S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell + \\ &S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + \\ &S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\ \Big]\end{aligned}$$

Definition of $\Delta\Gamma$, a_{sl}

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

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