BSM in Charming operators?

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(based on 1701.09183, 1910.12924 with S. Jäger, A. Lenz, K. Leslie)

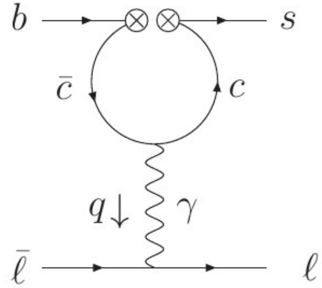
Motivation

- SM has two $(\bar{s}b)(\bar{c}c)$ operators
  - Turn up in lots of places
    - $\Delta\Gamma_s$
    - $\tau(B_s)/\tau(B_d)$
    - $B \to X_s\gamma$
    - ...

Motivation

- If you're into anomalies…
- Half of the C_9 coefficient in the SM comes from the SM $(\bar{s}b)(\bar{c}c)$ operator
  - Close charm loop, emit photon
  - Strong RG effect enhances the effect

$$Q_9 = (\bar{s}P_L b)(\bar{\ell}\gamma^\mu \ell)$$



New physics?

- Beyond the SM, what other operators can appear?
- And what effect could they have? / How much can we constrain their Wilson coefficients?

Complete basis set

- First task: enumerate the basis
- 20 operators (2 SM, 18 BSM)
  - Dirac structures: 1 SM, 4 BSM
  - x 2 for colour
  - x 2 for chirality

Complete basis set

$$\mathcal{H}_{\rm eff}^{cc} = \frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \sum_i C_i^c Q_i^c + C_i'^c Q_i'^c$$

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

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

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

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

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

- Plus primed operators with L ↔ R

Complete RG evolution

- RG evolution
- Necessary as we assume NP arises at weak scale or above
- But observables are calculated at b scale

Complete RG evolution

$$\begin{pmatrix} C_1^c(\mu_b) \\ C_2^c(\mu_b) \\ C_3^c(\mu_b) \\ C_4^c(\mu_b) \\ C_5^c(\mu_b) \\ C_6^c(\mu_b) \\ C_7^c(\mu_b) \\ C_8^c(\mu_b) \\ C_9^c(\mu_b) \\ C_{10}^c(\mu_b) \\ C_{7\gamma}^{\rm eff}(\mu_b) \\ C_{9V}(\mu_b) \end{pmatrix} = \begin{pmatrix} 1.1 & -0.27 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.27 & 1.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.92 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.33 & 1.9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.9 & 0.33 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.92 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.0 & 0.05 & 2.70 & 1.70 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.37 & 2.0 & 2.30 & -0.55 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.07 & 0.07 & 1.80 & 0.04 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.01 & -0.02 & -0.29 & 0.82 \\ 0.02 & -0.19 & -0.015 & -0.13 & 0.56 & 0.17 & -1.0 & -0.47 & 4.00 & 0.70 \\ 8.50 & 2.10 & -4.30 & -2.00 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} C_1^c(M_W) \\ C_2^c(M_W) \\ C_3^c(M_W) \\ C_4^c(M_W) \\ C_5^c(M_W) \\ C_6^c(M_W) \\ C_7^c(M_W) \\ C_8^c(M_W) \\ C_9^c(M_W) \\ C_{10}^c(M_W) \end{pmatrix}$$

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

Complete RG evolution

- What is new?
  - $Q_{3,4}^{c} \to Q_{7\gamma}, Q_{9V}$
    - Mixing into photon penguin arises at 2 loops
  - Done for our first paper in 2017

Complete RG evolution

$$
\begin{pmatrix} C_1^c(\mu_b) \\ C_2^c(\mu_b) \\ C_3^c(\mu_b) \\ C_4^c(\mu_b) \\ C_5^c(\mu_b) \\ C_6^c(\mu_b) \\ C_7^c(\mu_b) \\ C_8^c(\mu_b) \\ C_9^c(\mu_b) \\ C_{10}^c(\mu_b) \\ C_{7\gamma}^{\text{eff}}(\mu_b) \\ C_{9V}(\mu_b) \end{pmatrix}
=
\begin{pmatrix}
1.1 & -0.27 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-0.27 & 1.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.92 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.33 & 1.9 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1.9 & 0.33 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.92 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1.0 & 0.05 & 2.70 & 1.70 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.37 & 2.0 & 2.30 & -0.55 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.07 & 0.07 & 1.80 & 0.04 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.01 & -0.02 & -0.29 & 0.82 \\
0.02 & -0.19 & -0.015 & -0.13 & 0.56 & 0.17 & -1.0 & -0.47 & 4.00 & 0.70 \\
8.50 & 2.10 & -4.30 & -2.00 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix} C_1^c(M_W) \\ C_2^c(M_W) \\ C_3^c(M_W) \\ C_4^c(M_W) \\ C_5^c(M_W) \\ C_6^c(M_W) \\ C_7^c(M_W) \\ C_8^c(M_W) \\ C_9^c(M_W) \\ C_{10}^c(M_W) \end{pmatrix}
$$

Complete RG evolution

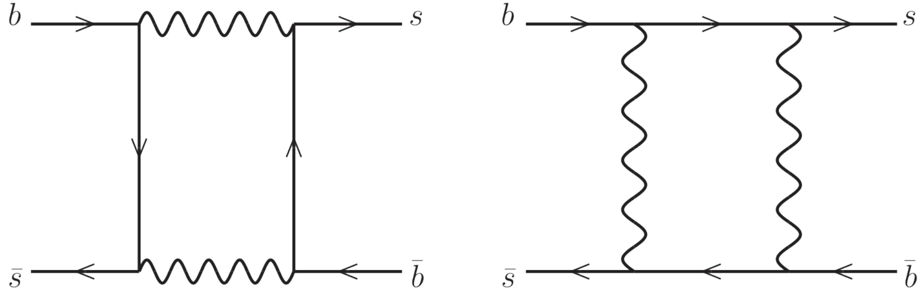
- What is new?
  - $Q^c_{3,4} \to Q_{7\gamma}, Q_{9V}$ – arise at 2 loops
  - Done for our first paper in 2017
- Everything else already known somewhere

Observables

- $\tau(B_s)/\tau(B_d)$
- $\Delta\Gamma_s$
- $B \to X_s\gamma$
- $B \to J/\psi K$

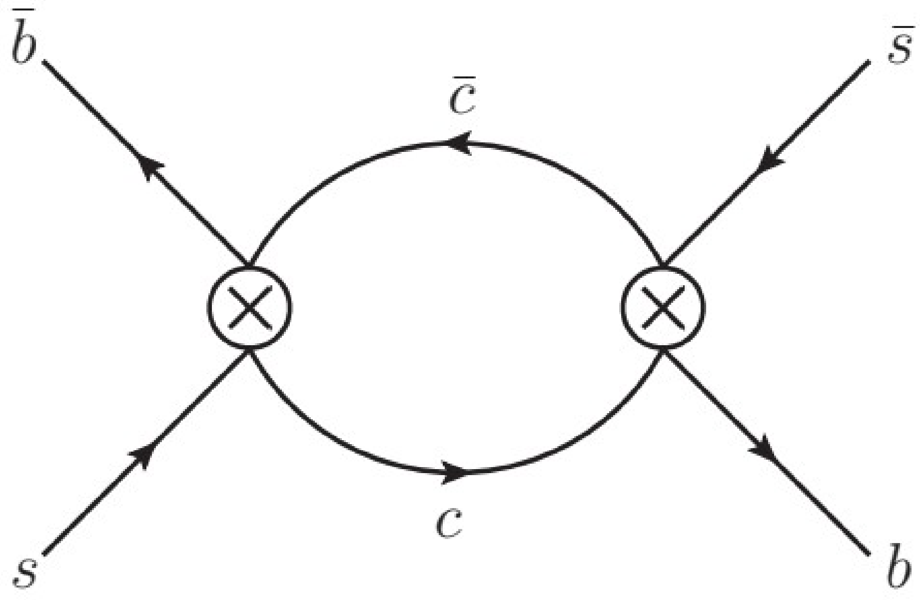
$\Delta\Gamma_s$

- B_s and $\bar{B}_s$ can mix
- New mass eigenstates
- Different masses and widths
- $\Delta\Gamma_s$ is width difference



$\Delta\Gamma_s$

- HQE expands the non-local loop in local operators



$\Delta\Gamma_s$

- Calculated within HQE
- $\Gamma_{12} = \frac{\Lambda^3}{m_b^3}\Gamma_3 + \frac{\Lambda^4}{m_b^4}\Gamma_4 + \ldots$
- $\Gamma_i = \left[\Gamma_i^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_i^{(1)} + \frac{\alpha_s^2}{(4\pi)^2}\Gamma_i^{(2)} + \ldots\right]\langle O^{d=i+3}\rangle$
- For summary of what's known, see talk by Lenz (1809.09452)

$\Delta\Gamma_s$

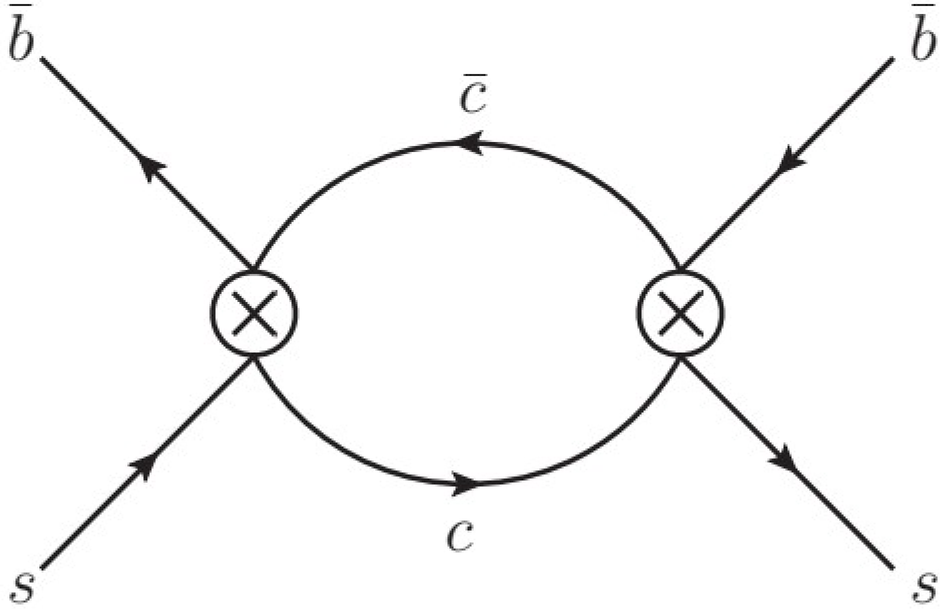
- Calculated within HQE
- SM: $\Delta\Gamma_s = (0.088 \pm 0.020)\,\mathrm{ps}^{-1}$
- Exp: $\Delta\Gamma_s = (0.088 \pm 0.006)\,\mathrm{ps}^{-1}$

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

- Theory prediction: 1 + $SU(3)_F$ breaking corrections
- Expected to be $\mathcal{O}(m_d/m_s) \approx 1\%$

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

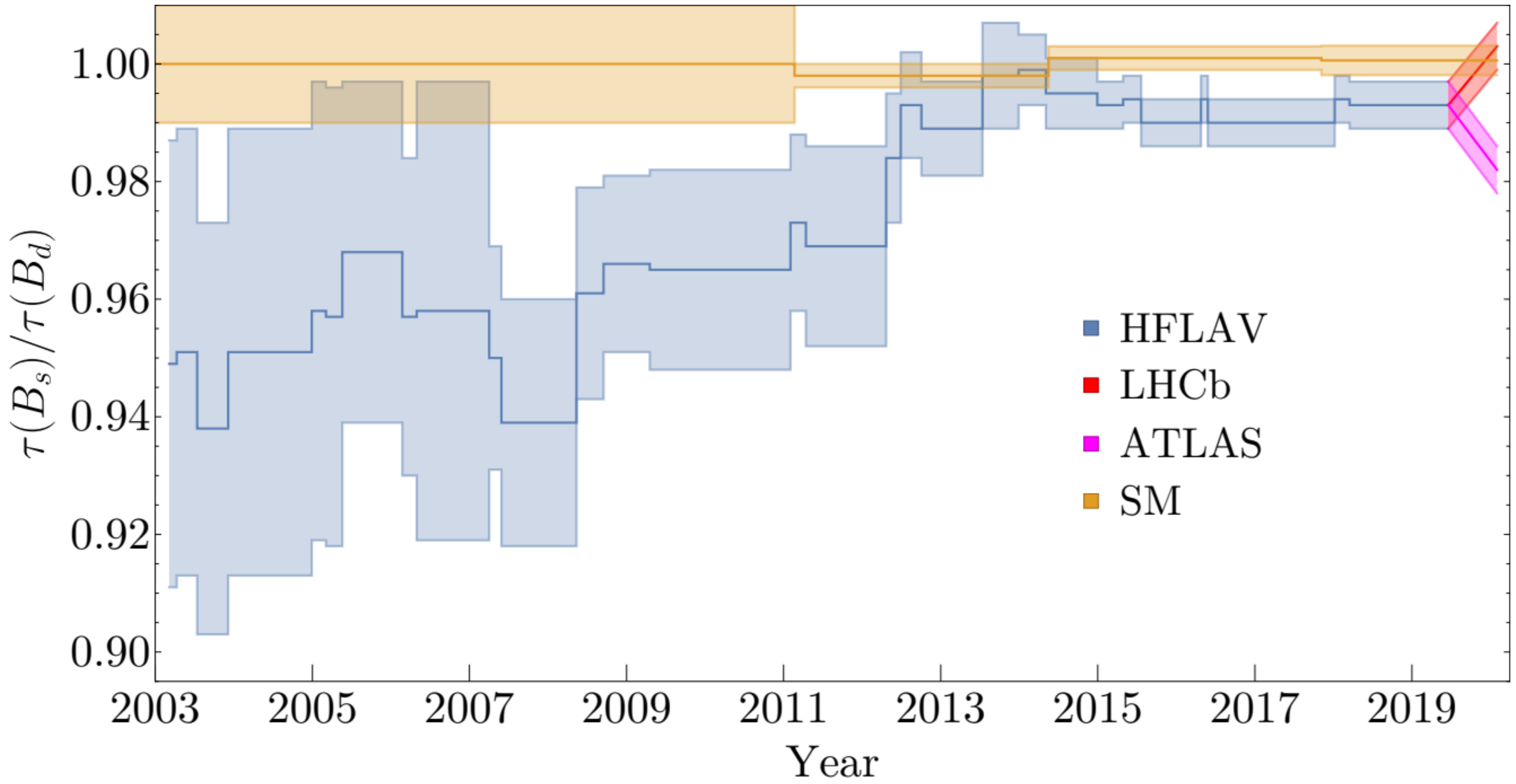
- Most recent prediction:
  - SM: 1.0006 ± 0.0025
    - (MK, Lenz, Rauh 1711.02100)
  - Exp: 0.993 ± 0.004
    - (HFLAV for PDG 2018)
- (Side note: new ATLAS result for $\tau(B_s)$ (2001.07115) is $\sim 2.5\,\sigma$ below HFLAV => ratio = 0.982!)



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

- Tremendous improvement from experiment over time

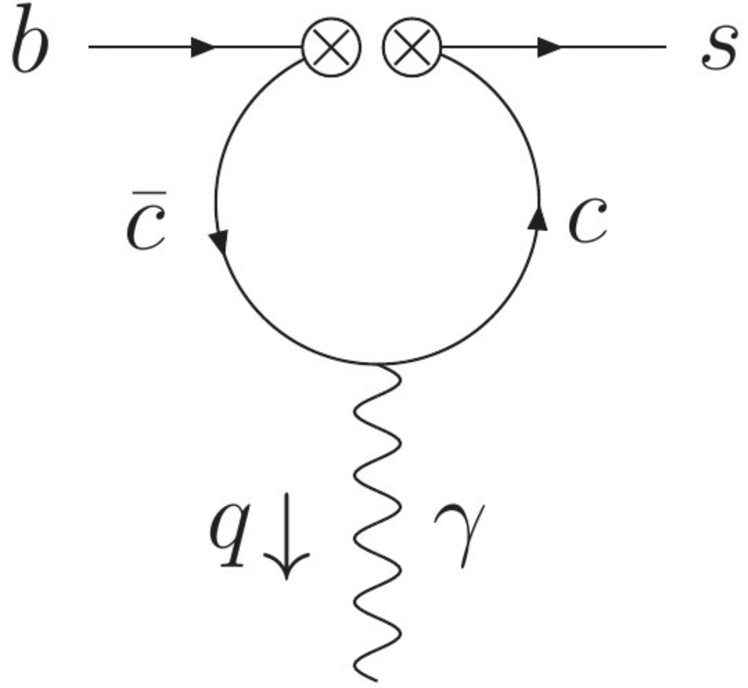
$\tau(B_s)/\tau(B_d)$



1.00
0.98
0.96
0.94
0.92
0.90
$\tau(B_s)/\tau(B_d)$
2003
2005
2007
2009
2011
2013
2015
2017
2019
Year
HFLAV
LHCb
ATLAS
SM

$B \to X_s\gamma$

- Radiative decay, quark level is $b \to s\gamma$
- SM known at NNLO in QCD
- In SM, $(\bar{s}b)(\bar{c}c)$ contributes at 2-loop
  - Attach gluon to charm loop to get chirality flip

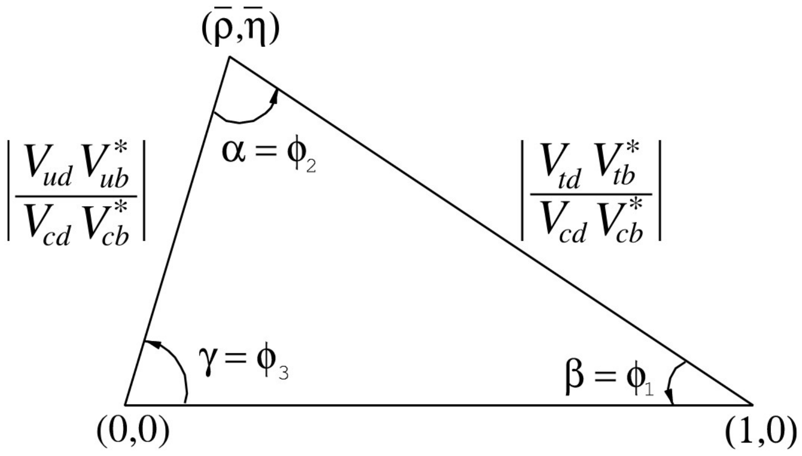


$B \to X_s \gamma$

- SM known at NNLO in QCD
- SM: $\mathcal{B}(B \to X_s \gamma) = (3.36 \pm 0.23) \times 10^{-4}$
- Exp: $\mathcal{B}(B \to X_s \gamma) = (3.32 \pm 0.15) \times 10^{-4}$

$$B \to J/\psi K$$

- So-called golden mode
  - Amplitude contains only a single CKM structure
  - Taking ratio of CP conjugate modes cancels out strong phase, allowing us direct access to CKM factor
- Determination of β – CKM triange angle



$B \to J/\psi K$

- $$A_{CP}(t) = \frac{\Gamma\left[\bar{B}_d(t) \to J/\psi K_S\right] - \Gamma\left[B_d(t) \to J/\psi K_S\right]}{\Gamma\left[\bar{B}_d(t) \to J/\psi K_S\right] + \Gamma\left[B_d(t) \to J/\psi K_S\right]}$$
  $$= S_{J/\psi K_S} \sin(\Delta M_d t) - C_{J/\psi K_S} \cos(\Delta M_d t)$$
- S is mixing induced, C is direct CP asymmetry
- In SM, $S \sim \sin 2\beta$
- Also $\mathcal{B}(B \to J/\psi K)$
- More later…

Expressions for BSM contributions

- For those interested in using our results
  - E.g. if your favourite NP model generates $(\bar{s}b)(\bar{c}c)$

Expressions for BSM contributions

$$\frac{\tau(B_s)^{\rm BSM}}{\tau(B_d)^{\rm BSM}} = \frac{G_F^2 m_b^2 M_{B_s} f_{B_s}^2 \tau(B_s)^{\rm exp}}{4\pi} N_c \sqrt{1-z}\, |\lambda_c|^2$$

$$\times \left[\sum_{i=1}^{20} \sum_{j=1}^{20} C_i^c (C_j^c)^* \Gamma(i,j) - \sum_{i=1}^{2} \sum_{j=1}^{2} C_i^{c,\rm SM} (C_j^{c,\rm SM})^* \Gamma(i,j) \right]$$

$$\begin{aligned}
&\Gamma(1,1) = \frac{1}{12}\left[2(z+2)B_2' + (z-4)B_1\right], \quad && \Gamma(1,3) = \frac{1}{8} z B_1, \quad && \Gamma(1,5) = -\frac{1}{2}\sqrt{z} B_2', \\
&\Gamma(1,9) = \frac{1}{2}\sqrt{z}(4B_2' - B_1), && \Gamma(1,11) = -\frac{1}{4} z B_3, && \Gamma(1,7) = \frac{1}{8}\sqrt{z} B_1, \\
&\Gamma(1,13) = -\frac{1}{24}\left[2(z+2)B_4' + (z-4)B_3\right], && \Gamma(1,15) = \frac{1}{2}\sqrt{z} B_4', && \\
&\Gamma(1,17) = \frac{1}{8}\sqrt{z}\left[B_3 - 2B_4'\right], && \Gamma(1,19) = -\frac{1}{2}\sqrt{z}\left[2B_4' + B_3\right]. &&
\end{aligned} \tag{3.9}$$

$$\Gamma(3,3) = \frac{1}{4}\Gamma(1,1), \quad \Gamma(3,7) = \frac{1}{16}\sqrt{z}\left(2B_2' - B_1\right), \quad \Gamma(3,5) = \frac{1}{2}\Gamma(1,5),$$

Expressions for BSM contributions

$$\Gamma_{12}^{c\bar{c}} = \frac{G_F^2 \lambda_c^2 m_b^2 M_{B_s} f_{B_s}^2}{12\pi} \sqrt{1-z} \left[8G(z)B + F(z)\tilde{B}'_S \right]$$

$$\begin{aligned}
F(z) = & \left(1+\frac{z}{2}\right)\left[\frac{C_1^{c,2} - (C_1^{c,\mathrm{SM}})^2}{2} + \frac{C_1^c C_2^c - C_1^{c,\mathrm{SM}} C_2^{c,\mathrm{SM}}}{3} - \frac{C_2^{c,2} - (C_2^{c,\mathrm{SM}})^2}{6} + \frac{C_3^{c,2}}{8} + \frac{C_3^c C_4^c}{12} - \frac{C_4^{c,2}}{24}\right] \\
& - \left(1-\frac{z}{2}\right)\left[18\, C_5^c C_9^c + 6(C_5^c C_{10}^c + C_6^c C_9^c - C_6^c C_{10}^c) + \frac{3}{2} C_5^c C_7^c + \frac{C_5^c C_8^c + C_6^c C_7^c - C_6^c C_8^c}{2}\right] \\
& + \sqrt{z}\left[6 C_1^c C_9^c + 2 C_1^c C_{10}^c + 2 C_2^c C_9^c - 2 C_2^c C_{10}^c - \frac{3}{2}(C_1^c C_5^c - C_3^c C_9^c) - \frac{3}{4} C_3^c C_5^c + \frac{3}{8} C_3^c C_7^c \right. \\
& \quad - \frac{C_1^c C_6^c + C_2^c C_5^c - C_2^c C_6^c - C_3^c C_{10}^c - C_4^c C_9^c + C_4^c C_{10}^c}{2} - \frac{C_3^c C_6^c + C_4^c C_5^c - C_4^c C_6^c}{4} \\
& \quad \left. + \frac{C_3^c C_8^c + C_4^c C_7^c - C_4^c C_8^c}{8}\right] + z\left[15 C_9^{c,2} + 10 C_9^c C_{10}^c - 5 C_{10}^{c,2} + \frac{3}{2} C_7^c C_9^c + \frac{3}{2} C_5^{c,2} + C_5^c C_6^c \right. \\
& \quad C_7^c C_{10}^c + C_8^c C_9^c - C_8^c C_{10}^c \quad C_6^{c,2} \quad C_7^c C_8^c \quad 3C_7^{c,2} - C_8^{c,2} \Big]
\end{aligned}$$

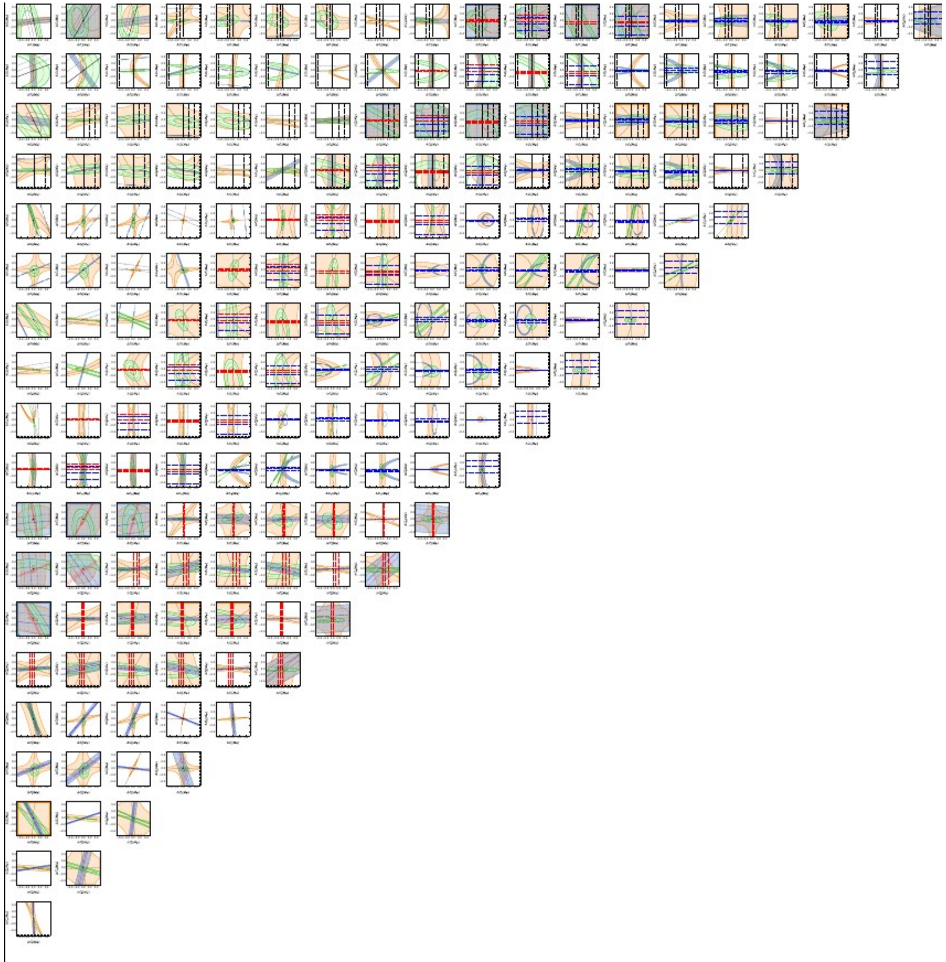
Expressions for BSM contributions

- Full algebra given in our paper
- Also Mathematica notebook on the arXiv for easy evaluation

Constraints on Wilson coefficients

- Many possible combinations
- ~200

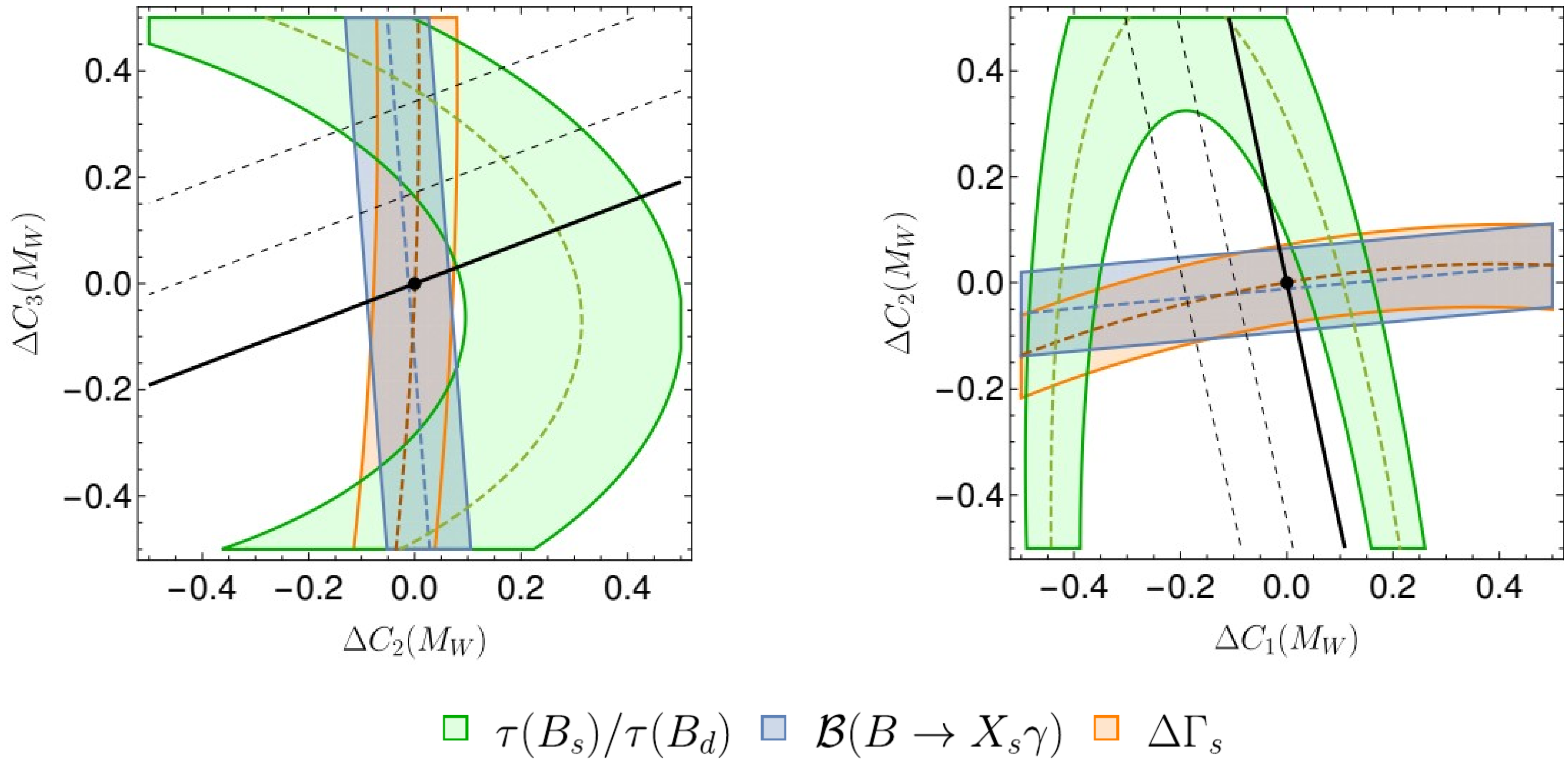
Constraints on Wilson coefficients



Constraints on Wilson coefficients

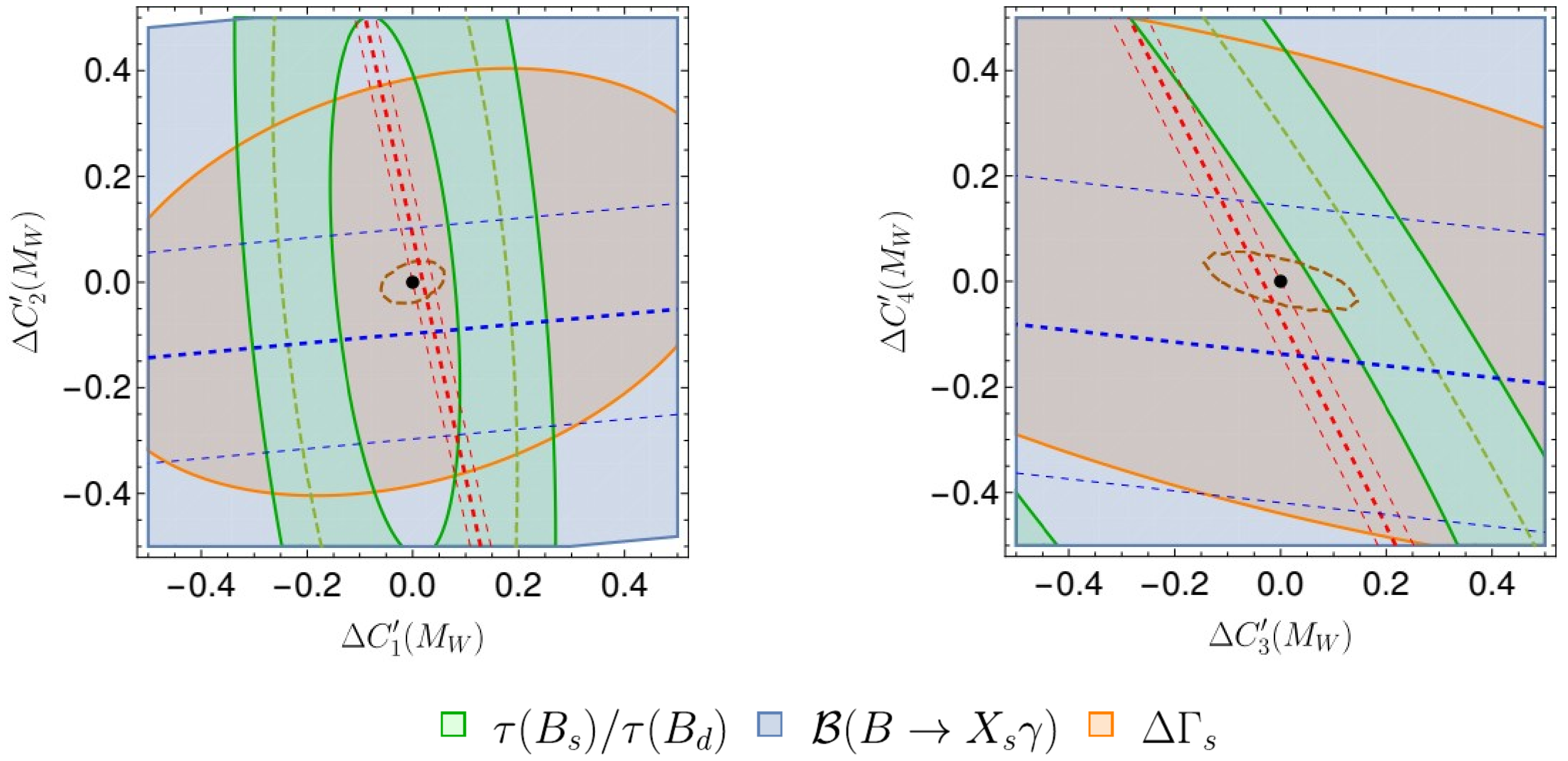
- Many possible combinations
- ~200
- I will pick out a few to try and show some interesting features
- For comparison: $C_1^{\mathrm{SM}} = -0.19\,,\ C_2^{\mathrm{SM}} = 1.1$

$C_1^c - C_4^c$



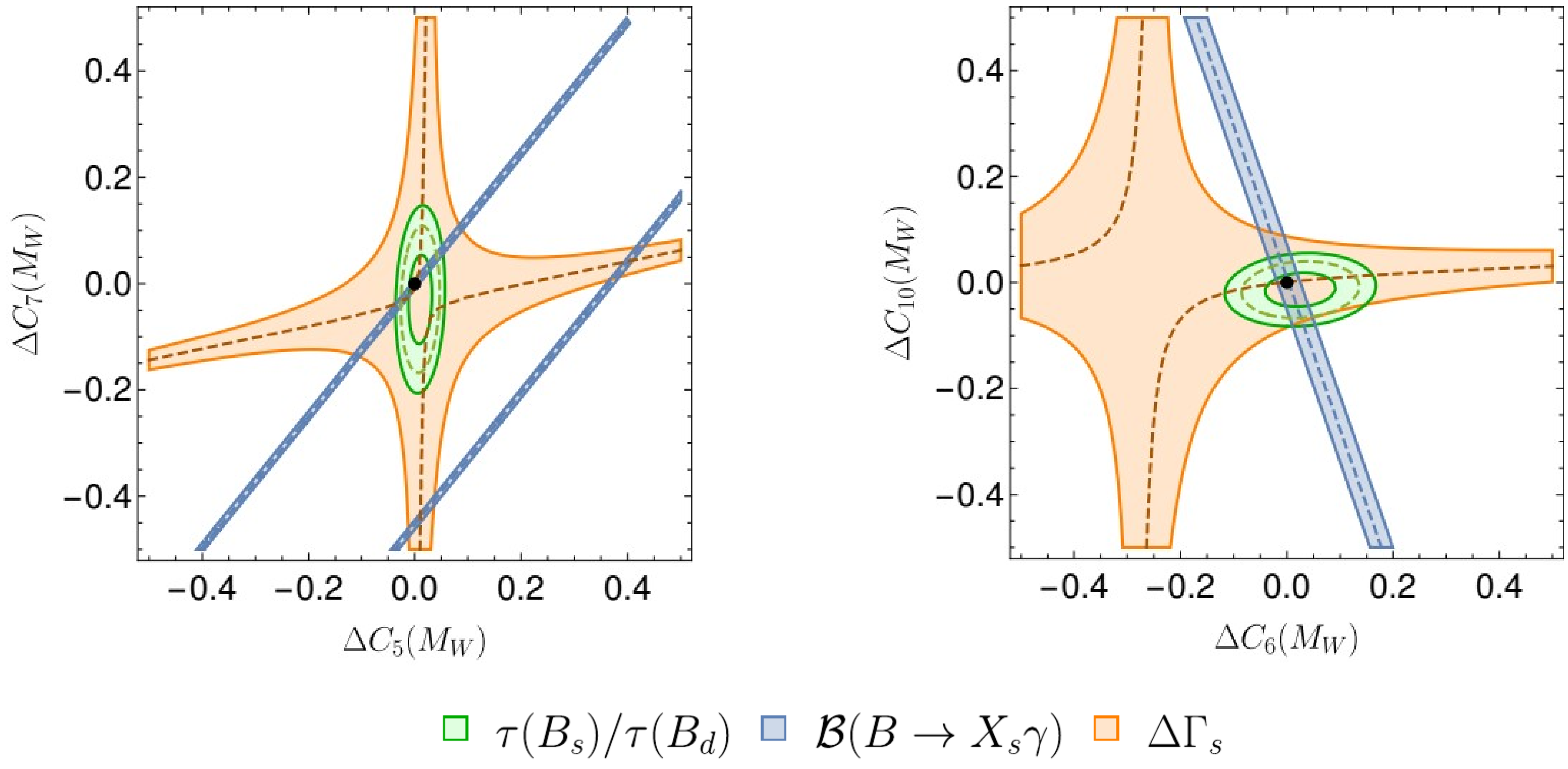
0.4
0.2
0.0
−0.2
−0.4
$\Delta C_3(M_W)$
−0.4
−0.2
0.0
0.2
0.4
$\Delta C_2(M_W)$
0.4
0.2
0.0
−0.2
−0.4
$\Delta C_2(M_W)$
−0.4
−0.2
0.0
0.2
0.4
$\Delta C_1(M_W)$
$\tau(B_s)/\tau(B_d)$
$\mathcal{B}(B \to X_s\gamma)$
$\Delta\Gamma_s$

$C_1'^c - C_4'^c$

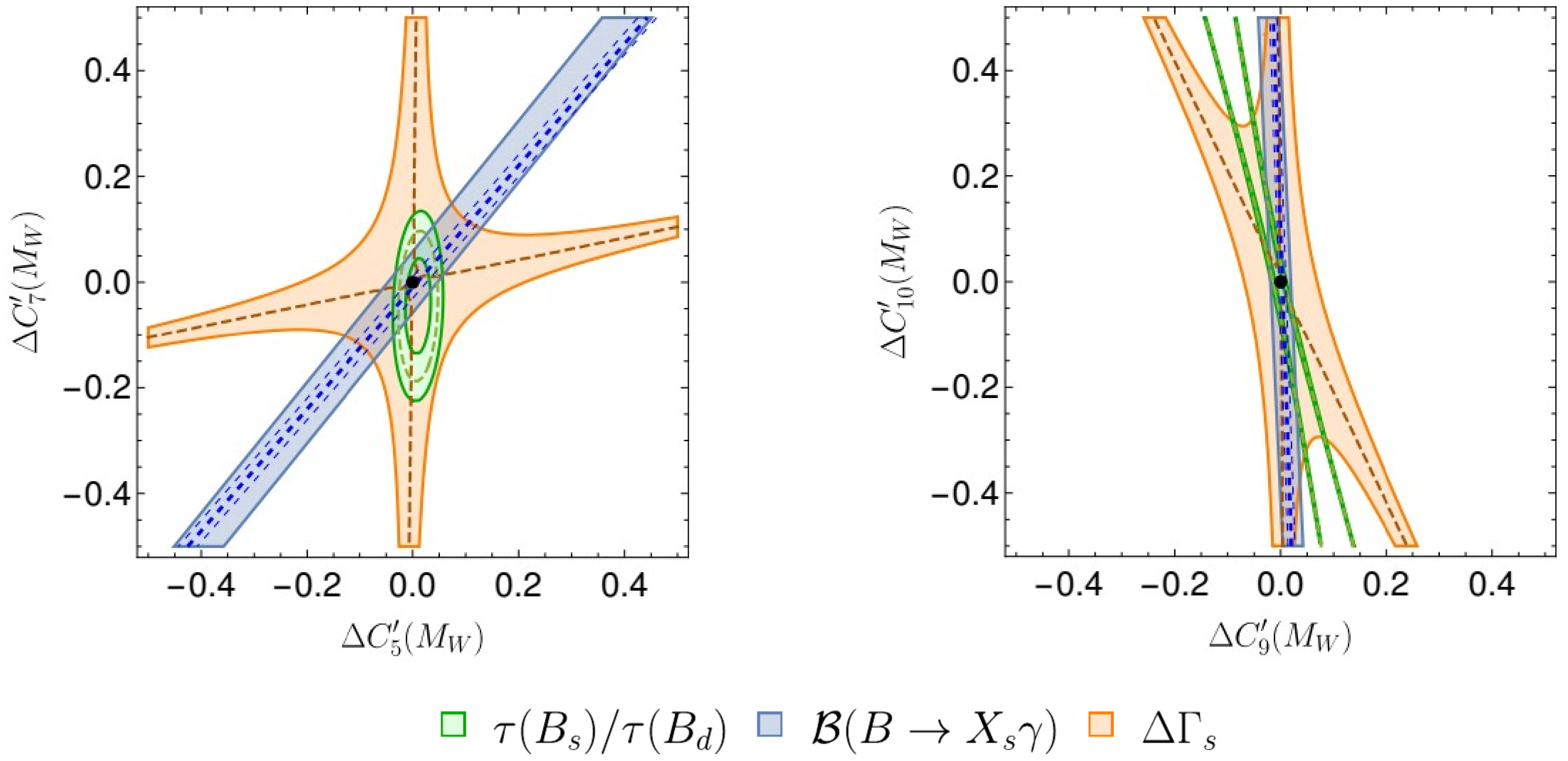


0.4
0.2
0.0
−0.2
−0.4
$\Delta C_2'(M_W)$
$\Delta C_1'(M_W)$
$\Delta C_4'(M_W)$
$\Delta C_3'(M_W)$
$\tau(B_s)/\tau(B_d)$
$\mathcal{B}(B \to X_s\gamma)$
$\Delta\Gamma_s$

$C_5^c - C_{10}^c$


0.4
0.2
0.0
−0.2
−0.4
$\Delta C_7(M_W)$
−0.4
−0.2
0.0
0.2
0.4
$\Delta C_5(M_W)$
0.4
0.2
0.0
−0.2
−0.4
$\Delta C_{10}(M_W)$
−0.4
−0.2
0.0
0.2
0.4
$\Delta C_6(M_W)$
$\tau(B_s)/\tau(B_d)$
$\mathcal{B}(B \to X_s\gamma)$
$\Delta\Gamma_s$

$C_5'^c - C_{10}'^c$



0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
$\Delta C_7'(M_W)$
$\Delta C_5'(M_W)$
$\Delta C_{10}'(M_W)$
$\Delta C_9'(M_W)$
$\tau(B_s)/\tau(B_d)$
$\mathcal{B}(B \to X_s\gamma)$
$\Delta\Gamma_s$

Constraints on Wilson coefficients

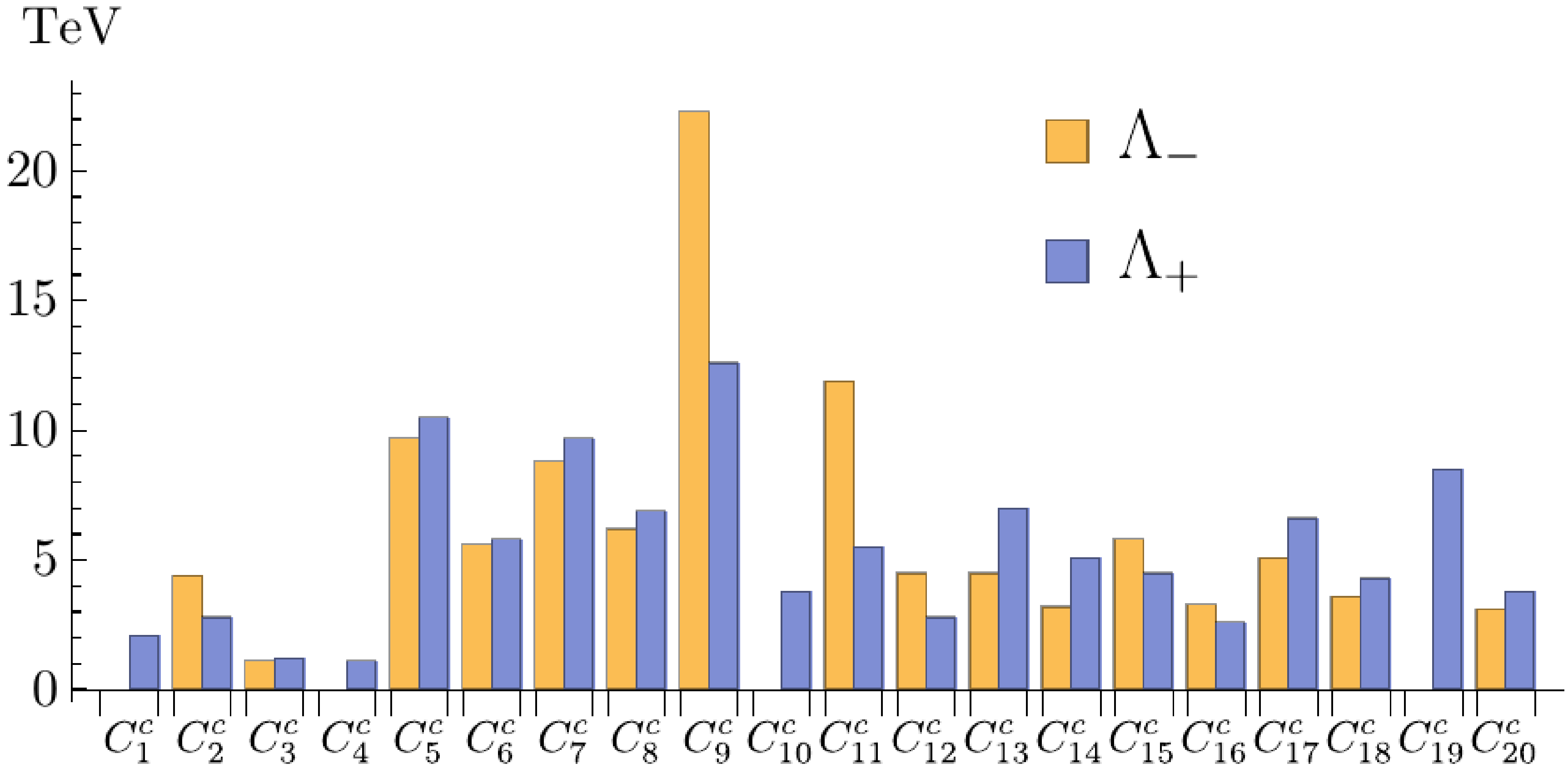
- Lots more plots in our paper

Limits on NP scale

- We can interpret our constraints as limits on the new physics scale: $\left|\frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \Delta C^c\right| = \frac{1}{\Lambda_{\text{NP}}^2}$

- When our limits are not symmetric, give two scales: one for positive BSM Wilson coefficients, and one for negative.

Limits on NP scale



CP violating BSM

- So far, assumed no extra CP violation
  - i.e. real Wilson coefficients
- So what if we include complex coefficients?

CP violating BSM

- $B \to J/\psi K$ – golden mode for determining CKM angle β

$$A_{CP}(t) = \frac{\Gamma\left[\bar{B}_d(t) \to J/\psi K_S\right] - \Gamma\left[B_d(t) \to \ J/\psi K_S\right]}{\Gamma\left[\bar{B}_d(t) \to J/\psi K_S\right] + \Gamma\left[B_d(t) \to J/\psi K_S\right]}$$

$$= S_{J/\psi K_S} \sin(\Delta M_d t) - C_{J/\psi K_S} \cos(\Delta M_d t)$$

- S is mixing induced, C is direct CP asymmetry

CP violating BSM

$$S_{J/\psi K_S} = \frac{2\,\mathrm{Im}\,\lambda_{J/\psi K_S}}{1+|\lambda_{J/\psi K_S}|^2}\,, \quad C_{J/\psi K_S} = \frac{1-|\lambda_{J/\psi K_S}|^2}{1+|\lambda_{J/\psi K_S}|^2}$$

$$\lambda_{J/\psi K_S} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{C_1^c + r_{21} C_2^c + r_{31} C_3^c + r_{41} C_4^c}{C_1^{c*} + r_{21} C_2^{c*} + r_{31} C_3^{c*} + r_{41} C_4^{c*}}$$

- If only real coefficients, simplifies to:
- $C = 0\,,\ S = \sin 2\beta$

$$B \to J/\psi K$$

- But with $C \neq C^*$, much more complicated
- In particular, need to know the $r_{i1} \equiv \frac{\langle Q_i^c \rangle}{\langle Q_1^c \rangle}$ matrix element ratios
- Totally hadronic decay – matrix elements very hard to calculate theoretically

Estimating hadronic matrix elements

- Naive factorisation:
  - $\langle J/\psi K|(\bar{s}b)(\bar{c}c)|B\rangle = \langle J/\psi|\bar{c}c|0\rangle\langle K|\bar{s}b|B\rangle$
  - Holds in the limit $N_c \to \infty$
- NF expectation:
  - $r_{21} = 1/3,\ r_{31} = 1,\ r_{41} = 1/3$

Constraining complex BSM

- No chance of constraining BSM coefficients…
- But including also

$$\mathcal{B}(B \to J/\psi K) \sim |\langle Q_1^c \rangle|^2 |C_1^c + C_2^c r_{21} + C_3^c r_{31} + C_4^c r 41|^2$$

we have 3 observables

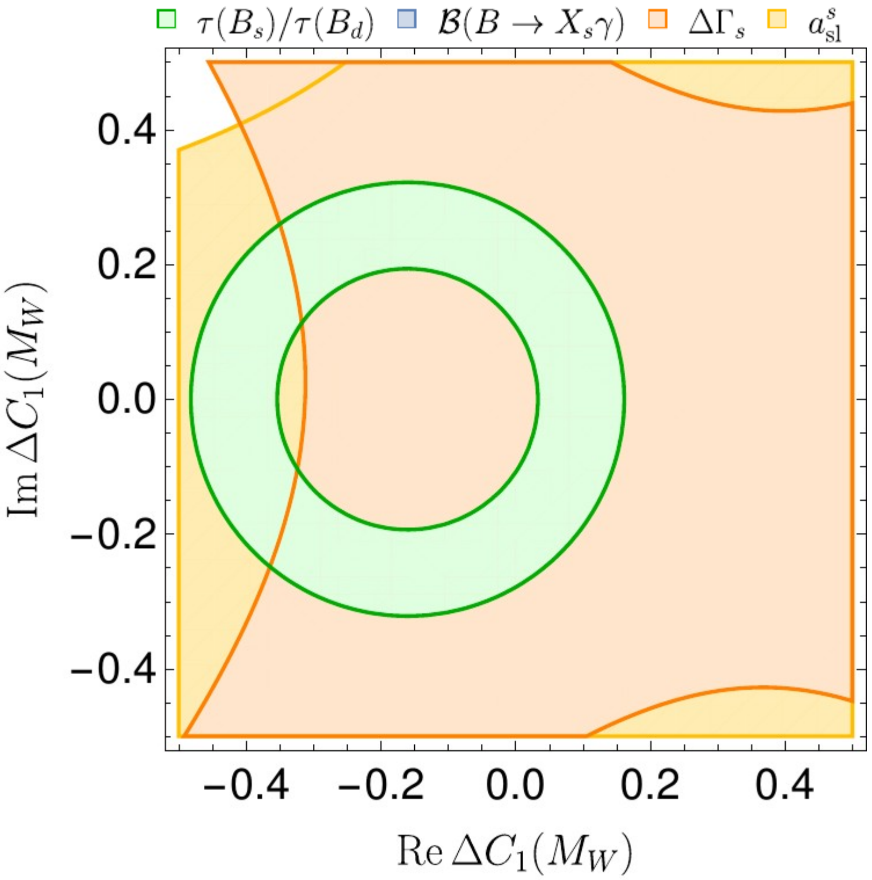
- So if we can control 1 of the hadronic parameters, we have enough information to reduce to a region on complex coefficient space

Constraining complex BSM

- Assuming only NP in one coefficient, have five real parameters: $\mathrm{Re}(C^c), \mathrm{Im}(C^c), \mathrm{Re}(r_{21}), \mathrm{Im}(r_{21}), |\langle Q_1^c \rangle|$
- Large N_c expansion tells us that the corrections to $\langle Q_1^c \rangle$ are $\sim 1/N_c^2$
- While r_{21} corrections are ~1
- So we can determine r_{21} from the data and also put limits on complex C_1^c/C_2^c

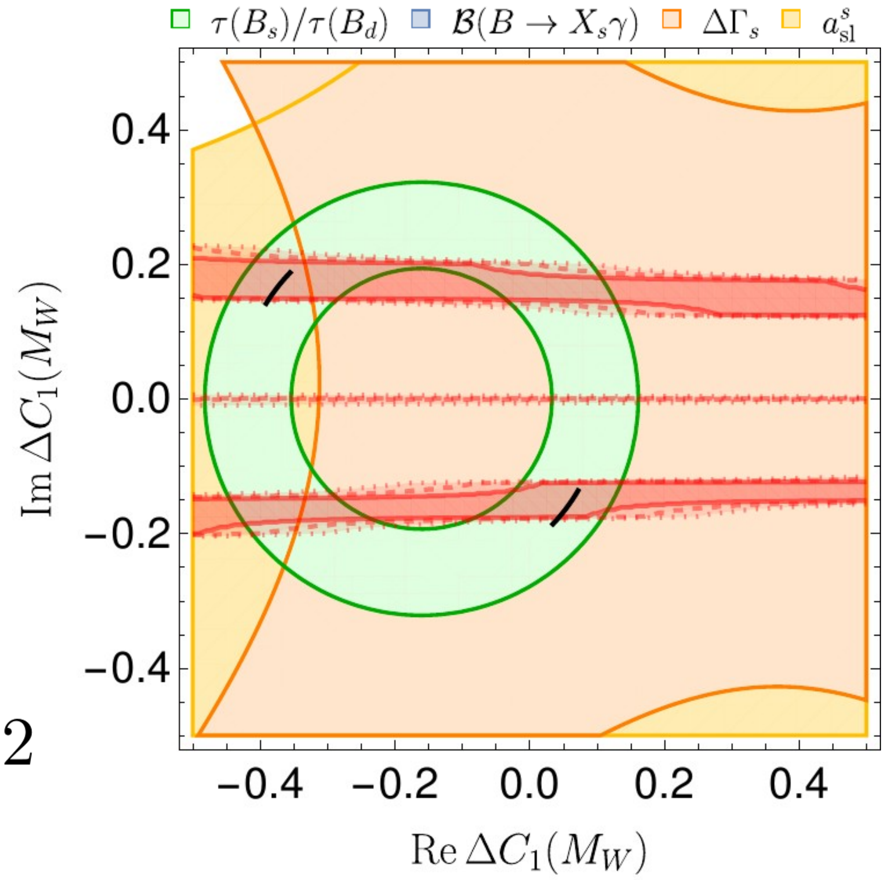
Complex C_1^c

- Lifetime ratio strongest
- Showing $a_{\rm sl}^s$, from $\mathrm{Im}(\Gamma_{12})$
  - But experimental precision low compared to theory
  - Exp ≈ $(-60 \pm 280) \times 10^{-5}$
  - SM ≈ $(2 \pm 0.2) \times 10^{-5}$
- Not showing $\mathcal{B}(B \to X_s\gamma)$ as the whole visible region is allowed



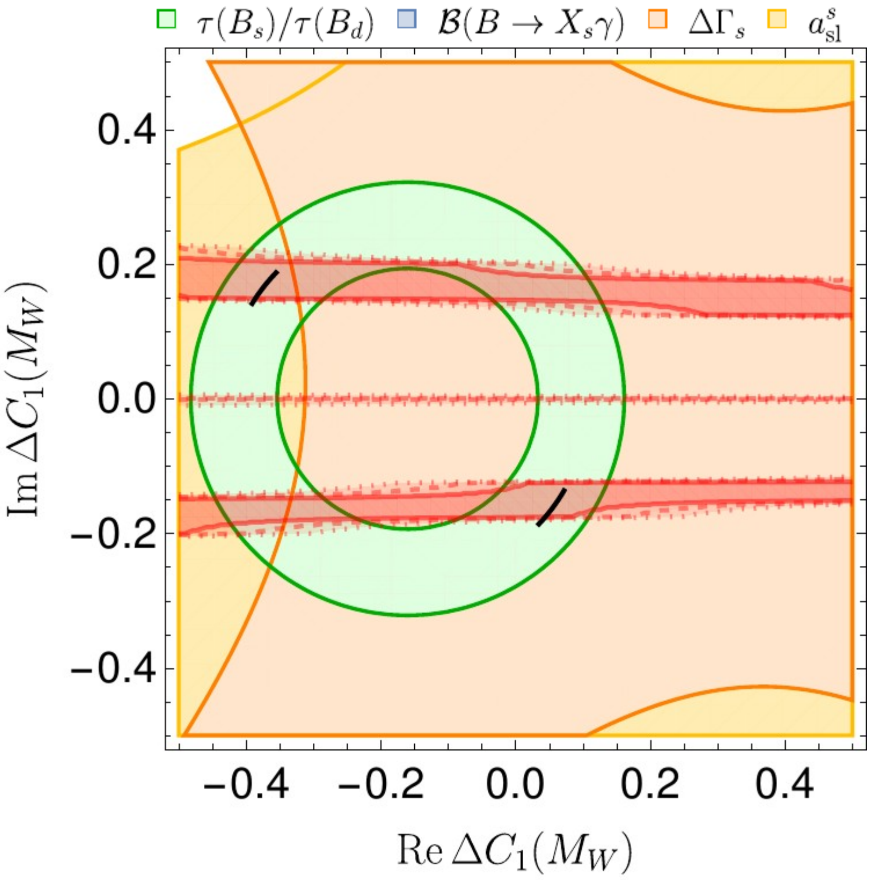
Complex C_1^c

- Do χ^2 fit to data
- Restrict $0 \leq \mathrm{Re}(r_{21}) \leq 2/3\,,$ $-1/3 \leq \mathrm{Im}(r_{21}) \leq 1/3$
- By making reasonable assumptions about $\langle Q_1^c \rangle$, can constrain complex C_1^c despite theory problems
- Data suggests $\mathrm{Im}(\Delta C_1^c) \approx \pm 0.2$



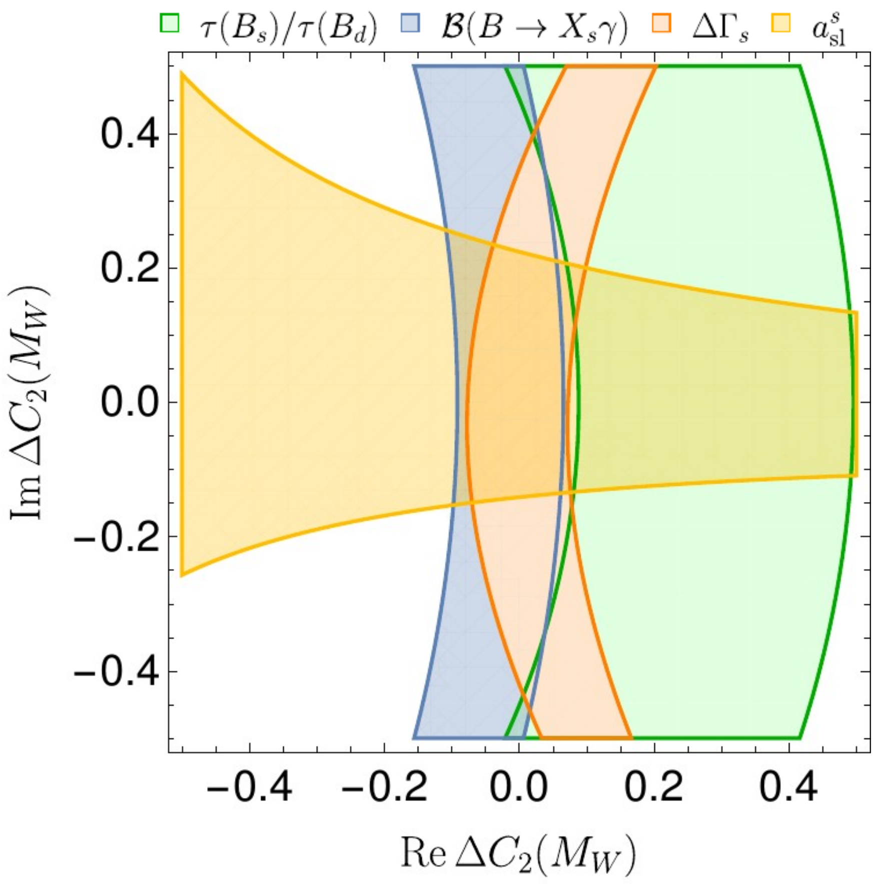
Complex C_1^c

- Within red regions, r_{21} has large range
- But we also shown that there is a limited region where $r_{21} \approx 1/3$ in areement with NF
- Not true that the data on $B \to J/\psi K$ implies there must be large corrections to NF.



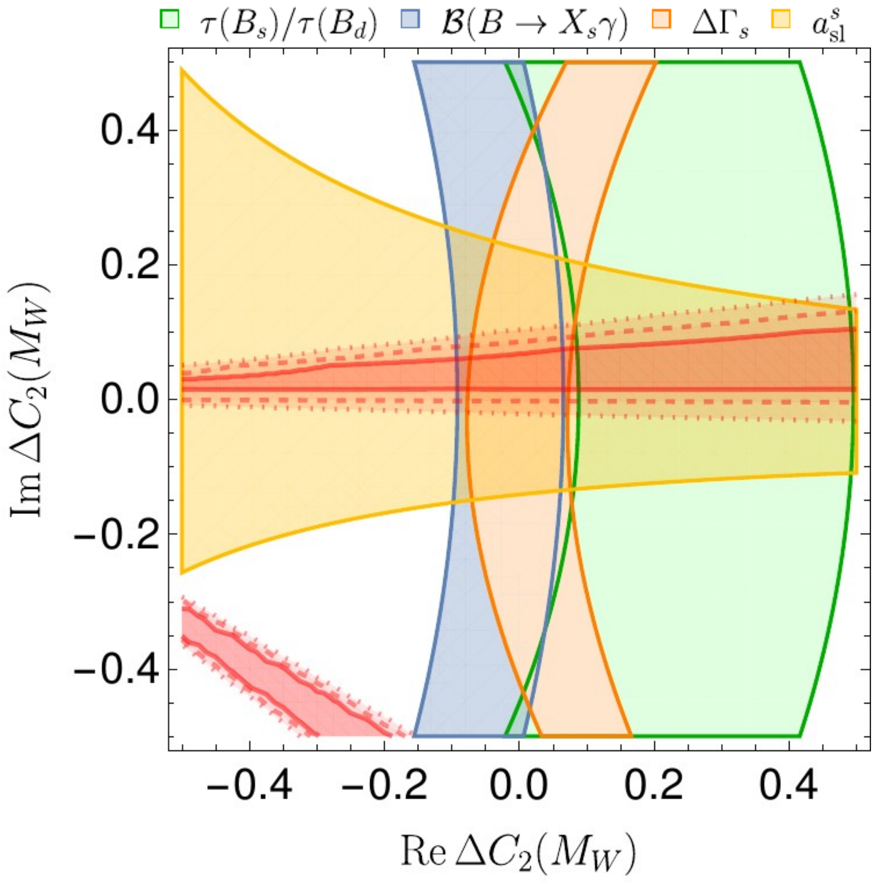
Complex C_2^c

- Same idea and process as for C_1^c
- No clear region where all the constraints agree



Complex C_2^c

- Add in $B \to J/\psi K$
- Data driven approach favours real (but v. small) BSM contribution
- Data allows us to make non-trivial constraints, but no indication of "NF" region as for C_1^c



Complex $C^c_{3,4}$

- In this case, also have to fit $r_{31,41}$
- r_{31} : large N_c corrections are $\sim 1/N_c^2$
- r_{41} : similar to r_{21}, no good theoretical control – expect large corrections from large N_c expansion
- Not enough observables to fit from data

Summary

- Comprehensive study of $b \to c\bar{c}s$ operators
  - Full mixing and RG evolution presented in one place
  - Full contribution to $\Delta\Gamma_s$ and $\tau(B_s)/\tau(B_d)$ calculated for first time (and available as Mathematica notebooks)
  - Lots of plots in paper showing various combinations

Summary

- Comprehensive study of $b \to c\bar{c}s$ operators
- CP violating BSM studies using the $B \to J/\psi K$ decay
  - Use a data driven approach to fit the matrix element ratio r_{21} from experiment
  - Still enough data to have meaningful constraints on complex Wilson coefficients

Summary

- Comprehensive study of $b \to c\bar{c}s$ operators
- CP violating BSM studies using the $B \to J/\psi K$ decay
  - Imaginary BSM contribution to $C_1^c \approx \pm 0.2i$
  - Contrary to expectation, NF can fit data well at $C_1^c \approx -0.2i$

Summary

- Comprehensive study of $b \to c\bar{c}s$ operators
- CP violating BSM studies using the $B \to J/\psi K$ decay
- Interpreting our constraints as NP scale, $b \to c\bar{c}s$ operators probe scales ≥ 2 TeV, and above 10 TeV in the strongest case
  - Strong complimentarity with direct LHC searches

Thanks!