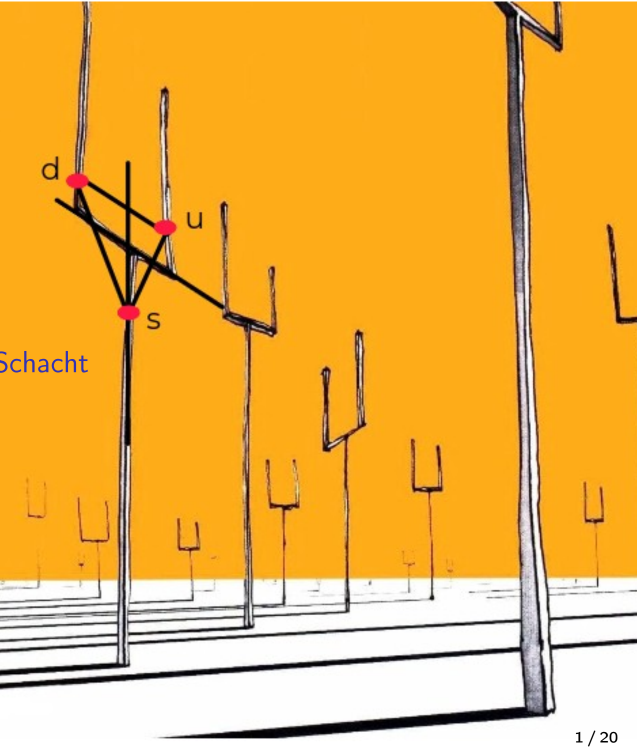
SU(3) ORIGIN OF SYMMETRY

Symmetries and Asymmetries with $B \to DD$ Decays

Jonathan Davies, Martin Jung, Stefan Schacht

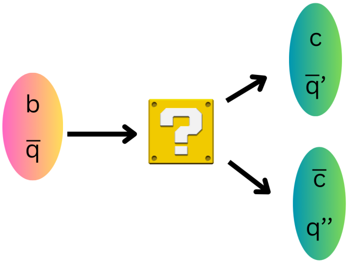
October 25, 2023



Some questions

What?:

- Testing the SM with $B \to DD$ data-branching ratios and CP asymmetries.
- Update of arxiv:1410.8396



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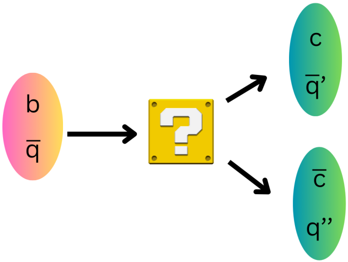

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Any generic BSM theory would have $\mathcal{O}(1)$ weak-phases $\implies$ significant CPV expected.

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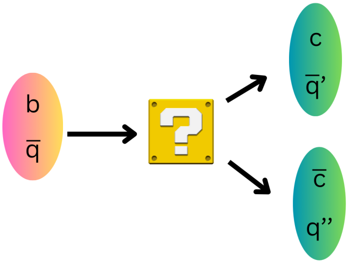

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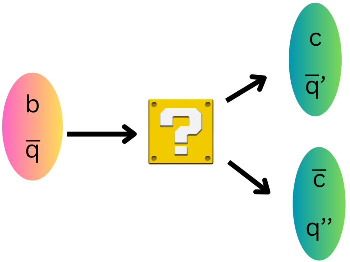

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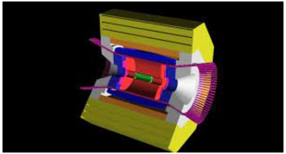
How?:
Let's see...

Where is this data coming from?



Which Observables?

Examples include (not an exhaustive list):

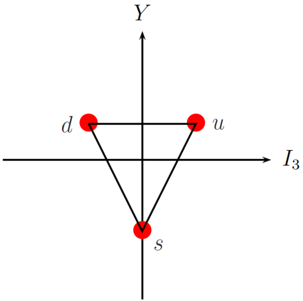
- $\frac{f_s}{f_d}\frac{\mathrm{BR}(D_s^+\to K^+K^-\pi^+)}{\mathrm{BR}(D^+\to K^-\pi^+\pi^+)}\frac{\mathrm{BR}(\bar{B}_s\to D_s^+D_s^-)}{\mathrm{BR}(\bar{B}^0\to D^+D_s^-)}$
- $2f_{+-}\mathrm{BR}(B^-\to D^0D_s^-)\mathrm{BR}(D^0\to K^-\pi^+)\mathrm{BR}(D_s^-\to\phi\pi^-)$
- $\mathrm{BR}(B_s^0\to D_s^+D_s^-)$
- $\mathrm{BR}(D_s^-\to K^+K^-\pi^+)$
- $A_{CP}(B^-\to D_s^-D^0)$ including brand new LHCb input! (arxiv:2306.09945)
- $S_{CP}(\bar{B}^0\to D^-D^+)$

We take into account correlations and use updated charm BR's to rescale older results

Adding Theory Arguments to the Mix

Can make approximation

$$m_u \approx m_d \approx m_s \ll \Lambda_{QCD}$$



u, d, and s represented by a triplet in an approximate $SU(3)_F$ symmetry

We could do this...

1. **Express everything in terms of $SU(3)$ states:**

   $u = |\mathbf{3}, (\frac{1}{2}, \frac{1}{2}, \frac{1}{3})\rangle$, $d = |\mathbf{3}, (\frac{1}{2}, -\frac{1}{2}, \frac{1}{3})\rangle$, $s = |\mathbf{3}, (0, 0, -\frac{2}{3})\rangle$, $c = |\mathbf{0}\rangle$, $b = |\mathbf{0}\rangle$

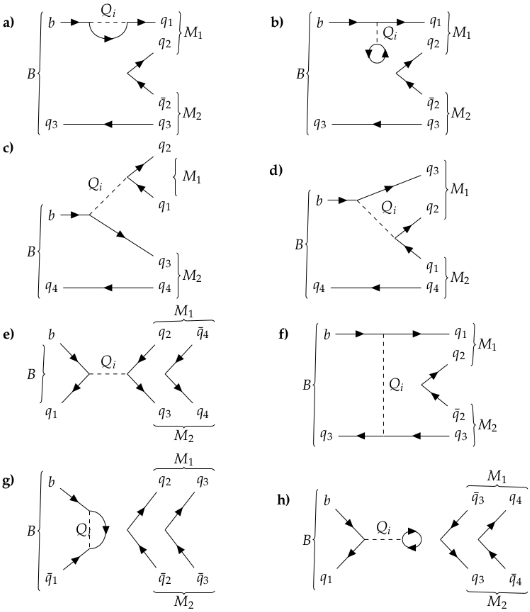
   $|\mathbf{r_1}, \alpha_1\rangle\, |\mathbf{r_2}, \alpha_2\rangle = \sum_i (\mathbf{R_i}, A_i | \mathbf{r_1}, \alpha_1, \mathbf{r_2}, \alpha_2)\, |\mathbf{R_i}, A_i\rangle$

   $\mathcal{H}_u^{b\to d} \sim \sqrt{\frac{3}{8}}(\mathbf{3}, \frac{1}{2}, -\frac{1}{2}, \frac{1}{3}) - \frac{1}{2}(\overline{\mathbf{6}}, \frac{1}{2}, -\frac{1}{2}, \frac{1}{3}) + \sqrt{\frac{1}{24}}(\mathbf{15}, \frac{1}{2}, -\frac{1}{2}, \frac{1}{3}) + \sqrt{\frac{1}{3}}(\mathbf{15}, \frac{3}{2}, -\frac{1}{2}, \frac{1}{3})$

2. **Parameterise our decays in terms of $SU(3)$ matrix elements**:

   $\langle D^- D^0 |\, \mathcal{H}^{b\to d}\, | B^- \rangle \quad \rightarrow \quad \sqrt{\frac{3}{8}}\, \langle 8 |\, (3)\, | \overline{3} \rangle_u - \sqrt{\frac{1}{20}}\, \langle 8 |\, (\overline{6})\, | \overline{3} \rangle_u + \dots$

… but diagrams are easier.



Linear combinations of $SU(3)$ matrix elements

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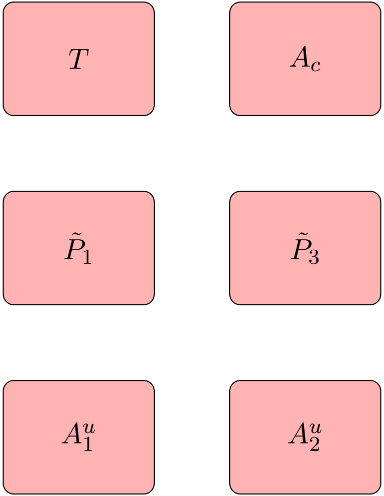

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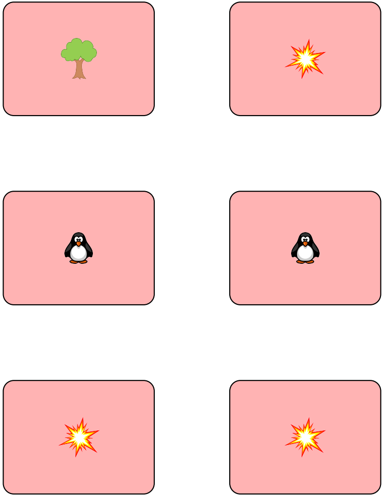


Theoretical Parameterisation

	Mode	$\lambda_{cD} T$	$\lambda_{cD} A^c$	$\lambda_{uD} \tilde{P}_1$	$\lambda_{uD} \tilde{P}_3$	$\lambda_{uD} A_1^u$	$\lambda_{uD} A_2^u$
Spoilers							
1	$B^- \to D^- D^0$	1	0	-1	0	1	0
2	$B^- \to D_s^- D^0$	1	0	-1	0	1	0
3	$\bar{B}^0 \to D_s^- D^+$	1	0	-1	0	0	0
4	$\bar{B}_s \to D^- D_s^+$	1	0	-1	0	0	0
5	$\bar{B}^0 \to D^- D^+$	1	1	-1	-1	0	0
6	$\bar{B}_s \to D_s^- D_s^+$	1	1	-1	-1	0	0
7	$\bar{B}^0 \to D_s^- D_s^+$	0	1	0	-1	0	0
8	$\bar{B}_s \to D^- D^+$	0	1	0	-1	0	0
9	$\bar{B}^0 \to \bar{D}^0 D^0$	0	-1	0	1	0	-1
10	$\bar{B}_s \to \bar{D}^0 D^0$	0	-1	0	1	0	-1

Generate vector of parameterised observables $\underline{\mathbf{P}}(\underline{\mathbf{x}})$

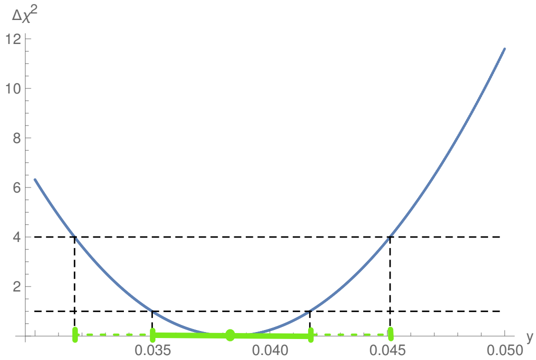
Predictions

Construct $\chi^2(\underline{\mathbf{x}})$

Scan function

$$\chi^2_\lambda(y) = \min(\chi^2(\underline{\mathbf{x}})|_{x_\lambda = y})$$

Find y range where
$\Delta\chi^2_\lambda < 1(4) \implies 68(95)\%$ CI



y is some variable of χ^2 $(BR(B^- \to D^- D^0)$ here)

D branching ratios, fragmentation fractions and efficiencies also floated.

Our main goal is to perform these scans for our **physical observables**

Power Counting

A way of managing the relative sizes of the diagrams.

We take $\epsilon \sim \mathbf{0.3}$ and consider the following contributions:

- **SU(3) structure-** $\mathcal{O}(\epsilon)$: For SU(3)-breaking contributions
- **CKM suppression-** $\mathcal{O}(\epsilon)$: Where CKM factors cannot be separated from the hadronic matrix elements.
- **Colour suppression:** Relative counting in $1/(\#\text{ colours}) \sim \mathcal{O}(\epsilon)$ for the topologies, based on [Buras, Gèrard, Rückl (1986)]
- **Penguin suppression:**
  - Tree matrix elements of penguin operators- $\mathcal{O}(\epsilon^2)$
  - Penguin matrix elements of tree operators- $\mathcal{O}(\epsilon^{1/2})$
- **Annihilation:** $\mathcal{O}(\epsilon^{1/2})$ for annihilation diagram + $\mathcal{O}(\epsilon)$ for $c\bar{c}$ creation.

Validation

Expected relative scaling from power counting for decay rates and CP asymmetries can be checked with data.

Relative rate	$b \to s$	$b \to d$
Tree-dominated	1	$\bar{\lambda}^2$
Annihilation-dominated	ϵ^3	$\bar{\lambda}^2 \epsilon^3$

CP asymmetry	$b \to s$	$b \to d$
Tree-dominated	$\bar{\lambda}^2 \epsilon^{2.5}$	$\epsilon^{2.5}$
Annihilation-dominated	$\bar{\lambda}^2 \epsilon^2$	ϵ^2

- Measured rates correspond to our scaling usually within 30%, as expected.
- Slightly larger deviations of $\sim 40\%$ for $\bar{B}^0 \to D^+ D^-$ and $\bar{B}_s \to D_s^+ D_s^-$- first sign for negative interference of the sizable A_c [arxiv:1410.8396].
- New LHCb measurement for $A_{CP}(B^- \to D^0 D^-) \sim 2\%$ is on the lower side of $\epsilon^{2.5} \sim 5\% \implies$ our penguin amplitude scaling is conservative.

Theoretical Parameterisation

	Mode	$\lambda_{cD} T$	$\lambda_{cD} A^c$	$\lambda_{uD} \tilde{P}_1$	$\lambda_{uD} \tilde{P}_3$	$\lambda_{uD} A_1^u$	$\lambda_{uD} A_2^u$
	Counting	1	$\varepsilon^{1.5}$	$\varepsilon^{2.5}$	$\varepsilon^{3.5}$	$\varepsilon^{2.5}$	$\varepsilon^{3.5}$
1	$B^- \to D^- D^0$	1	0	-1	0	1	0
2	$B^- \to D_s^- D^0$	1	0	-1	0	1	0
3	$\bar{B}^0 \to D_s^- D^+$	1	0	-1	0	0	0
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Power counting enters as hard parameter constraints during χ^2 minimisation.

SU(3) Breaking

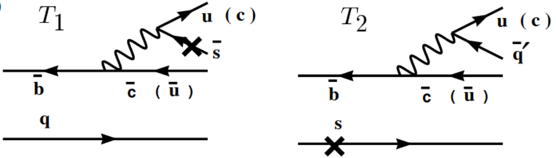
But $m_u \neq m_d \neq m_s$**!**

Must fix our assumption that $d \equiv s$:

$$\mathcal{H}_{SU(3)} \sim \frac{m_s - m_d}{\Lambda_{QCD}}(s\bar{s})$$

Fitting this into diagrammatic language [arxiv:9504326]:

(a)



Breaking table

	Mode	$\lambda_{cD}\delta T_1$	$\lambda_{cD}\delta T_2$	$\lambda_{cD}\delta A_1^c$	$\lambda_{cD}\delta A_2^c$
	Counting	$\varepsilon^{1(2)}$	$\varepsilon^{1(2)}$	$\varepsilon^{2.5}$	$\varepsilon^{2.5}$
1	$B^- \to D^- D^0$	0	$-\frac{1}{2}$	0	0
2	$B^- \to D_s^- D^0$	1	0	0	0
3	$\bar{B}^0 \to D_s^- D^+$	1	0	0	0
4	$\bar{B}_s \to D^- D_s^+$	-1	$\frac{1}{2}$	0	0
5	$\bar{B}^0 \to D^- D^+$	0	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$
6	$\bar{B}_s \to D_s^- D_s^+$	0	1	-1	1
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Observables

From amplitudes, it is simple to go to experimental observables:

- Branching Ratios

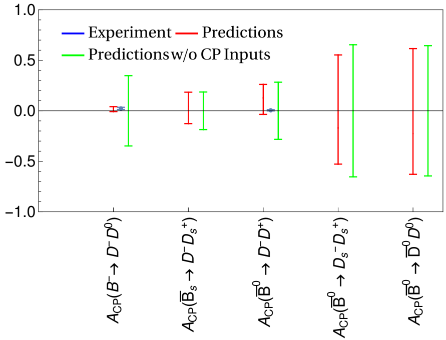
$$\mathcal{B}(\mathcal{D} \equiv B \to P_1 P_2) = |\mathcal{A}(\mathcal{D})|^2 \times \mathrm{phase-space}$$

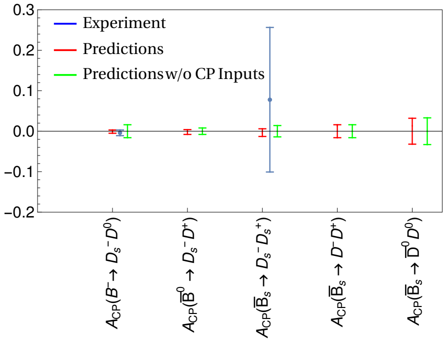
- CP Asymmetries

$$A_{CP}(\mathcal{D}) = -\frac{1 - |\lambda(\mathcal{D})|^2}{1 + |\lambda(\mathcal{D})|^2} = \frac{|\mathcal{A}(\mathcal{D})|^2 - |\overline{\mathcal{A}}(\mathcal{D})|^2}{|\mathcal{A}(\mathcal{D})|^2 + |\overline{\mathcal{A}}(\mathcal{D})|^2}, \quad S_{CP}(\mathcal{D}) = \frac{2\mathrm{Im}(\lambda(\mathcal{D}))}{1 + |\lambda(\mathcal{D})|^2}$$

$$\left[\lambda(\mathcal{D}) = \eta^f_{CP} e^{-i\phi_D} \frac{\mathcal{A}(\mathcal{D})}{\overline{\mathcal{A}}(\mathcal{D})}\right]$$

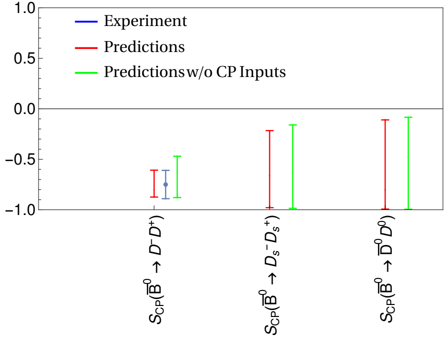
SM prediction for CP Asymmetries

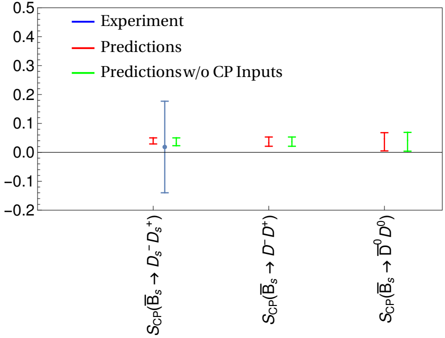




Predictions extracted both with and without experimental CP information.

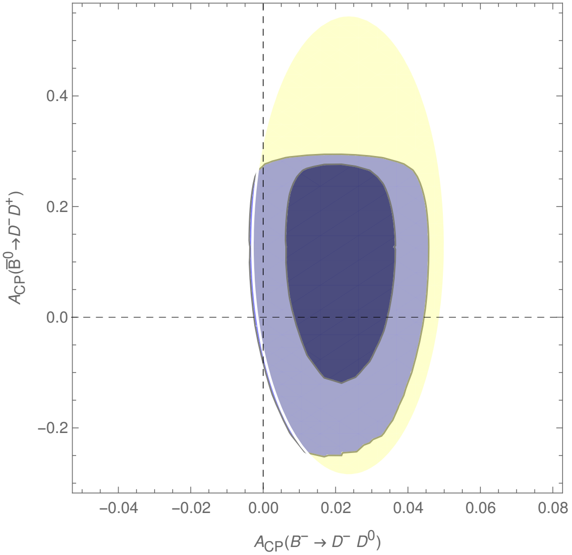
SM prediction for CP Asymmetries





Predictions extracted both with and without experimental CP information.

We can do 2D scans too!



Blue contours represent 68% and 95% CI from global fit. Yellow shows experiment-only constraints. Non-trivial correlations, resulting from underlying theory parameterisation, can be seen.

To conclude...

- Our predictions for CP asymmetries can be used to probe for new physics with future measurements at LHCb
- By working from an assumption of approximate SU(3) symmetry we can obtain predictions for observables by fitting to experimental data
- Symmetry assumptions found to be valid
- No significant tension with Standard Model found but precision is improved
- We provide predictions for many as-yet unmeasured modes
- Stay tuned for publication soon!

Time for grilling!

Thanks for your attention.

Hiring?- Find my CV here or email me at jonathan.edward.davies@cern.ch