CP violation in beauty and charm at LHCb

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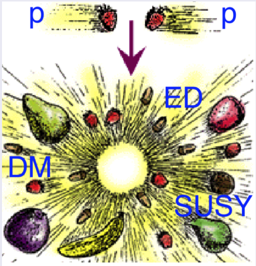
Why do we need CP violation?

- One of the necessary ingredients to create a baryon asymmetry is CP violation
- CPV is present in the Standard Model, but orders of magnitude too small
- In extensions of the SM, additional sources of CP violation can arise from the exchange of new particles
- There are two routes to these new physics models

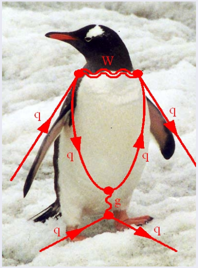
Direct searches

Limited by collision energy



Indirect searches

Sensitive to heavy virtual particles



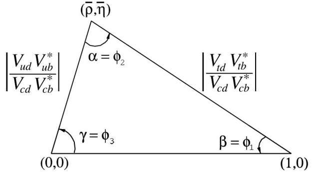
- CP violation is described in the quark sector of the Standard Model by a complex phase in the CKM matrix

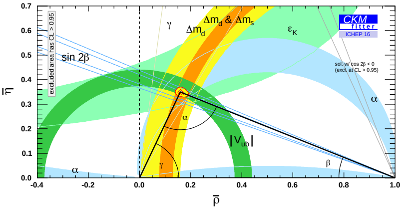
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Unitarity imposes conditions that are represented geometrically as triangles

B^0 **triangle**: large angles, similar sized sides

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{tb}V_{tb}^* = 0$$



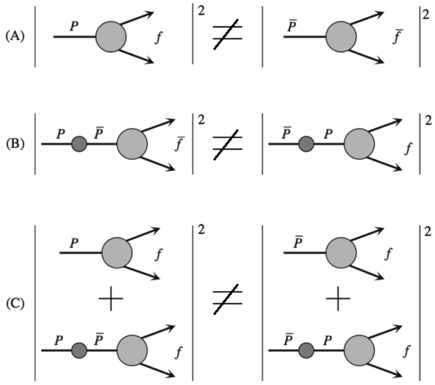


- Aim to experimentally **overconstrain** the Unitarity triangle to test that it closes

Types of CP violation

$$|P_1\rangle = p\,|P^0\rangle + q\,|\overline{P}^0\rangle$$
$$|P_2\rangle = p\,|P^0\rangle - q\,|\overline{P}^0\rangle$$

$$A_f = \langle f|\,H\,|P\rangle$$
$$\overline{A}_{\overline{f}} = \langle \overline{f}|\,H\,|\overline{P}\rangle$$

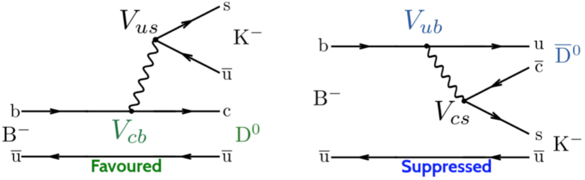


- CP violation in the **decay** (A)
  - $|A_f/\overline{A}_{\overline{f}}| \neq 1$
- CP violation in **mixing** (B)
  - Occurs in neutral mesons
  - $|q/p| \neq 1$
- CP violation in the **interference** between mixing and decay (C)
  - Neutral meson decaying into a non-flavour specific state
  - $\mathrm{Im}\left(\frac{q}{p}\frac{\overline{A}_{\overline{f}}}{A_f}\right) \neq 1$
- Measure CP violating parameters
  - $\frac{\overline{A}_f - A_f}{\overline{A}_f + A_f} = \frac{C_f cos(\Delta mt) - S_f sin(\Delta mt)}{cosh(\frac{\Delta\Gamma t}{2}) + D_f sinh(\frac{\Delta\Gamma t}{2})}$
  - S_f, D_f: CPV in the interference
  - C_f: CPV in decay

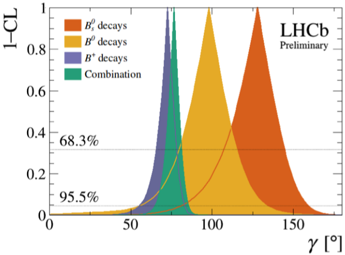
CP violation in beauty

CKM angle γ

- $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is the least well known angle of the Unitarity triangle
- The only CP violating parameter that can be measured through tree decays
  - Important Standard Model **benchmark**
  - Compare tree and loop level determinations to test for **new physics** - currently consistent but with large uncertainties
- Theoretically pristine $|\delta_\gamma \leq \mathcal{O}(10^{-7})|$
- Access through the interference of $b \to c$ and $b \to u$ decays
- World average of $(73.4^{+4.3}_{-5.0})^\circ$ [HFLAV] dominated by the combination of LHCb measurements $(76.8^{+5.1}_{-5.7})^\circ$ made with B^+, B^0 and B_s^0 [LHCb-CONF-2017-004]

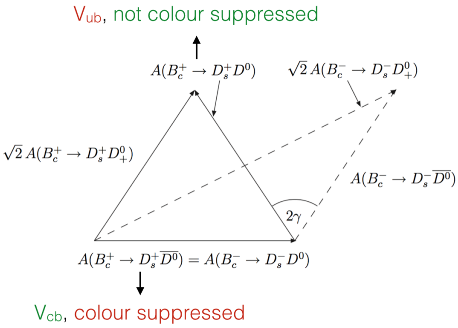


interference $\sim$ 10%



Search for B_c^+ decays to two charm mesons [arXiv:1712.04702]

- CP violation has **not yet been observed** in B_c^+ decays
- $B_c^+ \to D_{(s)}^{(*)+} D^{(*)}$ decays, where D is D^0 or $\overline{D}^0$, have been proposed to measure γ [Phys. Rev. D 62, 057503, Phys. Rev. D 65, 034016]
- Advantage over traditional $B \to DK$ since the triangle sides are of comparable length, interference $\sim$ 100%
- Disadvantage is small B_c^+ production cross section and branching fractions



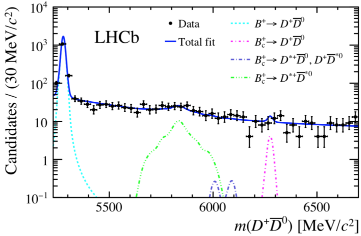
Channel	Prediction for the branching fraction $[10^{-6}]$			
$B_c^+ \to D_s^+ \overline{D}^0$	2.3 ± 0.5	4.8	1.7	2.1
$B_c^+ \to D_s^+ D^0$	3.0 ± 0.5	6.6	2.5	7.4
$B_c^+ \to D^+ \overline{D}^0$	32 ± 7	53	32	33
$B_c^+ \to D^+ D^0$	0.10 ± 0.02	0.32	0.11	0.32

[Phys. Rev. D 86, 074019, arXiv:hep-ph/0211021, Phys.Lett.B555:189-196,2003, Phys. Rev. D 73, 054024]

Search for B_c^+ decays to two charm mesons [arXiv:1712.04702]

$$\frac{f_c}{f_u} \times \mathcal{B}(B_c^+ \to D_{(s)}^+ D) = \mathcal{B}(B^+ \to D_{(s)}^+ \overline{D}^0) \times \frac{N(B_c^+)}{N(B^+)} \times \frac{\varepsilon(B^+)}{\varepsilon(B_c^+)}$$

- Fitted yield using run I data ($3\,\mathrm{fb}^{-1}$)
- Relative efficiency
- $D_s^+ \to K^+K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$
- $D^0 \to K^-\pi^+, K^-\pi^+\pi^-\pi^+$



- No evidence for signal found, upper limits at 90% (95%) confidence level:

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+\overline{D}^0)}{\mathcal{B}(B^+ \to D_s^+\overline{D}^0)} = (\ \ 3.0 \pm 3.7) \times 10^{-4}\ [< 0.9\,(1.1) \times 10^{-3}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ D^0)}{\mathcal{B}(B^+ \to D_s^+\overline{D}^0)} = (-3.8 \pm 2.6) \times 10^{-4}\ [< 3.7\,(4.7) \times 10^{-4}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+\overline{D}^0)}{\mathcal{B}(B^+ \to D^+\overline{D}^0)} = (\ \ 8.0 \pm 7.5) \times 10^{-3}\ [< 1.9\,(2.2) \times 10^{-2}],$$

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+ D^0)}{\mathcal{B}(B^+ \to D^+\overline{D}^0)} = (\ \ 2.9 \pm 5.3) \times 10^{-3}\ [< 1.2\,(1.4) \times 10^{-2}].$$

Assuming an optimistic $f_c/f_u = 1.2\%$,

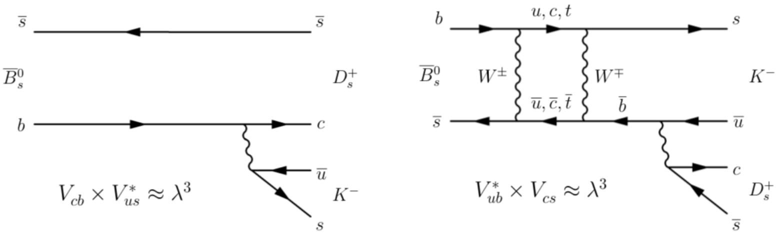
$\mathcal{B}(B_c^+ \to D^+\overline{D}^0) < 6.0(7.0) \times 10^{-4}$

Well above theoretical expectation

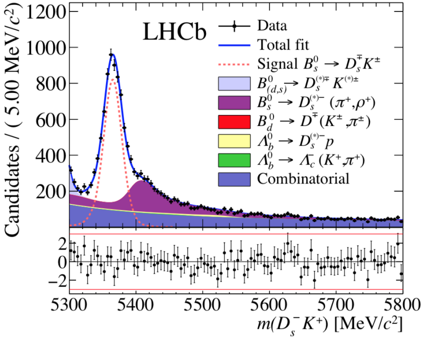
- Limits also set on excited D modes

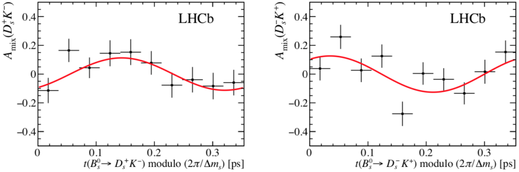
CP asymmetry in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays [arXiv:1712.07428]

- Sensitivity to γ and the B_s^0 mixing phase, $\gamma - 2\beta_s$, arises in $B_s^0 \to D_s^{\mp} K^{\pm}$ through the interference between mixing and decay
- Leading order diagrams are both $\mathcal{O}(\lambda^3)$, interference $\sim 35\%$
- $\gamma - 2\beta_s$ can be determined up to a **two-fold ambiguity**
- Full run I ($3\,\text{fb}^{-1}$) update of [JHEP 11 (2014) 060]
- $D_s^- \to K^+K^-\pi^-$, $\pi^+\pi^-\pi^-$, $K^-\pi^-\pi^+$



- Two-stage analysis strategy:
  - 1. Perform a multidimensional fit to $m(B_s^0)$, $m(D_s^+)$, and the PID distribution of the bachelor kaon to separate signal from background
  - 2. Subtract background and perform a fit to the weighted decay-time distribution
- Validate with $B_s^0 \to D_s^- \pi^+$





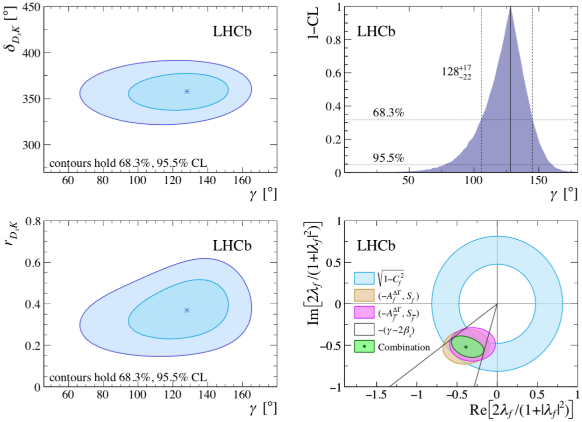
Measure

$$C_f = 0.73 \pm 0.14 \pm 0.05\,,$$
$$A_f^{\Delta\Gamma} = 0.39 \pm 0.28 \pm 0.15\,,$$
$$A_{\bar{f}}^{\Delta\Gamma} = 0.31 \pm 0.28 \pm 0.15\,,$$
$$S_f = -0.52 \pm 0.20 \pm 0.07\,,$$
$$S_{\bar{f}} = -0.49 \pm 0.20 \pm 0.07\,,$$

CP asymmetry in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays [arXiv:1712.07428]

- Using $\phi_s = -2\beta_s$ as external input

$$\gamma = (128\,^{+17}_{-22})^{\circ}\,,$$
$$\delta = (358\,^{+13}_{-14})^{\circ}\,,$$
$$r_{D_sK} = 0.37\,^{+0.10}_{-0.09}\,,$$



- **3.8 σ evidence** for CP violation in $B_s^0 \to D_s^{\mp} K^{\pm}$
- Measurement of γ is 2.3 σ from the LHCb combination

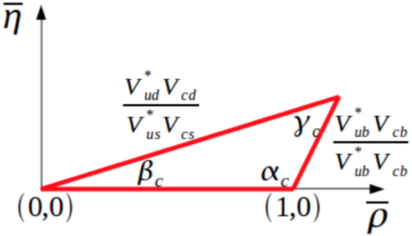
CP violation in charm

Charm triangle

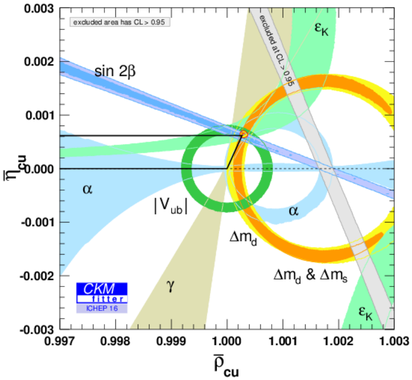
- Charm decays provide the only way to probe CP violation with up type quarks
- CP asymmetries in charm decays are at most $\mathcal{O}(10^{-3})$ in the SM
- Short distance effects expected to be small from stretched charm triangle, but long distance effects may dominate

Charm triangle: too stretched

$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0$$



$$\beta_c = \arg\left(-\frac{V_{cd}V_{ud}^*}{V_{cs}V_{us}^*}\right) \sim 0.03^\circ$$



- **No evidence for CP violation has yet been found in charm**

$D^0 - \overline{D}^0$ mixing and CP violating parameters with $D^0 \to K^- \pi^+$ [arXiv:1712.03220]

- $D^0 - \overline{D}^0$ oscillations are characterised by $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$
- Use 'right sign' (RS) $D^{*+} \to D^0(\to K^- \pi^+)\pi_s^+$ and 'wrong sign' (WS) $D^{*+} \to D^0(\to K^+ \pi^-)\pi_s^+$ from the suppressed D^0 decay and the favoured decay after oscillation
- Measure the time-dependent ratio of WS to RS decay rates

$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

- If R_D, the suppressed to favoured D^0 decay rate ratio, differs between D^0 and $\overline{D}^0$ $\to$ CPV in the **decay**
- If (x', y'), which are related to the mixing parameters, differ between D^0 and $\overline{D}^0$ $\to$ CPV in **mixing** or **interference**
- Fit data under three hypotheses: CPV allowed, no CPV in decay, no CPV
- $5\,\text{fb}^{-1}$ update of run I ($3\,\text{fb}^{-1}$) measurement [Phys. Rev. Lett. 111, 251801]

$D^0 - \overline{D}^0$ mixing and CP violating parameters with $D^0 \to K^- \pi^+$ [arXiv:1712.03220]

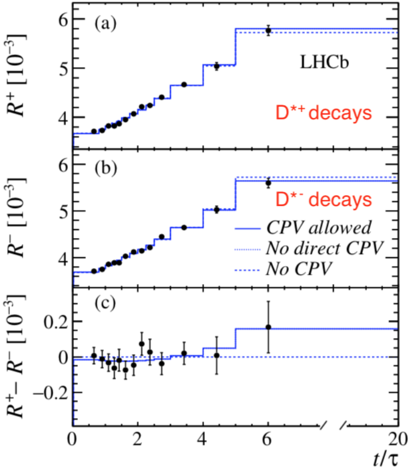
- Assuming CP symmetry, measure mixing parameters

  $x'^2 = (3.9 \pm 2.7) \times 10^{-5}$,
  $y'^2 = (5.28 \pm 0.52) \times 10^{-3}$,
  $R_D = (3.454 \pm 0.031) \times 10^{-3}$

- **No evidence for CP violation**

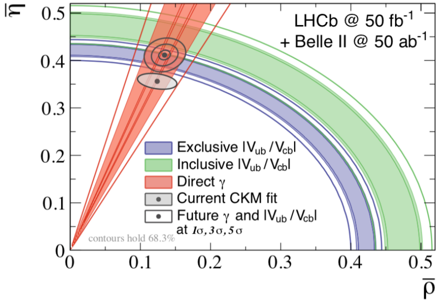
  $A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 9.1) \times 10^{-3}$,
  $1.00 < |q/p| < 1.35$ @ 68.3% $C.L.$

- Twice as precise as previous measurement

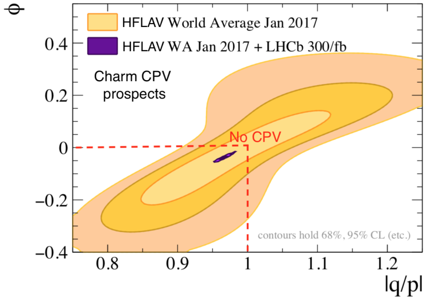


Conclusion

- **Precision flavour physics** is the way forward if no new particles are discovered in direct searches at the LHC
- Results so far are consistent with the Standard Model, however, many are statistically limited
- Many more exciting run II measurements coming soon
- **The future looks bright for CP violation measurements at LHCb**



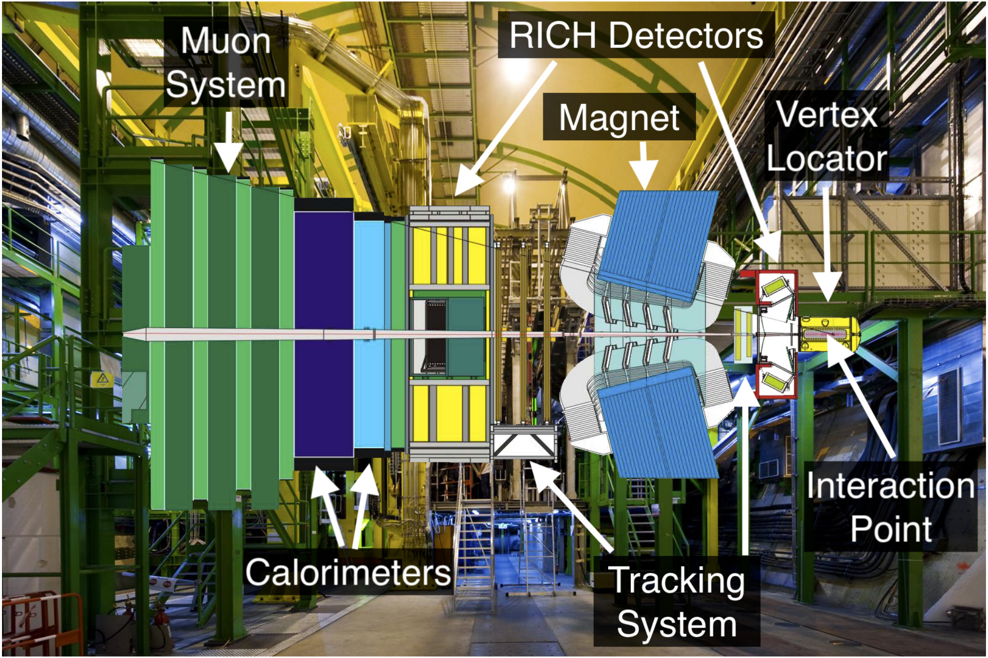
[arXiv:1709.10308]



[CERN-LHCC-2017-003]

Backup

LHCb detector



LHCb detector

- Specialised b physics experiment
- Unique forward acceptance $2 < \eta < 5$
  - 27% of b quarks fall inside the acceptance
- Also world's largest sample of charm decays
- Excellent performance [Int. J. Mod. Phys. A 30, 1530022 (2015)]
  - Impact parameter resolution $\approx 200\mu$m
  - Decay time resolution ≈ 45 fs
  - Momentum resolution $\approx 0.5\%$
  - Particle Identification (PID)
    - $\varepsilon(K) \approx 95\%$
    - Mis-ID$(\pi \to K) \approx 5\%$