Prospects for CP violation in Beauty and Charm at LHCb
Beyond the LHCb Phase-1 Upgrade

Dan Johnson
on behalf of the LHCb collaboration

29th May 2017
Today

Snapshot of LHCb CP violation studies & estimates for Phase-2 sensitivity

I will:

- refer to the milestones indicated above
- emphasise **theoretically clean UT angle** measurement & charm CPV
- highlight **systematic & detector challenges** in parallel
- return to the issue of **external inputs from CLEO and BES-III** at the end
Baryogenesis tells us that there must be New Physics in CP violation.
Can we find it in flavour-changing processes in the quark sector? Great progress:

SM picture accounts for wide range of measured CP observables.
But there is **room for more:**

- Assume no NP at tree-level
- Allow common (loop-level) NP effect in $B^0$ and $B_s^0$ mixing
- $M_{12} \rightarrow M_{12}^{SM}(\rho, \eta)(1 + h_d \exp(2i\sigma_d))$

$B^0$ mixing

$B_s^0$ mixing

Only limit amplitude of NP effects in $B_{d,s}$ mixing to $< 30\%!$  

*(PRD89 033016 (2014))*
Theoretically clean UT measurement

\( \gamma \)
The UT angle $\gamma$

- Least well-known UT angle
- Only one that can be measured at tree-level alone ($\sigma_{\text{th}}^{\text{tree}}/\gamma < \mathcal{O}(10^{-7})$) (JHEP 01 051 (2013))
- Sensitive NP probe: compare direct and indirect determination:

\[ \gamma = 73.2^{+6.3}_{-7.0} \quad \text{Indirectly:} \quad \gamma = 66.9^{+0.94}_{-3.44} \]

- NB: NP could manifest at tree-level - still room for 10% modifications to $C_1$ and $C_2$ (PRD 92 033002 (2015))
Exploit interference between decays via charm to a common final state

\[ X_b \rightarrow [F] Y_c \bar{Z} \]  
\[ \text{e.g. } B^\pm \rightarrow [K^\mp \pi^\pm]_D K^\pm \]

- \( F \) accessible to \( Y_c \) and \( \bar{Y}_c \):
- \( Z \in \{K, \pi, K^*, K\pi\pi\ldots\} \)

\( \gamma \) is the weak phase difference between decay amplitudes with \( b \rightarrow c \bar{u}s \) and \( b \rightarrow u\bar{c}s \) transitions
The UT angle $\gamma$

### 2-body ‘ADS’ : $B^{\pm} \to \left[ \pi^{\pm} K^{\mp} \right] h^{\pm}$
- Suppressed: 550 candidates in Run 1
- Large interference; $8\sigma$ CPV (PLB 760 117)

### ‘GGSZ’ : $B^{\pm} \to \left[ K_{S}^{0} h^{+} h^{-} \right] h^{\pm}$
- Mod. indep.; 2,600 candidates in Run 1
- Reduced $\gamma$ ambiguity (JHEP 1410 097)

### TD : $B^{0}_{s} \to D^{\pm}_{s} K^{\mp}$
- 1,800 candidates in $1\, fb^{-1}$ (JHEP 1411 060)
- Measures $\gamma - 2\beta_s$; $B^{0}_{s} \to J/\psi hh$ input

### Many more
- ADS/(pseudo-)GLW 2/4 body (PLB 760 117)
- GLS $B \to (K_{S}^{0} K^{\mp} \pi^{\pm})K$ (PLB 733 36)
- ADS $B^{0} \to DK^{*0}$ (PRD 90 112002)
- Dalitz $B^{0} \to [hh]_{D} K_{\pi}$ (PRD 93 112018)
- ADS $B^{0} \to [hh\pi^{0}]_{D} K$ (PRD 91 112014)
- GGSZ $B^{0} \to DK^{*0}$ (JHEP 06 131)
- ADS/GLW $B^{\pm} \to DK^{*\pm}$ (LHCb-CONF 2016 014)
The UT angle $\gamma$ 

$B^+$ combination 

$B^0$ combination 

$r^{DK}_B = 0.1019 \pm 0.0056$

$\delta^{DK}_B = (142.6^{+5.7}_{-6.6})^\circ$

$r^{DK*0}_B = 0.218^{+0.045}_{-0.047}$

$\delta^{DK*0}_B = (189^{+23}_{-20})^\circ$
The UT angle $\gamma$

Result for $\gamma^{(\text{JHEP 12 087})}$

- Improves the previous LHCb-only determination by 2°
- Reaches Run 1 target sensitivity; LHCb dominates world average
- Good agreement with the B-factory results:
  - BaBar: $\gamma = (70 \pm 18)^\circ$
  - Belle: $\gamma = (73^{+13}_{-15})^\circ$

Overall, $\gamma = 72.2^{+6.8}_{-7.3}$
The UT angle $\gamma$

Need $\sigma^{\text{direct}}(\gamma) < 1^\circ$ to match indir. determination ($\sigma_{\text{LQCD}}$ will fall more)

Statistical uncertainties:

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>Units of Run-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Run 2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Upgrade</td>
<td>$\sim 50$</td>
<td>$\sim 60$</td>
</tr>
<tr>
<td>Phase-2 Upgrade</td>
<td>$\sim 300$</td>
<td>$\sim 360$</td>
</tr>
</tbody>
</table>

$\sigma(b\bar{b}) \rightarrow 2\sigma(b\bar{b}); \uparrow \epsilon(\text{trig/offline})$

$\epsilon_{\text{hadrons}} \rightarrow 2\epsilon_{\text{hadrons}}$

$\epsilon_{\text{trig}} \rightarrow 2\epsilon_{\text{trig}}$
The UT angle $\gamma$

Need $\sigma^{\text{direct}}(\gamma) < 1^\circ$ to match indir. determination ($\sigma_{\text{LQCD}}$ will fall more)

- Some channels’ $\sigma(\gamma) \sim 1^\circ$; compare species/modes (tree-level NP)
- LHCb and Belle II precision similar in the Upgrade period

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_{\text{stat}}(\gamma)^[\circ]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>8</td>
</tr>
<tr>
<td>Run 2</td>
<td>4</td>
</tr>
<tr>
<td>Upgrade</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>Phase-2 upgrade</td>
<td>$&lt; 0.5$</td>
</tr>
</tbody>
</table>

HFLAV Winter 2016

(arXiv:1612.07233)
Prospects for existing systematic uncertainties:

- Diverse systematic uncertainty exposure
  - GGSZ: Dalitz efficiency. Insensitive to \( B \) prod or \( K \) det. asymmetry
  - ADS/GLW: inst. charge asymmetries/PID
  - TD: decay time resolution/acceptance
  - Differences between methods (systematic?) or modes (NP?)
- One’s signal is another’s background: constrain CPV in part. reco. modes
- Improved precision on charm inputs (more later)
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Must account for:

- Mixing and CPV in the kaon system (as we do for charm) and regeneration effects
- Correlations between systematic uncertainties in different modes
The UT angle $\gamma$

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Increased statistics and detector capability: power in combination

- Improved calorimetry for exploitation of $\pi^0$ $D$ final states or $D^{*0}$, $D_s^{*\pm}$
- Extended soft track reconstruction for higher multiplicity $B$ and $D$ final states
- Widen pool of modes: $D \to KK\pi\pi$, $D \to K_S^0\pi\pi\pi^0$, $B \to D^{*0}K$, $B_s^0 \to D_s^{*\pm}K$
Theoretically clean UT measurement

\[ \beta, \beta_s \]
The UT angle $\beta$

- Accessed via interference in $B^0$ mixing and decay
- Theory uncertainty due to mode-dependent role of penguin amplitudes
- Data-driven methods to control penguin pollution

Indirect determination (CKMfitter): $\sin(2\beta) = 0.7094^{+0.0098}_{-0.0094}$

\[\sin(2\beta) \equiv \sin(2\phi_1)\]
The UT angle $\beta$

- CKM hierarchy in $b \to c\bar{c}s$ transitions
  $\Rightarrow$ negligible theory uncertainty
  $\Rightarrow$ ‘gold-plated’ mode $B^0 \to J/\psi K^0_s$
- TD flavour tagged ($\epsilon_{\text{eff}} = 3\%$) Run 1 study of 42,000 $B^0, \bar{B}^0$ decays (PRL 115 031601)

Systematic uncertainties

- Main $\sigma_{\text{syst}}(S_{J/\psi K^0_s})$: possible bg tagging asymmetry ((2.5%). Others < 1%
- Main $\sigma_{\text{syst}}(C_{J/\psi K^0_s})$: $\Delta m$ input ((10%)).
  FT calib & z-scale ((7%))

Approaching B-factory precision:
$S = 0.731 \pm 0.035 \pm 0.020$; $C = -0.038 \pm 0.032 \pm 0.005$ $\Rightarrow \sin(2\beta) = 0.746 \pm 0.030$

Contribution of sub-dominant amplitudes well below experimental uncertainties ($\mathcal{O}(\%)$)

D. Johnson (CERN)
Phase 2 upgrade CPV at LHCb
29th May 2017
The UT$_s$ angle $\beta_s$

- CPV phase in int. between $B^0_s$ mixing and decay (assume $|q/p| = 1$ for now)
- Unlike $B^0$, $\Delta \Gamma/\Gamma$ not small; access $\beta_s$ in TD & untagged effective-lifetime studies
- Data-driven methods to control penguin pollution; $\phi_s \approx -2\beta_s$

Indirect determination (CKMfitter): $\beta_s = 0.01852 \pm 0.00032$
The UT$_s$ angle $\beta_s$

- Again, smallest theory uncertainty in $b \to c\bar{c}s$ transitions
- $B_s^0 \to J/\psi \phi$: Run 1 TD, tagged ang. analysis 96k $B_s^0 \to J/\psi K^+K^-$ ($\epsilon_{\text{eff}} = 3.9\%$)
  - $B \to VV$: ang. analysis disentangles CP odd/even components (PRL 114 041801)
- $B_s^0 \to J/\psi \pi^+\pi^-$: Run 1 TD analysis 22k signal candidates ($\epsilon_{\text{eff}} = 3.9\%$)
  - Final state found to be dominantly CP-even (PLB 736 186)

**Systematic uncertainties**

- Largest $\sigma_{\text{syst}}(\phi_s^{J/\psi K^+K^-})$: MC sample for angular efficiency ($< 0.1\sigma_{\text{stat}}$)
- Largest $\sigma_{\text{syst}}(\phi_s^{J/\psi \pi^+\pi^-})$: Production asymmetry & amp. model ($< 0.1\sigma_{\text{stat}}$)

$$\phi_s^{c\bar{c}s} = -0.010 \pm 0.039 \text{ rad}$$

Contribution of sub-dominant amplitudes well below experimental uncertainties ($O(\%)$)
The UT angles $\beta, \phi_s$

**Phase 2 penguin pollution:**

No immediate show-stoppers

- $\phi_s$ DCS penguin will be important
  - Assuming SU(3); pollution studied in $B^0 \rightarrow J/\psi \rho^0$ and $B_s^0 \rightarrow J/\psi \bar{K}^*0$ (PLB 742 38) (JHEP 11 082)
    - $\Delta \phi_s = 1.4^{+9.8}_{-12.6}^{+2.6} \text{ mrad}$
  - Expect control Phase 2 pollution: $\sigma(\phi_s) = 0.9 \text{ (stat)}, 1.2 \text{ (syst)} \text{ mrad}$

- Control $\beta$ penguin pollution using SU(3) and $B_s^0 \rightarrow J/\psi \rho^0$; will be a challenge in Phase 2
The UT angles $\beta$, $\phi_s$

**Systematic uncertainties:**
Well controlled. No problems anticipated, even at Phase 2:

- Apply full angular analysis to $B_s^0 \rightarrow J/\psi \pi^+\pi^-$ as for $B_s^0 \rightarrow J/\psi \phi$
- Model-independent $S$-wave description in $J/\psi \pi^+\pi^-$
- High pile-up $\Rightarrow$ maintain PV association & decay time resolution
- Lower momentum reconstruction $\Rightarrow$ improved flavour-tagging
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**Exploiting new modes in the high statistics era**

- Already widening the net:
  - $B_s^0 \to D_s^+ D_s^- : \phi_s^{c\bar c s} = 0.02 \pm 0.17 \pm 0.02 \text{ rad (PRL 113 211801)}$
  - $B^0 \to D^+ D^- : S = -0.54^{+0.17}_{-0.16} \pm 0.05, \quad C = 0.26^{+0.18}_{-0.17} \pm 0.02 \text{ (PRL 117 261801)}$
    - $\epsilon_{\text{eff}} = 8.1\%$
    - Benefit from upgrade $\epsilon_{\text{hadrons}}^{\text{trigger}}$
  - Penguin-free $B^0 \to D_{CP} \pi^+ \pi^-$

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- Wide range of $b \rightarrow q\bar{q}q'$ transitions;
  - differing penguin roles: $B_s^0 \rightarrow \phi \phi, B_s^0 \rightarrow K^* \bar{K}^*, B_s^0 \rightarrow K_S^0 K \pi$
  - improved calorimetry: $B_s^0 \rightarrow (J/\psi \rightarrow e^+ e^-) \phi$, penguins in $B_{s,d}^0 \rightarrow J/\psi \pi^0$
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  - differing penguin roles: $B^0 \to \phi \phi, B^0 \to K^* \bar{K}^*, B^0 \to K^0_S K \pi$
  - improved calorimetry: $B^0 \to (J/\psi \to e^+ e^-) \phi$, penguins in $B^0_{s,d} \to J/\psi \pi^0$
- In the $\sigma(\gamma) < 1^\circ$ era, $B^0_s \to D_s^{\pm} K^{\mp}$ constrains $\beta_s$ without penguin pollution
CP violation in Charm
CPV in charm

- SM predicts small mixing and $\mathcal{O}(10^{-3})$ CPV
- Mixing firmly established (significant $y \neq 0$ a good start for indirect CPV searches)
- CPV remains elusive:
  - **Direct**: charged $c$–hadrons or time-integrated $D^0$
  - **Indirect**: time-dependent $D^0$

**LHCb competes with B-factories:**
  - time resolution
  - huge LHC $\sigma_{\text{prod}}(c\bar{c})$

### Evolution of LHCb sensitivity (beginning from the W.A.)

|       | $x(10^{-3})$ | $y(10^{-3})$ | $|q/p|(10^{-3})$ | $\Phi$(mrad) |
|-------|--------------|--------------|-----------------|-------------|
| Run 1 | 1.2          | 0.5          | 59              | 89          |
| Run 2 | 0.9          | 0.4          | 44              | 70          |
| Upg.  | 0.2          | $<0.1$       | 8               | 14          |
| Phase2| 0.09         | $<0.05$      | 4               | 6           |
CPV in charm

**Searching for direct CPV**: focus on Cabibbo suppressed decays

1. Isolate $D^0 \rightarrow h^+ h^-$ direct component & reduce systematics:

Approaching the SM threshold \(\textit{PRL 116 191601}\)

\[ \Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+) = (-0.10 \pm 0.08 \pm 0.03)\% \]

2. Charged $D^\pm$ and $D_s^\pm$ decays

Most precise results are \(\textit{JHEP 10 025}\)

\[ \Delta A_{D^+ \rightarrow K_S^0 K^+} = (0.3 \pm 1.7 \pm 1.4) \times 10^{-3} \text{ and } \Delta A_{D_s^+ \rightarrow K_S^0 \pi^+} = (3.8 \pm 4.6 \pm 1.7) \times 10^{-3} \]

**In the Phase 2 era:**

- Low momentum track reconstruction: significant statistics increase
- Improved calorimetry: searches for CPV in, e.g., $D^0 \rightarrow \phi \gamma$, $D^0 \rightarrow \rho \gamma$
- Continued need for high statistics PID calibration samples
- Reco. asymmetries: continued reliance on absence of CPV in CF modes? Magnetic field reversal? Partial/full reconstruction methods may provide solutions.
CPV in charm

Searching for **indirect** CPV

1. Small $x, y \Rightarrow$ simple modifications to $D^0$ decay rate parameters: $y_{CP}, A_\Gamma$

$10^{-4}$ precision with well-controlled systematic uncertainties (arXiv:1702.06490)

$$A_\Gamma(D^0 \rightarrow K^- K^+) = (-3.0 \pm 3.2 \pm 1.4) \times 10^{-4},$$

$$A_\Gamma(D^0 \rightarrow \pi^+ \pi^-) = (4.6 \pm 5.8 \pm 1.6) \times 10^{-4}$$

2. TD analysis of $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

Determines $x, y, |q/p|, \phi_D$ (JHEP 04 033)

Mixing analysis: $x = (-8.6 \pm 5.3 \pm 1.7) \times 10^{-3}, y = (0.3 \pm 4.6 \pm 1.3) \times 10^{-3}$

In the Phase 2 era:

- Golden $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ mode will be stats limited
- Any non-zero signal with current precision would indicate NP
Encore: Charm for Beauty

Charm inputs for model-independent $\gamma$ at LHCb
Where will $\gamma$ become limited:

- Most $^1 \ B \to DK$ modes rely on CLEO strong phase measurements at the $\psi(3770)$
- Allows for model independence; crucial in the high-statistics era
- Current systematic due to CLEO inputs $\sim 2^\circ$
- Some $D$ modes not analysed by CLEO; some would benefit from $D$-phasespace-binned analysis

Available now:

- Quadruplication of the CLEO dataset at BES III ($\to$ systematic $\sim 1^\circ$)
  - Measurement in $D \to K\pi$ (Int.J.Mod.Phys.Conf.Ser. 31 1460305)
  - Preliminary results in $D \to K_S^0 \pi\pi$

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$^1$not, e.g., $B_s^0 \to D_s^+ K$
Alternative sources of charm information?

- Additional BES III run at $\psi(3770)$ - under consideration - gives $\sigma(\gamma) \sim 0.5^\circ$
- Exploit enormous LHCb charm samples? Require $\sim 1$ LHCb-upgrade of charm to match already available BES III sample, though good prospects remain via mixing measurements
- Float the charm parameters in the $\gamma$ combination?
  - Lose $\gamma$ precision
  - Reduce ability to compare decay modes

Best outcome:
- Full suite of charm inputs measured with current and future BES III datasets
Conclusion

**Beauty**

- Great progress in probing SM, but considerable space for NP remains
- LHCb will drive tree-level CPV ($\gamma$) precision through Phase 2 to sub-degree precision
- Vital role of BESIII in providing charm inputs
- Precise measurements of CPV in $B$-mixing; penguin pollution under control

**Charm**

- Direct and indirect CPV searches already probing SM territory
- No show-stoppers approaching Phase 2

Improvements in calorimetry and low-momentum track reconstruction will open up many little-explored modes