CP violation in B decays at LHCb

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Barcelona, Spain
July 23rd, 2018

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01 - INTRODUCTION

02 - MEASUREMENT OF THE CKM ANGLES
\[ \gamma, \beta, \beta_s \]

03 - CP VIOLATION IN CHARMLESS DECAYS
- \( B_s^0 \to \phi\phi \)
- \( B_s^0 \to (K^+\pi^-)(K^-\pi^+) \)
- \( B_{(s)}^0 \to hh' \)

04 - CP VIOLATION IN BARYON DECAYS
\[ \Lambda_b^0 \to ph \]

05 - SUMMARY
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04 - CP VIOLATION IN BARYON DECAYS
\[ \Lambda_b^0 \rightarrow ph \]

05 - SUMMARY
The huge matter/anti-matter asymmetry in the Universe remains unexplained. Precision measurements of CPV allow to constrain possible New Physics models.

**CP violation in the Standard Model**

- The only source of CP violation in the SM comes from the **CKM matrix**, governing the quark mixing.
- Unitarity matrix. → **Unitarity triangles**.

\[
\begin{pmatrix}
1 - \lambda^2/2 & \lambda & \lambda^3(\rho - \eta) \\
-\lambda & 1 - \lambda^2/2 & -\lambda^2 \\
\lambda^3(1 - \rho - \eta) & -\lambda^2 & 1
\end{pmatrix}
\]

\[B^0\] and \([B^0_s]\]
Types of CP violation

- **CP violation in the decay** (A)
  - \( |A_f / \bar{A}_f| \neq 1 \)
- **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
  - \( \text{Im} \left( \frac{q}{p} \frac{\bar{A}_f}{A_f} \right) \neq 1 \)

**Measure CP violating parameters**

- \( \frac{\bar{A}_f - A_f}{\bar{A}_f + A_f} = \frac{C_f \cos(\Delta m t) - S_f \sin(\Delta m t)}{\cosh(\frac{\Delta \Gamma t}{2}) + D_f \sinh(\frac{\Delta \Gamma t}{2})} \)
- \( S_f, D_f \): CPV in the interference
- \( C_f \): CPV in decay
Excellent track and vertex reconstruction, good PID separation, flexible trigger.

- Decay-time resolution: $\sim 45$ fs.
- Flavour tagging power: $4 - 8\%$. 

**The LHCb experiment**

**the LHCb detector**

TODAY’S AGENDA

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The CKM angle $\gamma$

$\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$

Until very recently, the angle $\gamma$ was the least known in the UT (now caught up with $\alpha$)

It can be measured in tree level decays $\Rightarrow$ Theoretically very clean.

Very small theoretical uncertainty, $|\delta \gamma| \lesssim \mathcal{O}(10^{-7})$ [JHEP 1401 (2014) 051].

- $\gamma$ can probe for new physics at extremely high energy scales [arXiv:1308.5663]
  - (N)MFV new physics scenarios: $\sim \mathcal{O}(10^2)$ TeV
  - gen. FV new physics scenarios: $\sim \mathcal{O}(10^3)$ TeV

- NP contributions to $C_{1,2}$ can cause sizeable shifts ($\mathcal{O}(4^\circ)$) in $\gamma$ [arXiv:1412.1446]

Experimentally more challenging.
Several methods offer complementary sensitivity.

- GLW - CP eigenstates e.g. $D \to KK, \pi\pi$

- ADS - Cabibbo favoured and doubly Cabibbo suppressed decays e.g. $D \to K\pi, \pi K$

- GGSZ - Three-body self-conjugate decays e.g. $D \to K_S^0\pi\pi$

- Time-dependent B decays e.g. $B_s^0 \to D_s^- K^+$

- Dalitz - Three-body B decays e.g. $B^0 \to DK^+\pi^-$

In the next slides:

Two selected analyses:

$B^\pm \to D K^\pm$ & $B^0 \to D^{\mp}\pi^\pm$

+ New LHCb combination
\[ B^\pm \rightarrow D K^\pm \ (D \rightarrow K_S^0 h^+ h^-) \]

[Model independent GGSZ method]

**Method:** simultaneous DK\(^\pm\) mass fits in decay & bin categories, accounting for backgrounds and efficiencies.

\[
N^{+}_{\pm i} = h_{B^+} (F_{\mp i} + (x^2_+ + y^2_+) F_{\pm i}) + 2 \sqrt{F_i F_{-i}} (x_+ c_{\pm i} + y_+ s_{\pm i})
\]

\[
N^{-}_{\pm i} = h_{B^-} (F_{\mp i} + (x^2_- + y^2_-) F_{\mp i}) + 2 \sqrt{F_i F_{-i}} (x_- c_{\pm i} + y_- s_{\pm i})
\]

- Fraction of \( D^0 \) and \( \bar{D}^0 \) in each bin (from semileptonic control sample)
- Strong phase measurements from CLEO-c measurements of QC \( D^0 \bar{D}^0 \) decays
- The parameters of interest!

**Model independent**

\[ \gamma = 80^\circ \pm 10^\circ \ (19^\circ) \]

[arXiv:1806.01202]  
Update with Run 2

LHCb

Run 1
2015 & 2016 data
Combined result

\[ \gamma = 80^\circ \pm 10^\circ \ (19^\circ) \]
\[ B^0 \rightarrow D^\mp \pi^\pm \ (D^\mp \rightarrow K^\pm \pi^\pm \pi^\pm) \]

[Time-dependent analysis]

\[
A_f(t) = \frac{\Gamma_{B^0 \rightarrow f}(t) - \Gamma_{\bar{B}^0 \rightarrow f}(t)}{\Gamma_{B^0 \rightarrow f}(t) + \Gamma_{\bar{B}^0 \rightarrow f}(t)} = \frac{C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta \Gamma/2 t) + A_f^{\Delta \Gamma} \sinh(\Delta \Gamma/2 t)}
\]

**Method:** decay-time fit to background-subtracted data, using FT, time acceptance and resolution obtained in a data-driven way.

Largest flavor-tagged sample at LHCb! (~500 K events)

\[
C_f = \frac{1 - r^2}{1 + r^2} = -C_{\bar{f}} \approx 1
\]

\[
S_f = -\frac{2r \sin[\delta - (2\beta + \gamma)]}{1 + r^2}
\]

\[
S_{\bar{f}} = \frac{2r \sin[\delta + (2\beta + \gamma)]}{1 + r^2}
\]

Intervals (at 68% CL):

\[
| \sin(2\beta + \gamma) | \in [0.77, 1.0] \\
\gamma \in [5, 86]^{\circ} \cup [185, 266]^{\circ} \\
\delta \in [-41, 41]^{\circ} \cup [140, 220]^{\circ}
\]
New LHCb combination

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Dataset</th>
<th>Status since last combination</th>
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<tbody>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW [14]</td>
<td>Run 1 &amp; 2</td>
<td>Minor update</td>
<td></td>
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<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>ADS [15]</td>
<td>Run 1</td>
<td>As before</td>
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<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+\pi^-\pi^+\pi^-$</td>
<td>GLW/ADS [15]</td>
<td>Run 1</td>
<td>As before</td>
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<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-\pi^0$</td>
<td>GLW/ADS [16]</td>
<td>Run 1</td>
<td>As before</td>
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<td>$D \rightarrow K^0\pi^+\pi^-$</td>
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<td>Run 1</td>
<td>As before</td>
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<td>$D \rightarrow K^0\pi^+\pi^-$</td>
<td>GGSZ [18]</td>
<td>Run 2</td>
<td>New</td>
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<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K^0\pi^+\pi^-$</td>
<td>GLS [19]</td>
<td>Run 1</td>
<td>As before</td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow D^*K^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW [14]</td>
<td>Run 1 &amp; 2</td>
<td>Minor update</td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^{*+}$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW/ADS [20]</td>
<td>Run 1 &amp; 2</td>
<td>Updated results</td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^{*+}$</td>
<td>$D \rightarrow h^+\pi^-\pi^+\pi^-$</td>
<td>GLW/ADS [20]</td>
<td>Run 1 &amp; 2</td>
<td>New</td>
<td></td>
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<td>$B^+ \rightarrow DK^{*+}\pi^-$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW/ADS [21]</td>
<td>Run 1</td>
<td>As before</td>
<td></td>
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<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$D \rightarrow K^+\pi^-$</td>
<td>ADS [22]</td>
<td>Run 1</td>
<td>As before</td>
<td></td>
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<tr>
<td>$B^0 \rightarrow DK^{*+}\pi^-$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW-Dalitz [23]</td>
<td>Run 1</td>
<td>As before</td>
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<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$D \rightarrow K^0\pi^+\pi^-$</td>
<td>GGSZ [24]</td>
<td>Run 1</td>
<td>As before</td>
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<td>$B^0 \rightarrow D^0\pi^+$</td>
<td>$D^0 \rightarrow h^+\pi^-\pi^+$</td>
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<td>Run 1</td>
<td>Updated results</td>
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<tr>
<td>$B^0 \rightarrow D^*\pi^+$</td>
<td>$D^+ \rightarrow K^+\pi^-\pi^+$</td>
<td>TD [26]</td>
<td>Run 1</td>
<td>New</td>
<td></td>
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</table>

- Everything consistent at the 2 sigma level currently
- In the SM they should be the same - if NP appears it could affect the different species differently due to differing decay topologies

The current world average, LHCb combination and indirect measurement

$$\gamma = (73.5^{+4.2}_{-5.1})^\circ$$  $$\gamma = (76.8^{+5.1}_{-5.7})^\circ$$  $$\gamma = (65.3^{+1.0}_{-2.5})^\circ$$

- With 50 ab$^{-1}$ at Belle-II and a possible 300 fb$^{-1}$ sample at LHCb: $\sigma(\gamma) \approx 0.4^\circ$
The CKM angle $\beta$

$\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$

The $\beta$ angle can be measured in the interference between $B^0$ mixing and decay.

The golden channel is: $B^0 \to J/\psi K_s$

Using Run 1 data, LHCb reached the precision of Belle/BaBar.

New Run 1 LHCb analysis of $B^0 \to J/\psi(ee)K_s$ and $B^0 \to \psi(2S)(\mu\mu)K_s$ [JHEP 11 (2017) 170].

LHCb combination:

$C = -0.017 \pm 0.029, \quad S = 0.760 \pm 0.034$

$\sin(2\beta) \equiv \sin(2\phi_1)$

$\frac{1}{2}$
The CKM angle \( \beta_s \)

The \( \beta_s \) angle can be measured in the interference between \( B_s^0 \) mixing and decay.

The golden channel is: \( B_s^0 \rightarrow J/\psi \phi \)

\[ \phi_{s}^c \bar{c}s = -2\beta_s \]

Angular analysis needed to disentangle the CP eigenstates.

- Global fit: \( \phi_s^{c\bar{c}s} = -21 \pm 31 \text{ mrad} \) [HFLAV], dominated by the LHCb measurement [PRL 114, 041801 (2015)].
- Focus on analysing more data and studying the penguin pollution [JHEP 1503 (2015) 145].
- Stay tuned for the LHCb analysis of Run 2!
**Today's Agenda**

1. **Introduction**
2. **Measurement of the CKM Angles**
   - $\gamma, \beta, \beta_s$
3. **CP Violation in Charmless Decays**
   - $B_s^0 \rightarrow \phi\phi$
   - $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$
   - $B_{(s)}^0 \rightarrow hh'$
4. **CP Violation in Baryon Decays**
   - $\Lambda_b^0 \rightarrow ph$
5. **Summary**
CP violation in $B^0_s \rightarrow \phi \phi$

Penguin dominated decay

Sensitivity to NP not only in mixing but also in decay.

Theoretical expectations:

QCD Factorisation (QCDf) predictions:

$|\phi^{s\bar{s}s}| < 0.02 \text{ rad}, \ A_{CP} = (0.2^{+0.6}_{-0.4})\%,$

$\ f_L = 0.36^{+0.23}_{-0.18}$


LHCb analysis: measure

time-dependent CP asymmetries,

polarization fractions and

triple-product asymmetries.

$U = \cos\Phi \times \sin\Phi$

$V = \eta_{\theta} \times \sin\Phi$

$A_U = \frac{N(U > 0) - N(U < 0)}{N(U > 0) + N(U < 0)}$

$A_V = \frac{N(V > 0) - N(V < 0)}{N(V > 0) + N(V < 0)}$
CP violation in $B_{s}^{0} \rightarrow \phi \phi$

Method: decay-time-dependent angular fit to background-subtracted data, using FT, angular acceptance (from simulation), and time acceptance and resolution (data-driven).

Combined with Run 1:

$$\phi_{s}^{s\bar{s}s} = -0.06 \pm 0.13 \text{ (stat)} \pm 0.03 \text{ (syst)} \text{ rad}$$

$$|\lambda| = 1.02 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (syst)}.$$

$$A_{U} = 0.0 \pm 1.2 \text{ (stat)} \pm 0.4 \text{ (syst)} \%$$

$$A_{V} = -0.3 \pm 1.2 \text{ (stat)} \pm 0.4 \text{ (syst)} \%$$

Compatible with no CPV and with the SM

Red: $CP$-even $VV$

Green: $CP$-odd $VV$

Purple: $SV + SS$

Julián García Pardiñas (UZH)  CPV in B decays at LHCb  SUSY 2018
**CPV in** $B^0_s \rightarrow (K^+\pi^-)(K^-\pi^+)$

$B^0_s \rightarrow K^{*0}(K^+\pi^-)\overline{K}^{*0}(K^-\pi^+)$ is another $P \rightarrow VV$ penguin-dominated decay.

Expected effective CPV phase: $\phi_s^{sdd} \sim 0$ rad [PRL 100, 031802].

Possibility to reduce the theoretical uncertainty on the phase using $B^0 \rightarrow K^{*0}\overline{K}^{*0}$.

QCDf predictions: $A_{CP} = (0.4^{+1.0}_{-0.6})\%$, $f_L = 0.56^{+0.22}_{-0.27}$ [Phys. Rev. D 80, 114026]

Several decays studied together using a large $M(K\pi)$ window.

### Channel | Decay | Polarization amplitudes
---|---|---
Channel #1 | $B^0_s \rightarrow (K^+\pi^-)_0(K^-\pi^+_0)$ | SS
Channel #2 | $B^0_s \rightarrow (K^+\pi^-)_0K^*(892)^0(K^-\pi^+_0)$ | SV
Channel #3 | $B^0_s \rightarrow K^*(892)^0(K^-\pi^+_0)$ | VS
Channel #4 | $B^0_s \rightarrow (K^+\pi^-)_0K^*_0(1430)^0$ | ST
Channel #5 | $B^0_s \rightarrow K^*_0(1430)^0K^*(892)^0(K^-\pi^+_0)$ | TS
Channel #6 | $B^0_s \rightarrow K^*_0(1430)^0K^*(892)^0(K^-\pi^+_0)$ | VV0, VV||, VV⊥
Channel #7 | $B^0_s \rightarrow K^*(892)^0K^*_0(1430)^0$ | V0T, VT||, VT⊥
Channel #8 | $B^0_s \rightarrow K^*_0(1430)^0K^*(892)^0$ | TV0, TV||, TV⊥
Channel #9 | $B^0_s \rightarrow K^*_0(1430)^0K^*_0(1430)^0$ | TT0, TT||1, TT⊥1, TT||2, TT⊥2

### Method: time-dependent angular and $M(K\pi)$ fit to background-subtracted data, using FT, angular, mass and time acceptance and time resolution (from simulation).

\[
\phi_s^{sdd} = -0.10 \pm 0.13 \text{ (stat)} \pm 0.14 \text{ (syst) rad}
\]

\[
|\lambda_{CP}| = 1.035 \pm 0.034 \text{ (stat)} \pm 0.089 \text{ (syst)}
\]

\[
f_L = 0.208 \pm 0.032 \text{ (stat)} \pm 0.046 \text{ (syst)}
\]

First measurement.
Compatible with no CPV and with the SM (apart from some tension in $f_L$)
Indirect determination of CKM phases

- The study of time-dependent CP violation in $B_{(s)}^0 \rightarrow hh'$ allows the determination of $\gamma$ and $-2\beta_s$ (also $\alpha$, when extra input is added) using loop-mediated decays.
- Presence of loop-diagrams $\implies$ sensitivity to New Physics.

New LHCb measurement using Run 1 data:
- Measure time-dependent asymmetries in $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$. 
- Measure time-integrated asymmetries in $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$. 
CP violation in $B^0_{(S)} \rightarrow hh'$

Method: fit with FT to the decay-time and M(hh') data distributions, simultaneously on $\pi\pi$, $KK$ and $K\pi$. Decay-time acceptance and resolution obtained in a data-driven way.

Most precise measurements from a single experiment. ($C_{K+K-}, S_{K+K-}, A^\Delta_{K+K-}$) deviates 4.0 $\sigma$ from (0, 0, -1) $\implies$ Strongest evidence for time-dependent CP violation in the $B^0_s$ sector!
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04 - CP VIOLATION IN BARYON DECAYS
\[ \Lambda_b^0 \rightarrow ph \]

05 - SUMMARY
CP violation in $\Lambda^0_b \to p\phi$

Previously, first evidence of CPV in a beauty baryon decay, $\Lambda^0_b \to p\pi^-\pi^+\pi^-$
[Nature Physics 13, 391-396 (2017)].

Direct CPV in $\Lambda^0_b \to pK^-$ and $\Lambda^0_b \to p\pi^-$ had only been measured by CDF.

Method: fit to M(hh'), simultaneously on $p\pi$ and $pK$. Production and detection asymmetries are accounted for.

$\sim 8.8k \Lambda^0_b \to pK^-$

$\sim 6.0k \Lambda^0_b \to p\pi^-$

$A^pK_{CP} = -0.020 \pm 0.013 \pm 0.019$

$A^{p\pi}_{CP} = -0.035 \pm 0.017 \pm 0.020$

Compatible with no CPV. Main syst. uncertainty from production asymmetry.

Main systematic cancels

$$\Delta A_{CP} \equiv A_{CP}^{pK^-} - A_{CP}^{p\pi^-} = 0.014 \pm 0.021 \pm 0.013$$

Error reduced by more than x4 with respect to CDF 😊
Today's agenda

01 - Introduction

02 - Measurement of the CKM angles
\[ \gamma, \beta, \beta_s \]

03 - CP violation in charmless decays
- \( B^0_s \to \phi\phi \),
- \( B^0_s \to (K^+\pi^-)(K^-\pi^+) \),
- \( B^0_{(s)} \to hh' \)

04 - CP violation in baryon decays
\[ \Lambda^0_b \to ph \]

05 - Summary
Summary and outlook

Precision measurements of CPV offer a rich scenario to constrain potential New Physics models.

Several recent results presented in this talk.

So far, no clear deviation from the SM is found.

However, some tension on the measurement of the $\gamma$ angle. Entering the precision era for this observable.

There is still plenty of room for New Physics in CPV.

Even if some Run 2 analyses have already been released, many of them are just awaiting at the gates.

Stay tuned!