CP violation in b hadrons at LHCb

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On behalf of the LHCb collaboration
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Outline

- Interest on CP violation
- CPV in quark sector
- $b$ hadron CP measurements in LHCb
- Summary

Note: most results shown are based on full Run 1 data. Few of them include 2015+2016 Run 2 data
Why do we need CP violation?

- Excess of matter over antimatter in the universe, \((n(B) - n(B))/n(\gamma) \sim 10^{-10}\)

- For this to happen, Sakharov converged to three conditions
  
  - (a) Need for baryon number violating interactions
  
  - (b)Need for CP violation to insure that a process in (a) does not have a CP conjugate with the same probability
  
  - (c) Universe out of thermal equilibrium: thermal equilibrium would turn any baryon asymmetry back into even numbers of baryons and antibaryons.

*Note: CPV in Standard Model is far off the requirement*
CPV in the quark sector

Weak eigenstates different from mass eigenstates:
Cabibbo Kobayashi Maskawa matrix

\[ V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \]

Clear hierarchy in the couplings: the further from diagonal, the weaker the element

QFT shows that from \( N = 3 \) generations, 1 CP violating phase is possible

Unitarity of CKM matrix imposes in particular

\[ \sum_{k} V_{ik} V_{jk}^* = 0 \]

Most convenient relation:

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]

Sides usually measured in semileptonic decays and oscillation frequency, angles in CP asymmetries

\[ V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0 \]

Most convenient relation:

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]

Sides usually measured in semileptonic decays and oscillation frequency, angles in CP asymmetries

\[ B^0_d \rightarrow J/\psi K_S \]

“Bs triangle” (very squeezed)

\[ B^0_s \rightarrow J/\psi h^+ h^- \]
CP violation, decay vs oscillations

Amplitudes:
- \( B \rightarrow f \) \( A_f = \langle f | H_{\text{eff}} | B \rangle \)
- \( \bar{B} \rightarrow \bar{f} \) \( \bar{A}_{\bar{f}} = \langle \bar{f} | H_{\text{eff}} | \bar{B} \rangle \)
- \( B \rightarrow \bar{f} \) \( A_{\bar{f}} = \langle \bar{f} | H_{\text{eff}} | B \rangle \)
- \( \bar{B} \rightarrow f \) \( \bar{A}_f = \langle f | H_{\text{eff}} | \bar{B} \rangle \)

1) CP violation in the decay \( A(\bar{B} \rightarrow \bar{f}) \neq A(B \rightarrow f) \)
Charged \( B \) or flavor-specific final state + at least two contributions to the amplitude \( A \) with different weak and strong phases

2) CP violation in the mixing \( A(B^0 \rightarrow B^0) \neq A(B^0 \rightarrow \bar{B}^0) \) : different measurement techniques. In LHCb, use of flavor-specific state and compare «wrong-sign » decays occurring because of the mixing. \( A(\bar{B}^0 \rightarrow B^0 \rightarrow f) \neq A(B^0 \rightarrow \bar{B}^0 \rightarrow \bar{f}) \). Typically: \( f = X \ell^- \nu \)

3) Combination of decay and mixing: needs CP final state accessible by both \( \bar{B}^0 \) and \( B^0 \). Induced by interference of \( B^0 \rightarrow \bar{B}^0 \rightarrow f_{\text{CP}} \) and \( B^0 \rightarrow f_{\text{CP}} \). Needs the tagging of the flavor of \( B \) at the production!
Measurement of CKM angles such as \( \beta, \beta_s \)
CP violation formulas

\[ A_f = A_1 e^{i\delta_1} e^{i\phi_1} + A_2 e^{i\delta_2} e^{i\phi_2} \]
\[ \delta_i \text{ strong phase} \]
\[ \phi_i \text{ : weak phase} \]

\[ A_{CP} = \frac{|A_f|^2 - |A_f|^2}{|A_f|^2 + |A_f|^2} \propto 2 A_1 A_2 \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \]
\[ \text{Non zero decay CP asymmetry requires } > 1 \text{ contribution} \]

Mixing + decay CP asymmetry

\[ A^q_{sl} = \frac{\Gamma(\bar{B}_q^0 \rightarrow B_q^0 \rightarrow f) - \Gamma(B_q^0 \rightarrow \bar{B}_q^0 \rightarrow \bar{f})}{\Gamma(\bar{B}_q^0 \rightarrow B_q^0 \rightarrow f) + \Gamma(B_q^0 \rightarrow \bar{B}_q^0 \rightarrow \bar{f})} \approx \frac{\Delta \Gamma^q}{\Delta m_q} \tan\left(\phi^q_{12}\right) \]
\[ \text{Mixing phase } \sim 0 \text{ in SM} \]

Mixing + decay CP asymmetry

\[ A_{CP}(t) = \frac{\Gamma(B^0(t) \rightarrow f_{CP}) - \Gamma(\bar{B}^0(t) \rightarrow \bar{f}_{CP})}{\Gamma(B^0(t) \rightarrow f_{CP}) + \Gamma(\bar{B}^0(t) \rightarrow \bar{f}_{CP})} = \frac{S_f \sin(\Delta M_B t) - C_f \cos(\Delta M_B t)}{\cosh(\Delta \Gamma_B t/2) + A_f^{\Delta \Gamma} \sinh(\Delta \Gamma_B t/2)} \]

For hadrons with small \( \Delta \Gamma / \Gamma \):
\[ A_{CP}(t) \approx S_f \sin(\Delta M_B t) - C_f \cos(\Delta M_B t) \]

Weak phase = \( \phi_{\text{mix}} - 2\phi_{\text{decay}} \)
$\beta_s$ angle results from $b \rightarrow c\bar{c}s$ tree decays

Mixing + decay

$\phi_s^{SM} = -2\beta_s = -2 \arg \left( \frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right) = -0.036 \pm 0.001 \text{ rad}$

Phys. Rev. D91(2015) 073007

<table>
<thead>
<tr>
<th>Final state</th>
<th>Result (rad)</th>
<th>publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\Psi \pi\pi$ (incl $f_0$)</td>
<td>$+0.070 \pm 0.068 \pm 0.008$</td>
<td>PLB B736 186 (2014)</td>
</tr>
<tr>
<td>$D_s D_s$</td>
<td>$+0.02 \pm 0.17 \pm 0.02$</td>
<td>PRL113 211801 (2014)</td>
</tr>
<tr>
<td>$J/\Psi KK$ (incl $\phi$)</td>
<td>$-0.058 \pm 0.049 \pm 0.006$</td>
<td>PRL114 041802 (2015)</td>
</tr>
<tr>
<td>$\Psi(2S)\phi$</td>
<td>$+0.23 \pm 0.029 \pm 0.02$</td>
<td>PLB B762, 252-262 (2016)</td>
</tr>
<tr>
<td>$J/\Psi KK$ above $\phi$</td>
<td>$+0.119 \pm 0.107 \pm 0.034$</td>
<td>JHEP08 (2017) 037</td>
</tr>
</tbody>
</table>
\[ \beta_s \text{ angle result from } B_s \rightarrow J/\Psi \text{ KK above } \phi \]

**Mixing + decay**

Time-dependent, angular, amplitude analysis of the KK spectrum

**Control channel** \( B^0 \rightarrow J/\Psi K^*0(K^+\pi^-) \)

Spectrum \( m_{KK} > 1.05 \text{ GeV/c}^2 \) is dominated by the \( f_2(1525) \) tensor

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**For \( m_{KK} > 1.05 \text{ GeV/c}^2 \)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_s ) [ps(^{-1})]</td>
<td>( 0.650 \pm 0.006 \pm 0.004 )</td>
</tr>
<tr>
<td>( \Delta \Gamma_s ) [ps(^{-1})]</td>
<td>( 0.066 \pm 0.018 \pm 0.010 )</td>
</tr>
<tr>
<td>( \phi_s ) [mrad]</td>
<td>( 119 \pm 107 \pm 34 )</td>
</tr>
<tr>
<td>(</td>
<td>\lambda</td>
</tr>
</tbody>
</table>
\( \beta \) angle results from \( b \rightarrow ccs \) tree decays

\[
\phi_d^{SM} = 2\beta = 2\arg \left( \frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}} \right)
\]

\[
\sin (2\beta)^{SM} = 0.771^{+0.017}_{-0.041} \quad \text{Phys. Rev. D91(2015) 073007}
\]

**Known golden mode:** \( B^0 \rightarrow J/\Psi K_S^0 \)

**LHCb Run 1 measurement**

\[
\sin(2\beta) = 0.731 \pm 0.035 \text{(stat)} \pm 0.020 \text{(syst)} \quad \text{PRL 115, 031601 (2015)}
\]

Recent publication LHCb-PAPER-2017-029 with \( B^0 \rightarrow J/\Psi (ee) K_S^0 \) \( B^0 \rightarrow \Psi (2S)(\mu \mu) K_S^0 \) → about to be submitted

**Overall LHCb average for \( \sin(2\beta) \):**

\[
S(B^0 \rightarrow [c\bar{c}] K_S^0) = 0.760 \pm 0.034
\]
β angle results from $B^0 \rightarrow D^+D^-$

Recent LHCb measurement on $\phi_d + \Delta \phi$ with
$\Delta \phi = -0.16^{+0.19}_{-0.21}$: small contribution from higher order diagrams
Decays involving tree and loop diagrams: strong phases involved.

- U-spin symmetry: possibility to extract $2\beta_s$ or $\gamma$. Effects of U-spin symmetry breaking = limitation of the accuracy on the CKM angles

- Experimentally: simultaneous fit to 4 channels: $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow K^+\pi^-$, $B^0_s \rightarrow K^+K^-$, $B^0_s \rightarrow K^+\pi^-$. Thorough modeling of misID and suppressed modes.
$B^0_{(s)} \rightarrow hh$ CP fit results

Fit performed with $\Gamma$, $\Delta \Gamma$ and $\Delta m$ fixed

- $C_{\pi \pi} = -0.243 \pm 0.069$
- $S_{\pi \pi} = -0.681 \pm 0.060$
- $C_{KK} = +0.236 \pm 0.062$
- $S_{KK} = +0.216 \pm 0.062$
- $A_{KK}^{\Delta m} = -0.751 \pm 0.075$

LHCb-CONF-2016-018
\( \gamma \) from \( B \to DK(-\text{like})\), the idea

Interference between tree decays leading to the same final state

\( D^0 \) and \( \bar{D}^0 \) must decay to the same final state

Theoretically (very clean), \( \delta\gamma/\gamma \sim 10^{-7} \) (JHEP 1401 (2014) 051)

\( r_i \): amplitude ratios

\( \delta_i \): relative strong phases

In general: \( r_D \) and \( \delta_D \) used as external inputs
γ from B \to DK(-like), different techniques

**Decay**

- \( f_D = \text{CP eigenstates, } D^0 \to K^+K^-, \pi^+\pi^-, Ks\pi^0 \)
- \( f_D = \text{flavour states: } D^0 \to K^+\pi^-, K^-\pi^+ \)
  - Atwood, Dunietz, Soni (ADS) 1997
    - Extension to multiple body \( K^\pm\pi^-/\pi^+\pi^- \)
- **Multibody** \( KsK^{\pm}\pi^-/+, \) GLS
- \( f_D = \text{multibody final states, Dalitz (variation of } \delta_D \text{ over phase space) } \)
  - \( Ks\pi^-/+, \) Giri, Grossman, Soffer, Zupan 2003; Poluektov 2004 (GGSZ-P)
- Some most recent channels involve neutrals, \( B^0 \) and \( B_s \), and \( D^{*+} \) or \( K^*/K\pi(\pi) \) in the final state

**Observables:** charge asymmetries and BF ratios of suppressed/favoured \( D \) decays (applies for self-tagging decays)
Combination in LHCb: huge improvement in techniques and precision

Many channels under study in LHCb

- Using either CP, flavour, or multibody final states of D


<table>
<thead>
<tr>
<th>B decay</th>
<th>D decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Status since last combination [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^+ \to DK^+)</td>
<td>(D \to h^+h^-)</td>
<td>GLW</td>
<td>[16]</td>
<td>Updated to Run 1 2 fb(^{-1}) Run 2</td>
</tr>
<tr>
<td>(B^+ \to DK^+)</td>
<td>(D \to h^+h^-)</td>
<td>ADS</td>
<td>[17]</td>
<td>As before</td>
</tr>
<tr>
<td>(B^+ \to DK^+)</td>
<td>(D \to h^+\pi^-\pi^+\pi^-)</td>
<td>GLW/ADS</td>
<td>[17]</td>
<td>As before</td>
</tr>
<tr>
<td>(B^+ \to DK^+)</td>
<td>(D \to h^+h^-\pi^0)</td>
<td>GLW/ADS</td>
<td>[18]</td>
<td>As before</td>
</tr>
<tr>
<td>(B^+ \to DK^+)</td>
<td>(D \to K^0\bar{s}h^+h^-)</td>
<td>GGSZ</td>
<td>[19]</td>
<td>As before</td>
</tr>
<tr>
<td>(B^+ \to DK^+)</td>
<td>(D \to K^0\bar{s}K^+\pi^-)</td>
<td>GLS</td>
<td>[20]</td>
<td>As before</td>
</tr>
<tr>
<td>(B^+ \to D^*K^+)</td>
<td>(D \to h^+h^-)</td>
<td>GLW</td>
<td>[16]</td>
<td>New</td>
</tr>
<tr>
<td>(B^+ \to DK^{*+})</td>
<td>(D \to h^+h^-)</td>
<td>GLW/ADS</td>
<td>[21]</td>
<td>New</td>
</tr>
<tr>
<td>(B^+ \to DK^{+}\pi^+\pi^-)</td>
<td>(D \to h^+h^-)</td>
<td>GLW/ADS</td>
<td>[22]</td>
<td>As before</td>
</tr>
<tr>
<td>(B^0 \to DK^{*0})</td>
<td>(D \to K^+\pi^-)</td>
<td>ADS</td>
<td>[23]</td>
<td>As before</td>
</tr>
<tr>
<td>(B^0 \to DK^{+}\pi^-)</td>
<td>(D \to h^+h^-)</td>
<td>GLW-Dalitz</td>
<td>[24]</td>
<td>As before</td>
</tr>
<tr>
<td>(B^0 \to DK^{*0})</td>
<td>(D \to K^0\bar{s}\pi^+\pi^-)</td>
<td>GGSZ</td>
<td>[25]</td>
<td>As before</td>
</tr>
<tr>
<td>(B^0 \to D_s^{+})</td>
<td>(D_s^+ \to h^+h^-\pi^+)</td>
<td>TD</td>
<td>[26]</td>
<td>Updated to 3 fb(^{-1}) Run 1</td>
</tr>
</tbody>
</table>

\[ \gamma = (76.8^{+5.1}_{-5.7})^\circ \]

dominates the world average:

\((76.2^{+4.7}_{-5.0})^\circ\)

HFLAV, summer 2017
Recent study: $\gamma$ from $B^+ \rightarrow DK^{*+}(K_S\pi^+)$

Use 2 and 4 body $D^0$ modes, with Run1 + 2015 + 2016 data
Rates and CP asymmetries allow extraction of $r_B(DK^*)$, $\delta_B(DK^*)$, and $\gamma$

<table>
<thead>
<tr>
<th>$D$ decay mode</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow D(K^\pm \pi^\mp)K^{*\pm}$</td>
<td>2031 ± 49</td>
</tr>
<tr>
<td>$B^\pm \rightarrow D(K^+K^-)K^{*\pm}$</td>
<td>255 ± 18</td>
</tr>
<tr>
<td>$B^\pm \rightarrow D(\pi^+\pi^-)K^{*\pm}$</td>
<td>78 ± 11</td>
</tr>
<tr>
<td><strong>$B^\pm \rightarrow D(K^+\pi^\pm)K^{*\pm}$</strong></td>
<td><strong>20 ± 7</strong></td>
</tr>
<tr>
<td>$B^\pm \rightarrow D(K^+\pi^+\pi^-)K^{*\pm}$</td>
<td>1144 ± 37</td>
</tr>
<tr>
<td>$B^\pm \rightarrow D(\pi^+\pi^-\pi^+\pi^-)K^{*\pm}$</td>
<td>115 ± 13</td>
</tr>
<tr>
<td>$B^\pm \rightarrow D(K^+\pi^+\pi^-\pi^+)K^{*\pm}$</td>
<td>13 ± 7</td>
</tr>
</tbody>
</table>

\[ R_{K\pi}^\pm = \frac{\Gamma(B^\pm \rightarrow D(K^\pm \pi^\mp)K^{*\pm})}{\Gamma(B^\pm \rightarrow D(K^\pm \pi^\mp)K^{*\pm})} = \frac{r_B^2 + (r_{K\pi}^D)^2 + 2\kappa r_B r_{K\pi}^D \cos(\delta_B + \delta_{K\pi}^D \pm \gamma)}{1 + r_B^2 (r_{K\pi}^D)^2 + 2\kappa r_B r_{K\pi}^D \cos(\delta_B - \delta_{K\pi}^D \pm \gamma)} \]

4.2σ evidence for suppressed $D^0 \rightarrow K\pi$

Charge asymmetry visible by eye

\[ R_{K\pi}^+ = 0.020 \pm 0.006 \text{ (stat)} \pm 0.001 \text{ (syst)} \]

\[ R_{K\pi}^- = 0.002 \pm 0.004 \text{ (stat)} \pm 0.001 \text{ (syst)} \]

$\kappa$: dilution factor due to $K_S\pi$ nonres component in $K^*$ spectrum
CP violation in baryon decays $\Lambda_b \rightarrow p\pi hh$

CPV seen in B and K decays, never in baryons

Search for direct CPV in $\Lambda_b \rightarrow p\pi hh$ decays

Relative weak phase: $\alpha$

Look at triple scalar products

$$C^T = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+})$$

$$\overline{C}^T = \vec{p}_p \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})$$

$C^T \neq -\overline{C}^T$ establishes CP violation

See e.g., Phys. Rev. D 84, 096013 (2011)

$$A_T(C^T) = \frac{N(C^T > 0) - N(C^T < 0)}{N(C^T > 0) + N(C^T < 0)}$$

$$\overline{A}_T(\overline{C}^T) = \frac{\overline{N}(-\overline{C}^T > 0) - \overline{N}(-\overline{C}^T < 0)}{\overline{N}(-\overline{C}^T > 0) + \overline{N}(-\overline{C}^T < 0)}$$

Observable measuring CPV:

$$a_{CP}^{T-\text{odd}} = \frac{1}{2} \left( A_T - \overline{A}_T \right)$$

arXiv:1508.03054
First observation of both $\Lambda_b \rightarrow p\pi KK$ and $\Lambda_b \rightarrow p\pi\pi\pi$

Overall $3.3\sigma$ CP violation found for $\Lambda_b \rightarrow p\pi\pi\pi$

First evidence of CP violation in baryon decays

No CP violation for $\Lambda_b \rightarrow p\pi KK$

$C_T \propto \sin(\Phi)$
\[ A_{sl} \text{ asymmetries} \]

\[
\frac{N(B_q^0 \to D_{(s)}^- \mu^+ \nu, t) - N(B_q^0 \to D_{(s)}^+ \mu^- \nu, t)}{N(B_q^0 \to D_{(s)}^- \mu^+ \nu, t) + N(B_q^0 \to D_{(s)}^+ \mu^- \nu, t)} = A_D + \frac{A_{sl}^q}{2} - (A_P + \frac{A_{sl}^q}{2}) \cdot \frac{\cos(\Delta M_q t)}{\cosh(\Delta \Gamma_q t/2)}
\]

Detection asymmetry (inferred from control samples)

\[ A_{sl}^{s,d} \sim 10^{-5}, 10^{-4} \text{ in SM} \]

LHCb measures:

\[ A_{sl}^d = \left( -0.02 \pm 0.19 (\text{stat}) \pm 0.30 (\text{syst}) \right) \%
\]

\[ PRL 114, 041601 (2015) \]

\[ A_{sl}^s = \left( 0.39 \pm 0.26 (\text{stat}) \pm 0.20 (\text{syst}) \right) \%
\]

\[ PRL 117, 061803 (2016) \]

D0 dimuon result is \( \sim 3\sigma \) from SM

B_{q}^0 \text{ production asymmetry (\~1\%)}
Summary

- Remarkable advances in CP studies with the b hadrons
- But still need for precision measurements with Run 2 (ongoing) and Run 3,4,... data
- E.g., will the CKM picture stay consistent between tree and loop diagrams?
Back up
Mixing formalism and asymmetries

\[ i \frac{d}{dt} \left( \begin{array}{c} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{array} \right) = \left( \begin{array}{cc} M_{11} & M_{12} \\ M^*_1 & M_{22} \end{array} \right) \left( \begin{array}{c} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{array} \right) - \frac{i}{2} \left( \begin{array}{cc} \Gamma_{11} & \Gamma_{12} \\ \Gamma^*_1 & \Gamma_{22} \end{array} \right) \left( \begin{array}{c} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{array} \right) \]

\[ \phi_{12} = \arg(-M_{12}/\Gamma_{12}) \]

Mass and width differences between eigenstates:

\[ \Delta M \approx 2|M_{12}| \quad \Delta \Gamma \approx 2|\Gamma_{12}| \cos \phi_{12} \]

\[ B^0_{L,H} = p |B^0\rangle \pm q |\bar{B}^0\rangle \]

\[ \lambda_f \equiv \frac{q}{p} \frac{\tilde{A}_f}{A_f} \]

\[ A_{CP}(t) = \frac{\Gamma(B^0(t) \rightarrow f_{CP}) - \Gamma(\bar{B}^0(t) \rightarrow f_{CP})}{\Gamma(B^0(t) \rightarrow f_{CP}) + \Gamma(\bar{B}^0(t) \rightarrow f_{CP})} = \frac{S_f \sin(\Delta M_B t) - C_f \cos(\Delta M_B t)}{\cosh(\Delta \Gamma_B t/2) + A_{\Delta \Gamma}^f \sinh(\Delta \Gamma_B t/2)} \]

\[ C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad S_f \equiv \frac{2\text{Im}\lambda_f}{1 + |\lambda_f|^2}, \quad A_{\Delta \Gamma}^f \equiv -\frac{2\text{Re}\lambda_f}{1 + |\lambda_f|^2} \]
Semileptonic $A_{sl}$ asymmetries

Topology of separated B and D vertices, restricting $K \pi (K) \pi \mu$ mass window

Fitting simultaneously mass and time distributions of $K \pi (K) \pi$ candidates

Reconstructed time is corrected for non-visible mass:

$$ t = \frac{L \cdot M_{B}^{nom}}{P_{vis}} K \left( M_{vis} \right) $$

However, precise knowledge of K factor has limited impact on $A_{sl}$

$p_{vis} / p_{true}$ from simulation