CP violation in b hadrons at LHCb

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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, \((n(\bar{B}) - n(\bar{B}))/n(\gamma) \sim 10^{-10}\)

- 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

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

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:
\[ \alpha = \angle \delta_{CP} \]

\[ B_d^0 \rightarrow \pi^+ \pi^- \]

\[ B_d^0 \rightarrow J/\psi K_S \]

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

Amplitudes:
\[ B \to f \quad A_f = \langle f | H_{\text{eff}} | B \rangle \quad \bar{B} \to \bar{f} \quad \bar{A}_f = \langle \bar{f} | H_{\text{eff}} | \bar{B} \rangle \]
\[ B \to \bar{f} \quad A_{\bar{f}} = \langle \bar{f} | H_{\text{eff}} | B \rangle \quad \bar{B} \to f \quad \bar{A}_f = \langle f | H_{\text{eff}} | \bar{B} \rangle \]

1) CP violation in the decay \( A(\bar{B} \to \bar{f}) \neq A(B \to f) \)
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 \( A(B^0 \to B^0) \neq A(B^0 \to \bar{B}^0) \): different measurement techniques. In LHCb, use of flavor-specific state and compare «wrong-sign » decays occurring because of the mixing.
\( A(B^0 \to B^0 \to f) \neq A(B^0 \to \bar{B}^0 \to \bar{f}) \). 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 \( B^0 \to \bar{B}^0 \to f_{\text{CP}} \) and \( B^0 \to f_{\text{CP}} \). Needs the tagging of the flavor of \( B \) at the production!
Measurement of CKM angles such as \( \beta, \beta_s \)
CP violation formulas

\[ A_f = A_1 e^{i\delta_1} e^{i\phi_1} + A_2 e^{i\delta_2} e^{i\phi_2} \]

\[ \delta_i \text{ strong phase} \]
\[ \phi_i : \text{ weak phase} \]

\[ A_{CP} = \frac{|A_f|^2 - |A_f^*|^2}{|A_f|^2 + |A_f^*|^2} \propto 2A_1A_2 \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \]

Non zero decay CP asymmetry requires > 1 contribution

Mixing + decay CP asymmetry

\[ A_{q_{sl}} = \frac{\Gamma(B_q^0 \rightarrow B_q^0 \rightarrow f) - \Gamma(B_q^0 \rightarrow B_q^0 \rightarrow \bar{f})}{\Gamma(B_q^0 \rightarrow B_q^0 \rightarrow f) + \Gamma(B_q^0 \rightarrow B_q^0 \rightarrow \bar{f})} \approx \frac{\Delta \Gamma_q}{\Delta m_q} \tan(\phi_{12}^{q}) \]

Mixing phase \sim 0 \text{ in SM}

Mixing + decay CP asymmetry

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

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

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

*Phys. Rev. D91(2015) 073007*

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

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

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

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

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

| Parameter     | Value                  |
|---------------|------------------------|
| \( \Gamma_s \text{ [ps}^{-1}] \) | \( 0.650 \pm 0.006 \pm 0.004 \) |
| \( \Delta \Gamma_s \text{ [ps}^{-1}] \) | \( 0.066 \pm 0.018 \pm 0.010 \) |
| \( \phi_s \text{ [mrad]} \)     | \( 119 \pm 107 \pm 34 \)   |
| \( |\lambda| \)                  | \( 0.994 \pm 0.018 \pm 0.006 \) |
β angle results from $b \to c c s$ tree decays

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

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

Known golden mode: $B^0 \to J/\Psi K_S^0$

LHCb Run 1 measurement $\sin(2\beta) = 0.731 \pm 0.035 \text{(stat)} \pm 0.020 \text{(syst)} \text{ PRL 115, 031601 (2015)}$

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

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

$$S(B^0 \to [c \bar{c}] K_S^0) = 0.760 \pm 0.034$$
$\beta$ 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

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**Graphs:**

- **Left Graph:**
  - LHCb
  - $m_{D^+D^-}$ (MeV/$c^2$) vs. Candidates / (3.5 MeV/$c^2$)
  - $B^0 \rightarrow D^+D^-$
  - $B^0 \rightarrow D^+D^-$
  - $B_s^0 \rightarrow D^+_sD^-$
  - Comb. bkg.
  - $B_s^0 \rightarrow D^-D^+$

- **Right Graph:**
  - LHCb
  - Signal yield asymmetry vs. $t'$ (ps)
$B^0_{(s)} \rightarrow hh$

- 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 \text{hh CP fit results}

Fit performed with \(\Gamma, \Delta\Gamma\) and \(\Delta m\) fixed

\[
\begin{align*}
C_{\pi\pi} &= -0.243 \pm 0.069 \\
S_{\pi\pi} &= -0.681 \pm 0.060 \\
C_{KK} &= +0.236 \pm 0.062 \\
S_{KK} &= +0.216 \pm 0.062 \\
A_{KK,\Delta\Gamma} &= -0.751 \pm 0.075
\end{align*}
\]
γ 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
\( \gamma \) from B → DK(-like), different techniques

**Decay**

- \( f_D = \) CP eigenstates, \( D^0 \rightarrow K^+K^-\), \( \pi^+\pi^-\), \( Ks\pi^0\)
  - Gronau, London, Wyler (GLW) 1991
- \( f_D = \) flavour states: \( D^0 \rightarrow K^+\pi^-\), \( K^-\pi^+\)
  - Atwood, Dunietz, Soni (ADS) 1997
  - Extension to multiple body \( K^{\pm}\pi^-/\pi^+\pi^-\)
- Multibody \( KsK^{\pm}\pi^-/\pi^+\), GLS
- \( f_D = \) multibody final states, Dalitz (variation of \( \delta_D \) over phase space)
  - \( Ks\pi^0\) Giri, Grossman, Soffer, Zupan 2003; Poluektov 2004 (GGSZ-P)
- Some most recent channels involve neutrals, \( B^0 \) and \( Bs \), 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)
\[ \gamma \] combination in LHCb: huge improvement in techniques and precision

**Decay**

- Many channels under study in LHCb
  - Using either CP, flavour, or multibody final states of D

*New comb LHCb-CONF-2017-004 since last one JHEP 12 (2016) 087, arXiv:1611.03076*

| \( B \) decay | \( D \) decay | Method | Ref. | Status since last combination [1] |
|----------------|----------------|--------|------|----------------------------------|
| \( B^+ \to DK^+ \) | \( D \to h^+h^- \) | GLW | [16] | Updated to Run 1 2 fb\(^{-1}\) Run 2 |
| \( B^+ \to DK^+ \) | \( D \to h^+h^- \) | ADS | [17] | As before |
| \( B^+ \to DK^+ \) | \( D \to h^+\pi^-\pi^+\pi^- \) | GLW/ADS | [17] | As before |
| \( B^+ \to DK^+ \) | \( D \to h^+h^-\pi^0 \) | GLW/ADS | [18] | As before |
| \( B^+ \to DK^+ \) | \( D \to K^0_S h^+h^- \) | GGSZ | [19] | As before |
| \( B^+ \to DK^+ \) | \( D \to K^0_S K^+\pi^- \) | GLS | [20] | As before |
| \( B^+ \to D^*K^+ \) | \( D \to h^+h^- \) | GLW | [16] | New |
| \( B^+ \to DK^{*+} \) | \( D \to h^+h^- \) | GLW/ADS | [21] | New |
| \( B^+ \to DK^{+\pi^+\pi^-} \) | \( D \to h^+h^- \) | GLW/ADS | [22] | As before |
| \( B^0 \to DK^{*0} \) | \( D \to K^+\pi^- \) | ADS | [23] | As before |
| \( B^0 \to DK^{+\pi^-} \) | \( D \to h^+h^- \) | GLW-Dalitz | [24] | As before |
| \( B^0 \to DK^{*0} \) | \( D \to K^0_S \pi^+\pi^- \) | GGSZ | [25] | As before |

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

**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 $\gamma$

| $D$ decay mode          | Yield     |
|-------------------------|-----------|
| $B^\pm \rightarrow D(K^{\pm}\pi^{\mp})K^{*\pm}$ | 2031 ± 49 |
| $B^\pm \rightarrow D(K^+K^-)K^{*\pm}$           | 255 ± 18  |
| $B^\pm \rightarrow D(\pi^+\pi^-)K^{*\pm}$       | 78 ± 11   |
| $B^\pm \rightarrow D(K^+\pi^\pm\pi^-)K^{*\pm}$ | 20 ± 7    |
| $B^\pm \rightarrow D(K^+\pi^\pm\pi^\mp\pi^-)K^{*\pm}$ | 1144 ± 37 |
| $B^\pm \rightarrow D(\pi^+\pi^\mp\pi^\pm\pi^-)K^{*\pm}$ | 115 ± 13  |
| $B^\pm \rightarrow D(K^+\pi^\pm\pi^\mp\pi^\pm)K^{*\pm}$ | 13 ± 7    |

$R_{K\pi}^\pm = \frac{\Gamma(B^\pm \rightarrow D(K^{\pm}\pi^{\pm})K^{*\pm})}{\Gamma(B^\pm \rightarrow D(K^{\pm}\pi^{\mp})K^{*\pm})} = \frac{r_B^2 + (r_D^K\pi)^2 + 2\kappa r_B r_D^{K\pi} \cos(\delta_B + \delta_D^{K\pi} \pm \gamma)}{1 + r_B^2 (r_D^K\pi)^2 + 2\kappa r_B r_D^{K\pi} \cos(\delta_B - \delta_D^{K\pi} \pm \gamma)}$

$\kappa$: dilution factor due to $K_S\pi$ nonres component in $K^*$ spectrum

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

Charge asymmetry visible by eye
CP violation in baryon decays $\Lambda_b \rightarrow p\pi hh$

$\text{ Decay}$

CPV seen in B and K decays, never in baryons
Search for direct CPV in $\Lambda_b \rightarrow p\pi hh$ decays

$\text{Relative weak phase: } \alpha$

Look at triple scalar products

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

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

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

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

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

Observable measuring CPV:

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

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

Phys. Rev. D 92, 076013 (2015)

arXiv:1609.05216

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

Overall $3.3\sigma$ CP violation found for $\Lambda_b \to p\pi\pi\pi$
First evidence of CP violation in baryon decays
No CP violation for $\Lambda_b \to p\pi KK$

$C_T \propto \sin(\Phi)$

Nature Physics 13 391 (2017)
arXiv:1609.05216
$A_{sl}$ asymmetries

\[
\frac{N(B_q^0 \rightarrow D_{(s)}^- \mu^+ \nu, t) - N(\bar{B}_q^0 \rightarrow D_{(s)}^+ \mu^- \nu, t)}{N(B_q^0 \rightarrow D_{(s)}^- \mu^+ \nu, t) + N(\bar{B}_q^0 \rightarrow D_{(s)}^+ \mu^- \nu, t)} = A_D + \frac{A_{sl}^q}{2} \left( A_P + \frac{A_{sl}^q}{2} \right) \cos(\Delta M_q t) \cosh\left(\frac{\Delta \Gamma_q t}{2}\right)
\]

Detection asymmetry (inferred from control samples)

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

LHCb measures:

$A_{sl}^d = (-0.02 \pm 0.19 \text{ (stat)} \pm 0.30 \text{ (syst)}) \%$

*PRL 114, 041601 (2015)*

$A_{sl}^s = (0.39 \pm 0.26 \text{ (stat)} \pm 0.20 \text{ (syst)}) \%$

*PRL 117, 061803 (2016)*

$B_q^0$ 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

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

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

Mass and width differences between eigenstates:

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

\[ B_{L,H}^0 = p \left| B^0 \right\rangle \pm q \left| \overline{B}^0 \right\rangle \]

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

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

\[ C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad S_f \equiv \frac{2 \text{Im} \lambda_f}{1 + |\lambda_f|^2}, \quad A^{\Delta \Gamma}_f \equiv -\frac{2 \text{Re} \lambda_f}{1 + |\lambda_f|^2} \]
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