$CP$ violation: $\gamma$, $\beta$ and $\beta_s$

Francesca Dordei
on behalf of the LHCb collaboration
CERN

Implications of LHCb measurements and future prospects -
November, 08th 2017
Why do we study CPV?

**A huge success...**

- Measurements overconstrain the SM picture of $\mathcal{CP}$ ⇒ potential high sensitivity to NP.

**$B^0$ Triangle:** larger angles, similar size sides

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

- All of the measurements agree very well
- In the presence of relevant NP, the various contours would not cross each other in a single point
- The SM works so remarkably well that we have to make more and more precise measurements
Why do we study CPV?

CKM metrology

Outline and upgrade reminder

In this talk I will:

- Summarise current status of art of $\gamma$, $\beta$ and $\beta_s$
- Give some perspectives for the evolution of these measurements, following LHCb Upgrade II Expression of interest;
- Refer to the milestones indicated below.
- Don’t miss Greig Cowan’s talk on *Future LHCb upgrades and long-term physics prospects*
Status of $\gamma$

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

- $\gamma$ is still the least well-known angle of the Unitarity Triangle
- Measurements of $\gamma$ from $B$ decays mediated only by tree-level transitions provide a “standard candle” for the SM (assuming no new physics in tree-level decays [Phys. Rev. D 92, 033002 (2015)]) $\Rightarrow$ Theoretically clean $[\delta \gamma/\gamma] \lesssim O(10^{-7})$ [JHEP 1401 (2014) 051]
- This can be compared with $\gamma$ values from $B$ decays involving loop-level transitions, such as $B_{d,s}^0 \rightarrow hh'$ decays ($h = K, \pi$), to get signs of NP.

Can be measured in the interference between $b \rightarrow c$ and $b \rightarrow u$ transitions, eg:

Small signal yields (BR $\approx 10^{-7}$), small interference effects ($\sim 10\%$) $\Rightarrow$ Combining a plethora of independent decay modes is the key to achieve the ultimate precision.
State of art of $\gamma$

LHCb combination of several Run 1 measurements:

- 71 observables and 32 parameters
- Frequentist and Bayesian interpretations
- Both show good agreement

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

[LHCb-CONF-2017-004]

- LHCb precision ($\sim 5.5^\circ$) dominates world average

\[ \gamma(\text{HFLAV CKM 2017}) = (73.5^{+4.3}_{-5.0})^\circ \]

[arXiv:1612.07233]

- To be compared with the CKM fit indirect determination:

\[ \gamma(\text{CKM FITTER}) = (65.3^{+1.0}_{-2.5})^\circ \]

[CKMfitter Group]
Prospects for $\gamma$

- Indirect uncertainties will decrease as lattice becomes better: **need to improve direct precision!**
  
<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 I</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>Upgrade II</td>
<td>$&lt;0.5$</td>
</tr>
</tbody>
</table>

- Belle-II targets a precision of $\sim 1.5^\circ$ at the end of data-taking (2025)
- Studies underway to quantify the impact of better reconstruction of $hh\pi^0$ modes and better low momentum tracking for high multiplicity modes $\Rightarrow$ **Huge statistical potential not included in table above!**
- Future BESIII **charm inputs** also need to be considered
  - Current $\gamma$ combination syst. due to CLEO inputs $\sim 2^\circ$ [LHCb-PUB-2016-025]
  - Additional BESIII run at $\psi(3770)$ under consideration - $\sigma(\gamma) \sim 0.5^\circ$ [LHCb-PUB-2016-025]
- Comparison of $\gamma$ measurements made in single decay modes interesting after Upgrade II (1° sensitivity) $\Rightarrow$ **NP in tree level different for different final states**
- Constrain $\beta_s$ without penguin contaminations $\Rightarrow$ 2° sensitivity on $\gamma - 2\beta_s$ from $B^0_s \to D_sK$
**CP violation in interference between mixing and decay**

- **Dominant SM “tree” contribution**

- **Higher order “penguin”**
  contributions from non-perturbative hadronic effects

- **NP could be difficult to distinguish from penguins...**

\[
\phi_q = \phi_M - 2\phi_D = -2\beta_q + \Delta \phi_q + \delta_{q}^{NP},
\]

\[
\beta_q = \arg \left( \frac{V_{tq}V_{tb}^{*}}{V_{cq}V_{cb}^{*}} \right)
\]

\(\phi_s\) and \(\phi_d\) determined via global fit to experimental results ignoring contributions from penguin diagrams:

- \(\phi_{s}^{SM} \equiv -2 \arg \left( -\frac{V_{ts}V_{tb}^{*}}{V_{cs}V_{cb}^{*}} \right) = -37.6^{+0.7}_{-0.8} \text{ mrad} \)
  [CKM Fitter]

- \(\sin 2\beta_{s}^{SM} \equiv \sin 2\arg \left( -\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}} \right) = 0.740^{+0.020}_{-0.025} \)
  [CKM Fitter]

Predictions are very precise!
State of art of $\phi_S$

Extensively studied in LHCb, CMS, ATLAS with Run 1. Although there has been impressive progress since the initial measurements at CDF/D0, the uncertainty needs to be further reduced:

**LHCb:**
- $J/\psi \phi$ [PRL114, 041801 (2015)]
- $J/\psi K^+ K^-$ above $\phi$ (1020) [arXiv:1704.08217 (2017)]
- $D_s^+ D_s^-$ [PRL113, 211801 (2014)]

**CMS:**

**ATLAS:**
- $J/\psi \phi$ [JHEP 08 (2016) 147]

$\phi_s = -21 \pm 31 \text{ mrad}$

$\phi_s^{SM} = -37.6^{+0.7}_{-0.8} \text{ mrad}$

- World average (dominated by LHCb) consistent with SM prediction;
- Exp. uncertainty almost a factor of 30 larger than uncertainty of indirect determination when penguin pollution is ignored.
Future of $\phi_s$ at LHCb

Evolution of the statistical uncertainty on $\phi_s$ as function of collected integrated luminosity at LHCb, scaled using present performances of the detector and expected running conditions:

- Complementary channels like $b \rightarrow s\bar{s}s$ would greatly benefit from the more eff. hadron-trigger
- Overall LHCb statistical uncertainty @300 fb$^{-1}$: $\sigma_{\phi_b \rightarrow c\bar{c}s} < 3$ mrad and $\sigma_{\phi_b \rightarrow s\bar{s}s} < 10$ mrad
# State of art of sin $(2\beta)$

\[
\sin(2\beta) = \sin(2\phi_1) \quad \text{HFLAV Summer 2016}
\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar PRD 79 (2009):072009</td>
<td>0.69 ± 0.03 ± 0.01</td>
</tr>
<tr>
<td>BaBar $\chi_{c0}$, $K_S$ PRD 80 (2009):112001</td>
<td>0.69 ± 0.52 ± 0.04 ± 0.07</td>
</tr>
<tr>
<td>BaBar J/$\psi$ (hadronic) $K_S$ PRD 69 (2004):052001</td>
<td>1.58 ± 0.42 ± 0.21</td>
</tr>
<tr>
<td>Belle PRL 108 (2012):171802</td>
<td>0.67 ± 0.02 ± 0.01</td>
</tr>
<tr>
<td>ALEPH PLB 492, 259 (2000)</td>
<td>0.84 ± 0.04 ± 0.16</td>
</tr>
<tr>
<td>OPAL EPJ C5, 379 (1998)</td>
<td>3.20 ± 0.30 ± 0.50</td>
</tr>
<tr>
<td>CDF PRD 61, 072005 (2000)</td>
<td>0.79 ± 0.04 ± 0.04</td>
</tr>
<tr>
<td>LHCb PRL 115 (2015):031601</td>
<td>0.73 ± 0.04 ± 0.02</td>
</tr>
<tr>
<td>Belle5S PRL 108 (2012):171801</td>
<td>0.57 ± 0.58 ± 0.06</td>
</tr>
<tr>
<td>Average HFLAV</td>
<td>0.69 ± 0.02</td>
</tr>
</tbody>
</table>

- **LHCb:**
  - $S_{J/\psi K_S} = 0.731 \pm 0.035 \pm 0.020$ [PRL 115, 031601 (2015)]

- **Belle:**
  - $S_{J/\psi K_S} = 0.670 \pm 0.029 \pm 0.013$ [PRL 108, 171802 (2012)]

- **Babar:**
  - $S_{J/\psi K_S} = 0.662 \pm 0.039 \pm 0.012$ [PRD 79, 072009 (2009)]

**HFLAV Summer 2017**

- LHCb has a similar precision to the B-factories
- Small tension of B-factories results with SM predictions to be clarified

**HFLAV Summer 2017**

\[
S \equiv \sin 2\beta = 0.691 \pm 0.017
\]

\[
S^{SM} \equiv \sin 2\beta^{SM} = 0.740^{+0.020}_{-0.025}
\]

[CKM Fitter]
\[
\sin(2\beta) \text{ from } B^0 \text{ to } J/\psi(ee)K_S^0 \text{ and } \psi(2S)K_S^0
\]

The asymmetry between \(B^0\) and \(\bar{B}^0\) decays to \(J/\psi(ee)K_S^0\) and \(\psi(2S)K_S^0\) is (taking \(\Delta \Gamma_d \equiv 0\)):

\[
\mathcal{A}_{[c\bar{c}]K_S^0}(t) \approx S \sin(\Delta m t) - C \cos(\Delta m t)
\]

where \(S = \sin(2\beta)\)

\[
\begin{align*}
C(B^0 \rightarrow J/\psi(e^+e^-)K_S^0) &= 0.12^{+0.07}_{-0.07} \text{ (stat)} \pm 0.02 \text{ (syst)} \\
S(B^0 \rightarrow J/\psi(e^+e^-)K_S^0) &= 0.83^{+0.07}_{-0.08} \text{ (stat)} \pm 0.01 \text{ (syst)} \\
C(B^0 \rightarrow \psi(2S)(\mu^+\mu^-)K_S^0) &= -0.05^{+0.10}_{-0.10} \text{ (stat)} \pm 0.01 \text{ (syst)} \\
S(B^0 \rightarrow \psi(2S)(\mu^+\mu^-)K_S^0) &= 0.84^{+0.10}_{-0.10} \text{ (stat)} \pm 0.01 \text{ (syst)}
\end{align*}
\]

New LHCb average:

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

\[
C(B^0 \rightarrow [c\bar{c}]K_S^0) = -0.017 \pm 0.029
\]

- Precision of \(\sin(2\beta)\) from LHCb improved by 20%;
- Reduce tension with SM predictions.
Future of $\sin(2\beta)$ at LHCb

Prospects:

- Sizeable systematic uncertainties wrt statistical ones.
- Overall LHCb statistical uncertainty \( @300 \, fb^{-1} : < 0.003 \)
Penguin pollution

Experimentally

- Penguin contribution is suppressed by a factor of $\lambda^2$ in the $C\bar{P}$ key modes
  \[ B^0 \rightarrow J/\psi K^0_S = T + P \]
  \[ B^0_s \rightarrow J/\psi \phi = T + P + E + PA \]

- Access to penguin contribution via SU(3) counterparts not suppressed w.r.t. tree level
  [Fleischer, De Bruyn]

- Ignore non-factorisable SU(3) breaking


$\phi_S$:
- $B^0 \rightarrow J/\psi K^0_S$ - JHEP 11 (2015) 082
- $B^0 \rightarrow J/\psi \rho^0$ - Phys. Lett. B742 (2015) 38
- $B^0 \rightarrow J/\psi \omega$ - Under study

$\beta$:
- $B^0 \rightarrow J/\psi K_S$ - Phys. Rev. Lett. 115 (2015) 031601
- $B^0 \rightarrow J/\psi \pi^0$ - Under study
New measurements
New results

\[ \gamma \] from \( B_s^0 \rightarrow D_s^\mp K^\pm \) decays

- \( CP \) asymmetry in mixing and decay in \( B_s^0 \rightarrow D_s^\mp K^\pm \) decays sensitive to \( (\gamma - 2\beta_s) \).
- Both decay amplitudes are \( \mathcal{O}(\lambda^3) \)
  \( \Rightarrow \) large interference \( (\mathcal{O}(35\%))! \)

The analysis is based on \( pp \) collision data sample of 3 \( fb^{-1} \) collected at LHCb in Run 1.

- Update of LHCb-CONF-2016-015 (2016)
- Three \( D_s^- \) final states considered: \( KK\pi \) (\( \phi\pi^- \), \( K^0K^- \), Non Resonant), \( K\pi\pi \), \( \pi\pi\pi \).
New results

\[ \gamma \text{ from } B^0_s \rightarrow D_s^{\mp} K^{\pm} \text{ decays} \]

[LHCb-PAPER-2017-047 (2017)]

- Perform multivariate fit (MDFit) to \( m(D_s^{\mp} K^{\pm}) \), \( m(hhh) \) (with \( h = K, \pi \) from \( D_s^{\mp} \) decays) and the companion PIDK distribution.

- Use MDFit results to **subtract background** events and perform a time-dep. signal only fit.

- Use \( B^0_s \rightarrow D_s^- \pi^+ \) as control channel.


\[ \Rightarrow \text{ Overall tagging power } 5.80 \pm 0.25\% \]

- Most of the **systematic sources** have been revisited after several cross checks.

\[ C_f = 0.73 \pm 0.14 \pm 0.05, \]
\[ A_{\Delta f}^\Gamma = 0.39 \pm 0.28 \pm 0.15, \]
\[ A_{\Delta f} = 0.31 \pm 0.28 \pm 0.15, \]
\[ S_f = -0.52 \pm 0.20 \pm 0.07, \]
\[ S_f^- = -0.49 \pm 0.20 \pm 0.07, \]
New results

\[ \gamma \text{ from } B_s^0 \rightarrow D_s^{\mp} K^{\pm} \text{ decays} \]

Assuming \( \phi_s \approx -2\beta_s \) as external input:

\[ \gamma = (128^{+17}_{-22})^\circ \quad \delta = (358^{+13}_{-14}) \quad r_{Ds K} = (0.37^{+0.010}_{-0.09}) \]

- 3.6 \( \sigma \) evidence for CP violation in \( B_s^0 \rightarrow D_s^{\mp} K^{\pm} \) decays.
- 2.3 \( \sigma \) from all other LHCb measurements combined.
Decays of charmed b-mesons to two c-mesons

[LHCb-PAPER-2017-045 (2017)]

- Decays of $B_c^+$ mesons to two open-charm (excited) mesons, like $B_c^+ \rightarrow D_{(s)}^+ D$, have been proposed to measure $\gamma$.
- Smaller yields than $B^+ \rightarrow DK^+$, but interference is larger: $r_{B_c^+} \approx 1$
- **Challenges**: small production cross-section, the short lifetime, the complex final state, and possibly small branching fractions.

LHCb performed the **first search of these decays** using Run 1 data.

Charm mesons are reconstructed in the following final states:

- $D^0 \rightarrow K^- \pi^+$
- $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D_s^+ \rightarrow K^+ K^- \pi^+$

**Strategy**: branching fractions are measured relative to large $B^+$ signals in data
Decays of charmed b-mesons to two c-mesons

Measured branching fractions (in parentheses upper limits @95 C.L. from asymptotic $\text{CL}_s$ method):

\[
\begin{align*}
\frac{f_c}{f_u} \mathcal{B}(B^+_c \rightarrow D^+_s D^0) &= (3.0 \pm 3.7) \times 10^{-4} (< 1.1 \times 10^{-3}), \\
\frac{f_c}{f_u} \mathcal{B}(B^+_c \rightarrow D^+_s \bar{D}^0) &= (-3.8 \pm 2.6) \times 10^{-4} (< 4.7 \times 10^{-4}), \\
\frac{f_c}{f_u} \mathcal{B}(B^+_c \rightarrow D^+_s D^0) &= (8.0 \pm 7.5) \times 10^{-3} (< 2.2 \times 10^{-2}), \\
\frac{f_c}{f_u} \mathcal{B}(B^+_c \rightarrow D^+_s \bar{D}^0) &= (2.9 \pm 5.3) \times 10^{-3} (< 1.4 \times 10^{-2}),
\end{align*}
\]

Also BR for excited c-mesons ($D^*_s$, $D^{*0}$, $D^{*+}$) have been measured

$\Rightarrow$ No evidence found
Near future of $\phi_s$ at LHCb

Currently finalising analysis of $B_s^0 \rightarrow J/\psi K^+ K^-$ decays from 2015 and 2016

$N_{\text{sig}}^{2015} \sim 16000$

$N_{\text{sig}}^{2016} \sim 96000$

Peaking background subtracted $J/\psi K^+ K^-$ invariant mass distributions

WARNING: Central value for Run II shifted to Run I

WARNING: Run II syst from Run I

Expected statistical uncertainty on main physics parameters using 2015 + 2016 data:

- $\sigma_{\text{stat}}(\phi_s) \sim 0.042 \text{ rad} \ (\text{Run I: 0.049 rad})$
- $\sigma_{\text{stat}}(\Delta \Gamma_s) \sim 0.0080 \text{ ps}^{-1} \ (\text{Run I: 0.0091 ps}^{-1})$
- $\sigma_{\text{stat}}(\Gamma_s/\Gamma_d) \sim 0.005 \ (\text{HFLAV: 0.004})$

No limiting systematic uncertainties foreseen.
Near future of $\phi_s$ at LHCb

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- $\sigma_{\text{stat}}(\Gamma_s/\Gamma_d) \sim 0.005 \text{ (HFLAV: 0.004)}$

No limiting systematic uncertainties foreseen.
• Interest in precision flavour measurements is stronger than ever ⇒ If no direct evidence of NP pops out of the LHC, flavour physics can play a key role;

• All results in this sector in good agreement with SM;

• Majority of measurements still statistically limited and on Run 1;

• Time to exploit the potentials of Run 2!!

• Good prospects for the precision measurements in the upgrade phase.
Thanks for your attention!
Backup Slides
**CP violation phenomenology**

Due to interfering amplitudes with different CKM phases in transitions of particles and antiparticles

### CP violation in decay (direct $\mathcal{CP}$)

Different $\mathcal{CP}$ conjugate decay amplitudes:

$$\mathcal{A}(P \to f) \neq \mathcal{A}((\bar{P} \to \bar{f})$$

possible also for charged hadrons

**Ex.** $B^0_{(s)} \to K^+\pi^- \text{ vs } \bar{B}^0_{(s)} \to K^-\pi^+$

### CP violation in mixing

$\mathcal{CP}$ in mixing arises for neutral mesons:

$$\mathcal{P}(P \to \bar{P}) \neq \mathcal{P}(\bar{P} \to P)$$

or in terms of mass/flavour eigenstates:

$$|q/p| \neq 1, (|P_L,H> = p|P^0> \pm q|P^0>)$$

**Ex.** Semileptonic asymmetry $a_{s,d}^{s,d}$

### CP violation in interference between mixing and decay

Interference between $P \to f$ and $P \to \bar{P} \to f$, where $f$ is a non-flavour specific final state:

$$\frac{\mathcal{A}(\bar{P} \to f) - \mathcal{A}(P \to f)}{\mathcal{A}(\bar{P} \to f) + \mathcal{A}(P \to f)} = \frac{C_f \cos(\Delta M t) - S_f \sin(\Delta M t)}{\cosh(\Delta \Gamma t/2) + A_f \Delta \Gamma \sinh(\Delta \Gamma t/2)}$$

$S_f$: $\mathcal{CP}$ in interference between mixing and decay.

$C_f$: direct $\mathcal{CP}$.

**Ex.** $\mathcal{CP}$ phase $\phi_s$, golden channel: $B^0_s \to J/\psi \Phi$
Beauty and charm phenomenology

**Impact parameter resolution**
- E.g. LHCb: $\sigma_{IP} \sim 20 \mu m$ for high-$p_T$

**Momentum & invariant mass resolution**
- E.g. LHCb: $\sigma_p/p \sim 0.5 - 1\%$

**Decay-time resolution**
- E.g. LHCb: $\sigma_t \sim 45 \text{ fs}$

**Particle Identification**
- E.g. LHCb: Kaon ID eff. $\sim 95\%$
- Pion mis-ID fraction of $10\%$
- Muon ID eff. $\sim 97\%$

**Large number of beauty and charm hadrons**
- $\sigma(b\bar{b}) \approx 515 \mu b$ @ 13 TeV
  [*JHEP 10 (2015) 172]*
- Charm rate $\sim 20$ times larger

**BEAUTY SIGNATURES**
- Mass $m(B^+) = 5.28$ GeV
- Daughter $p_T \mathcal{O}(1 \text{ GeV})$
- Lifetime $\tau(B^+) \sim 1.6 \text{ ps}$
- Flight distance $\sim 1 \text{ cm}$
- Common signature: detached $\mu\mu$
  $B \rightarrow J/\Psi(\rightarrow \mu\mu)X$

**CHARM SIGNATURES**
- Mass $m(D^0) = 1.86$ GeV
- Sizeable daughter $p_T$
- Lifetime $\tau(D^0) \sim 0.4 \text{ ps}$
- Flight distance $\sim 4 \text{ mm}$
- Can be produced in $B$ decays

*F. Dordei (CERN)*
Tree vs loop measurements

If we assume NP enters only (mainly) at loop level, it is interesting to compare:

Parameters \((\rho, \eta)\) from processes dominated by tree diagrams \((V_{ub}, V_{cb}, \gamma, \ldots)\)

with the ones from loop diagrams \((\Delta M_d, \Delta M_s, \beta, \varepsilon_K, \ldots)\)

- At LHC we measure all relevant quantities but \(\varepsilon_K\)

Need to improve the precision of the measurements at tree level to (dis-)prove the existence of NP contributions in loops.
**Limiting factors on $\gamma$ in the high-statistics era**

Where will we become limited, as things stand:

- Most $B \rightarrow DK$ 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 ($\rightarrow$ systematic $\sim 1^\circ$)
- Measurement in $D \rightarrow K\pi$ (*Int.J.Mod.Phys.Conf.Ser. 31 1460305*)
- Preliminary results in $D \rightarrow K^0_s\pi\pi$

To avoid systematic limitation in the upgrade era:

- Full spectrum of strong phase measurements with full 15-20 fb$^{-1}$ at BES III
Penguin pollution in the HL-LHC era

Modes to be investigated in the future.

Control Modes for $B^0_s \rightarrow J/\psi \Phi$

- High precision CP analysis of $B^0 \rightarrow J/\psi \rho^0$: Determination of penguin parameters
- Search for $B^0_s \rightarrow J/\psi \rho^0$ and/or $B^0 \rightarrow J/\psi \phi$: Control contribution from E + PA
- High precision CP analysis of $B^0 \rightarrow J/\psi \omega$: Control contribution from E + PA
- High precision CP analysis of $B^0_s \rightarrow J/\psi K^*_0$: Cross check, test of SU(3)

Control Modes for $B^0 \rightarrow J/\psi K^0_S$

- High precision CP analysis of $B^0_s \rightarrow J/\psi K_S$: Determination of penguin parameters
- High precision CP analysis of $B^0 \rightarrow J/\psi \pi^0$: Determination of penguin parameters
- Search for $B^0_s \rightarrow J/\psi \pi^0$: Control contributions from E + PA in $B^0 \rightarrow J/\psi \pi^0$
## LHCb upgrade

### End of Run 2

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \to J/\psi \phi)$ (rad)</td>
<td>0.05</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \to J/\psi f_0(980))$ (rad)</td>
<td>0.09</td>
<td>0.05</td>
<td>0.016</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{sl}(B_s^0)$ ($10^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$\phi_{s,\text{eff}}(B_s^0 \to \phi \phi)$ (rad)</td>
<td>0.18</td>
<td>0.12</td>
<td>0.026</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$\phi_{s,\text{eff}}(B_s^0 \to K^0 K^0)$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.029</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_{s,\text{eff}}(B_s^0 \to \phi K_S^0)$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$\phi_{s,\text{eff}}(B_s^0 \to \phi \gamma)$</td>
<td>0.20</td>
<td>0.13</td>
<td>0.030</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{s,\text{eff}}(B_s^0 \to \phi \gamma)/\tau_{B_s^0}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>$S_3(B^0 \to K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$q^2_{FB}(B^0 \to K^{*0} \mu^+ \mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_1(K \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4)$</td>
<td>0.14</td>
<td>0.07</td>
<td>0.024</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+ \mu^+ \mu^-)/B(B^+ \to K^+ \mu^+ \mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B_s^0 \to \mu^+ \mu^-)$ (10^{-9})</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \to \mu^+ \mu^-)/B(B_s^0 \to \mu^+ \mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma(B \to D^{(<em>)}K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>1.1°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma(B_s^0 \to D_s^{(<em>)}K^{(</em>)})$</td>
<td>17°</td>
<td>11°</td>
<td>2.4°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta(B^0 \to J/\psi K_S^0)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T(D^0 \to K^+ K^-)$ (10^{-4})</td>
<td>3.4</td>
<td>2.2</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$ (10^{-3})</td>
<td>0.8</td>
<td>0.5</td>
<td>0.12</td>
<td>–</td>
</tr>
</tbody>
</table>