CPV in charm and b-decays at LHCb

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On behalf of the LHCb Collaboration

CAPRI 2012, 11-13 June 2012
Outline

• Introduction

• Recent measurements of CPV in beauty and charm decays

  1. \( B_s \) decays (e.g. \( B_s \rightarrow J/\psi \phi \))
  2. \( B^\pm \rightarrow D K^\pm \)
  3. \( B \rightarrow h^+h'^- \) (where \( h \) and \( h' = \pi, K, p \))
  4. \( \Delta A_{CP} \) from \( D^0 \rightarrow \pi^+\pi^-, K^+K^- \)

(Rare decays covered by J. Albrecht)

Many thanks to G. Wilkinson, G. Lanfranchi, P. Campana, MN. Minard and many others for (un)knowingly helping me!
LHCb detector: the essentials

- Experiment optimized for heavy-flavour physics
  - Forward acceptance
  - Efficient trigger for hadronic and leptonic modes
  - Acceptance down to low $p_T$
  - Precision tracking and vertexing (VELO@7 mm from beam)
  - Excellent particle identification
LHCb detector

A general purpose, high resolution spectrometer in the forward direction
Running conditions

- LHCb running at \( \sim 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
i.e. factor of 2 above design value

- Luminosity is leveled through vertical beam displacement – operation in harmony with higher luminosity for ATLAS/CMS

- 2011: 1.2 fb\(^{-1}\) delivered
  1.1 fb\(^{-1}\) recorded (~91% efficiency)
  - Huge production cross section:
    - \( \sigma_{\text{inel}} = 60 \text{ mb} @ 7 \text{ TeV} \)
    - \( \sigma_{\text{cc}} = 6 \text{ mb} \)
    - \( \sigma_{\text{bb}} = 0.3 \text{ mb} (~1 \text{nb} @ \Upsilon(4s)) \)

\[ 10^{11} \text{ b decays} \]
\[ 10^{12} \text{ charm decays} \]
in LHCb acceptance
2012 data taken so far (10-June)

Target is 1.5 fb$^{-1}$ recorded in 2012

Delivered Lumi: 507.88 /pb
Recorded Lumi: 473.74 /pb
CPV phase $\phi_s$ in $B_s$ mixing-decay interference
CPV phase $\phi_s$ in $B_s$ mixing-decay interference

- Interesting Tevatron results with early data and intriguing with final sample

PRD 85 (2012) 032006

PRD 85 (2012) 072002

- Results are consistent, both $\sim$1$\sigma$ away from SM

What about LHCb?
Golden channel: $B_s \rightarrow J/\psi \phi$

- Measurement of $B_s$-$\bar{B}_s$ mixing phase $\phi_s$ in $B_s \rightarrow J/\psi \phi$ sensitive to NP effects in mixing
- The phase arises from interference between $B$ decays with and without mixing
- $\phi_s$ is small in SM:
  \[ \phi_{s}^{\text{SM}} = \phi_{s}^{\text{M}} - 2\phi_{s}^{D} \simeq -2\beta_s = -2\text{arg} \left( \frac{V_{ts}V_{tb}^{*}}{V_{cs}V_{cb}^{*}} \right) = -(2.1 \pm 0.1)^{\circ} \]
- NP can add large phases:
  \[ \phi_{s} = \phi_{s}^{\text{SM}} + \phi_{s}^{\text{NP}} \]
Golden channel: $\text{B}_s \rightarrow \text{J}/\psi(\mu^+\mu^-) \phi(K^+K^-)$

- Theoretically and experimentally clean
  - $b \rightarrow ccs$ tree dominance leads to precise prediction of $\phi_s$ in SM
  - Relatively large branching ratio and clean topology
  - Easy to trigger on muons from $\text{J}/\psi \rightarrow \mu^+\mu^-$

- Likelihood fit of proper time and angular decay rates for $\text{B}_s^0$, $\bar{\text{B}}_s^0$
  - 6 observables:
    - invariant mass $m_{\text{B}}$, proper time, 3 angles of the decay products, $\text{B}_s$ flavour
    - Needs flavour-tagged, time-dependent angular analysis to disentangle the CP-even and CP-odd components
      \[
      \text{CP } |\text{J}/\psi \phi\rangle = (-1)^l |\text{J}/\psi \phi\rangle \quad l = 0,1,2
      \]

- Determine 10 physics parameters:
  $\phi_s$, $\Delta \Gamma_s$, $\Gamma_s$, $\Delta M_s$, 3 amplitude ratios, 3 strong phase differences
\( B_s \to J/\psi \phi \): key experimental ingredients

- **Selection of signal and control channels**
  - Very clean signal with \( \sim 21200 \) events (\( t > 0.3 \text{ ps} \))
  - \( \sim 8 \text{ MeV mass resolution} \)

- **Tagging of the initial flavour**
  - Effective tagging efficiency \( \sim 2.3\% \) from Opposite Side Tagging (exploits the decay of the other b-hadron in the event)
  - Calibrated with \( B^+ \to J/\psi K^+ \)

- **Decay time resolution**
  - Effective time resolution \( \sim 45 \text{ fs} \) from prompt events (\( B_S \) oscillation period \( \sim 350 \text{ fs} \))

1 fb-1 @ 7TeV in 2011
LHCb-CONF-2012-002
\( \text{B}_s \rightarrow \text{J}/\psi \ \phi: \text{fit projections} \)

- Maximum likelihood fit using angular information used to statistically separate different CP eigenstates

![Graphs showing fit projections for \( \text{B}_s \rightarrow \text{J}/\psi \ \phi \)]
\( B_s \rightarrow J/\psi \, \phi \): preliminary results

- Fit of the tagged and untagged rates as a function of \( B_s \) mass, proper time and angles

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>( \Gamma_s ) [ps(^{-1})]</td>
<td>0.6580</td>
<td>0.0054</td>
<td>0.0066</td>
</tr>
<tr>
<td>( \Delta \Gamma_s ) [ps(^{-1})]</td>
<td>0.116</td>
<td>0.018</td>
<td>0.006</td>
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<tr>
<td>(</td>
<td>A_\perp(0)</td>
<td>^2 )</td>
<td>0.246</td>
</tr>
<tr>
<td>(</td>
<td>A_0(0)</td>
<td>^2 )</td>
<td>0.523</td>
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<tr>
<td>( F_S )</td>
<td>0.022</td>
<td>0.012</td>
<td>0.007</td>
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<td>( \delta_\perp ) [rad]</td>
<td>2.90</td>
<td>0.36</td>
<td>0.07</td>
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<tr>
<td>( \delta_\parallel ) [rad]</td>
<td>[2.81, 3.47]</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>( \phi_s ) [rad]</td>
<td>-0.001</td>
<td>0.101</td>
<td>0.027</td>
</tr>
</tbody>
</table>

\( \Delta M_s \) constrained to LHCb measurement: \( \Delta M_s = (17.63 \pm 0.11 \) ps\(^{-1}\)] 

- World’s most precise measurement of \( \phi_s \)
- First direct observation for a non-zero value for \( \Delta \Gamma_s \)
- \( \phi_s \) and \( \Delta \Gamma_s \) compatible with SM predictions

\[ \text{LHCb-CONF-2012-002 (1/fb)} \]

\[ \text{Phys. Lett. B 709 (2012) 177} \]
CPV in $B_s \to J/\psi \, \phi$

Pictorial representation

- No big NP effects in $\phi_s$ !! $\to$ must increase precision

Ambiguity removed by LHCb
Sign of $\Delta \Gamma_s = \Gamma_L - \Gamma_H$

- Two ambiguous solutions because decay rates invariant under transformation $(\phi_s, \Delta \Gamma_s) \rightarrow (\pi-\phi_s, -\Delta \Gamma_s)$ (plus strong phase changes)
- Remove ambiguity through P-wave ↔ S-wave interference
  - S-wave $K^+K^-$ contribution to dominant P-wave $\phi \rightarrow K^+K^-$ decay
  - Measure strong phase difference between S-wave and P-wave amplitudes as function of $K^+K^-$ invariant mass
  - Expect
    - P-wave phase to rise through the $\phi(1020)$ region
    - S-wave is expected to vary slowly
    - Hence strong phase to decrease for physical solution
  - Solution I is selected:
    - $\Gamma_L - \Gamma_H > 0$ at the 4.7$\sigma$ level
    - Heavier $B_S$ meson lives longer!

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LHCb, arXiv:1202.4717
PRL 108.241801

Capri 2012
MPA, CPV in charm and b-decays at LHCb
\[ \mathbf{B}_s \to \mathbf{J}/\psi \pi^+\pi^- \]

- \( \phi_s \) also measured in \( \mathbf{B}_s \to \mathbf{J}/\psi \pi^+\pi^- \)
  - Previous analysis was \( \mathbf{B}_s \to \mathbf{J}/\psi f_0(980) \) \cite{PLB 707 (2012) 497}
    - This is CP eigenstate \( \to \) no need of angular analysis
  - Mass window extended to \( 775 < m(\pi\pi) < 1550 \text{ MeV}/c^2 \)
  - Angular analysis shows CP-odd fraction > 97.7% at 95% C.L.
  - Smaller BR \( \sim 20\% \) wrt \( \mathbf{B}_s \to \mathbf{J}/\psi \phi \) \( \sim 7400 \) events in signal region
  - \( \phi_s = -0.02 \pm 0.17 \pm 0.02 \) rad

- \( \mathbf{B}_s \to \mathbf{J}/\psi \phi \) and \( \mathbf{B}_s \to \mathbf{J}/\psi \pi\pi \) combined preliminary result
  \[ \phi_s = -0.002 \pm 0.083\text{(stat.)} \pm 0.027\text{(syst.)} \text{ rad} \]
The semi-leptonic asymmetry

- D0 measurement, with dileptons, measures a superposition of $a_{SL}^d$ and $a_{SL}^s$

$$A_{SL}^b = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = C_d a_{SL}^d + C_s a_{SL}^s$$

- Result 3.9 $\sigma$ away from SM!

- Most easily interpreted as a $B_s$ driven effect, however difficult to reconcile with other measurements such as $B_s \rightarrow J_\psi \phi$

- LHCb finalising a time integrated study of $B_s \rightarrow D_s(\phi\pi)\mu\nu$ decays to measure $a_{SL}^s$
Towards $\gamma$
State of the art

- Very precise picture has emerged
- $\gamma$ is least well measured angle
- Current measurement error $\sim 10-12^\circ$; indirect (through loops) is $\sim 4^\circ$

CKMfitter, S.Descotes-Genon
UTFit, M.Bona
CPV in $B^{\pm}\rightarrow DK^{\pm}$

- Sensitivity to $\gamma$ through final states accessible to both $D^0$ and $\bar{D}^0$ leading to interference
- No “pollution” from penguin loops

1. $D$ decays to CP eigenstates, e.g. $\pi^+\pi^-$, $K^+K^-$ (“Gronau London Wyler”)

2. $D$ decays to flavour specific states, e.g. $K^+\pi$ (“Atwood Dunietz Soni”)

Reverse-suppression between $B$ and $D$ decays results in similar amplitudes $\Rightarrow$ high sensitivity to $\gamma$
CPV in $B^\pm \to DK^\pm$

LHCb, arXiv:1203.3662
Submitted to PLB

• Recent LHCb analysis towards measurement of $\gamma$:
  – Combines “GLW” and “ADS”
  – Measures 16 decay rates:
    • $B^- \to Dh^-$ and $B^+ \to Dh^+$ ($h=K$ or $\pi$) and $D \to K^-\pi^+$, $K^+\pi^-$, $\pi^+\pi^-$, $K^+K^-$
  – Extracts 3 ratios of partial widths, 6 CP asymmetries, 4 ratios of ADS to favoured partial widths
CPV in $B^\pm \rightarrow D K^\pm$ and $B^\pm \rightarrow D\pi^\pm$

1 fb$^{-1}$

LHCb, arXiv:1203.3662
Submitted to PLB
CPV in $B^{\pm} \rightarrow DK^{\pm}$ and $B^{\pm} \rightarrow D\pi^{\pm}$

First observation of $B^{\pm} \rightarrow DK^{\pm}$ ADS mode (~10 $\sigma$)

Evidence of a large negative asymmetry in DK: $A_{ADS}(K) = (-52 \pm 15 \pm 2\%)$ (4 $\sigma$)

With KK, $\pi\pi$, CPV in $B^{\pm} \rightarrow DK^{\pm}$ observed with 5.8 $\sigma$ significance

LHCb, arXiv:1203.3662
Towards $\gamma$

• LHCb is on-track to make a combined measurement of $\gamma$ using $B^\pm$, $B^0$, $B_s$ tree decays, to an accuracy of 5~8° with the 2011+2012 data

• Anticipated LHCb sensitivity by 2018 ~ 4° (i.e. matching current indirect precision)
Charmless two-body B decays
Charmless two-body B decays

\[ B \rightarrow h^+h'^- \] (where h and h’ = \(\pi, K, p\))

- Interesting class of decays
- Sensitive to \(V_{ub}\) so to CKM angle \(\gamma\)
- ‘Simple’ interpretation of measurements in terms of CKM phases not possible (penguin pollution, etc)
- NP can contribute to penguin loops
- Important interplay among the various B \(\rightarrow h^+h'^-\) channels
  - e.g. assuming U-spin symmetry (d – s interchange)

...plus other diagrams
Charmless two-body B decays

- Very large yields at LHCb
  - e.g. \([1/fb] \sim 41k (B^0 \rightarrow K\pi); 7k (B^0 \rightarrow \pi\pi); 2k (B_s \rightarrow K\pi); 11k (B_s \rightarrow KK)\)
- PID capability with RICH detectors to isolate clean samples of \(B \rightarrow h^+h^- (h = \pi, K, p)\)
- Direct CP asymmetries in \(K\pi\) modes \(\Gamma(B^0 \rightarrow f) \neq \Gamma(\bar{B}^0 \rightarrow \bar{f})\)
  - Detection asymmetries (acceptance, reconstruction, interaction in material)
    - Studied with high stat. \(D^*\) and \(D^0\) samples with inversion of magnet field polarity
  - \(B-B\) production asymmetries
    - Studied with \(B^0 \rightarrow J/\psi K^{*0}\) (No CPV in \(b \rightarrow c\bar{c}s\))
- Time-dependent CPV in \(\pi\pi\) and \(KK\) modes
  - Needs flavour tagging (tagging power \(\sim 2.3\%\))
Direct CPV in \( B_{(s)} \rightarrow K\pi \)

- With 0.35 fb\(^{-1}\)

\[
A_{CP}(B^0 \rightarrow K\pi) = \frac{-0.088 \pm 0.011 \pm 0.008}{\text{Good agreement with HFAG average}}
\]

First observation (>6\(\sigma\)) of direct CPV in B decays at a hadron collider

\[
A_{CP}(B_s \rightarrow K\pi) = \frac{+0.27 \pm 0.08 \pm 0.02}{\text{First evidence (3.3 }\sigma\text{) of direct CPV in } B_s \text{ decays}}
\]
Time dependent CPV in $B^0 \rightarrow \pi^+ \pi^-$ and $B^0_s \rightarrow K^+ K^-$

$$A_{CP}(t) = \frac{A_f^{dir} \cos(\Delta m t) + A_f^{mix} \sin(\Delta m t)}{\cosh \left(\frac{\Delta \Gamma}{2} t\right)} - A_f^{\Delta \Gamma} \sinh \left(\frac{\Delta \Gamma}{2} t\right)$$

$\rightarrow A_f^{dir}$ and $A_f^{mix}$

- $B^0 \rightarrow \pi^+ \pi^-$
  - $A_{\pi\pi}^{dir} = 0.11 \pm 0.2 \pm 0.03$
  - $A_{\pi\pi}^{mix} = -0.56 \pm 0.17 \pm 0.03$
  - First measurement at a hadron collider
  - Compatible with B factories

- $B^0_s \rightarrow K^+ K^-$
  - $A_{KK}^{dir} = 0.02 \pm 0.18 \pm 0.04$
  - $A_{KK}^{mix} = 0.17 \pm 0.18 \pm 0.05$
  - First measurement

LHCb-CONF-2012-007 0.69 fb$^{-1}$

~5.4k $B^0 \rightarrow \pi^+ \pi^-$

~5.4k $B^0_s \rightarrow K^+ K^-$
Very rare topologies in $B \rightarrow h^+h^-$

$BR(B^0 \rightarrow K^+K^-) = (0.13^{+0.06}_{-0.05} \pm 0.07) \cdot 10^{-6}$

$BR(B_S^0 \rightarrow \pi^+\pi^-) = (0.98^{+0.23}_{-0.19} \pm 0.11) \cdot 10^{-6}$

First observation of $B_S \rightarrow \pi^+\pi^-$ with $5.3\sigma$ significance
CPV in charm
Search for direct CPV in SCS charm decays

- Direct CPV in charm expected to be small in SM
- In Singly Cabibbo Suppressed (SCS) decays, interference between tree and penguin diagrams gives possibility to NP to manifest itself
- LHCb has very large samples (e.g. statistics in $D^0 \rightarrow hh$ for 2011 data alone are order of magnitude higher than total B-factory yields)
- Clear opportunity for NP search!
CPV in time-integrated $D^0 \rightarrow h^+h^-$ decay rates

- Raw asymmetry for tagged $D^0$ to final state $f$ ($\pi^+\pi^-$ or $K^+K^-$):
  \[
  A_{raw}(f) = \frac{N(D^{*+} \rightarrow D^0(f)\pi^+_s) - N(D^{*-} \rightarrow \bar{D}^0(f)\pi^-_s)}{N(D^{*+} \rightarrow D^0(f)\pi^+_s) + N(D^{*-} \rightarrow \bar{D}^0(f)\pi^-_s)}
  \]

- First order Taylor Expansion:
  \[
  A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})
  \]

- Physics CP asymmetry
- Detection asymmetry of $D^0$
- Production asymmetry
- Detection asymmetry of soft pion
- $A_D(\pi^+\pi^-) = A_D(K^+K^-) = 0$ (Independent of $f$)
CPV in time-integrated $D^o \rightarrow h^+ h^-$ decay rates

- Raw asymmetry for tagged $D^0$ to final state $f$ ($\pi^+\pi^-$ or $K^+K^-$):

$$A_{\text{raw}}(f) = \frac{N(D^{*+} \rightarrow D^0(f)\pi_s^+)}{N(D^{*+} \rightarrow D^0(f)\pi_s^+)} - \frac{N(D^{*-} \rightarrow \bar{D}^0(f)\pi_s^-)}{N(D^{*-} \rightarrow \bar{D}^0(f)\pi_s^-)}$$

- First order Taylor Expansion:

$$A_{\text{RAW}}(f)^* = A_{\text{CP}}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

- Independent of $f$

\[ A_{\text{CP}}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow \bar{f})} \]

\[ A_D(\pi^+\pi^-) = A_D(K^+K^-) = 0 \]

\[ A_{\text{RAW}} = A_{\text{RAW}}(K^+K^-) - A_{\text{RAW}}(\pi^+\pi^-) = \Delta A_{\text{CP}} \]

Nice bonus: in U-spin limit $A_{\text{CP}}(KK) = -A_{\text{CP}}(\pi\pi)$ for any direct CPV, so effect amplified by taking difference
Evidence of CPV in time-integrated $D^{0}\rightarrow h^{+}h^{-}$ decay rates

- $\Delta A_{CP}$ mainly related to direct CP violation. $a_{CP}^{\text{ind}}$ is to a good approx. universal. Contribution from indirect CPV remains if time acceptance is different for $\pi^{+}\pi^{-}$ and $K^{+}K^{-}$ final states:

$$\Delta A_{CP} = \left[a_{CP}^{\text{dir}}(K^{-}K^{+}) - a_{CP}^{\text{dir}}(\pi^{-}\pi^{+})\right] + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\text{ind}}$$

- Result, based on 0.62/fb of 2011 data is

$$\Delta A_{CP} = (-0.82 \pm 0.21_{\text{stat}} \pm 0.11_{\text{syst}})\%$$

(Note also recent preliminary CDF result: [-0.62 +- 0.21 +- 0.10]% [CDF note 10784] )
Evidence of CPV in time-integrated $D^0 \rightarrow h^+ h^-$ decay rates

- **Prospects**
  - Analysis of remainder of 2011 data is ongoing (~0.4/fb)
  - Published analysis selects prompt charm $\rightarrow$ only ~3% of total yield is charm from B
  - Alternative analysis ongoing in which $D^0$ flavour is tagged using charge of $\mu$ in semileptonic B decays $\rightarrow$ completely different systematics, interesting experimental cross-check
  - Precision study of other SCS modes
Conclusions

• Wealth of LHCb results with the first 1/fb collected in 2001 at “CERN’s flavour factory”
  – Everything works (LHC, luminosity leveling, detector, trigger, collaboration, data analysis, ..)
  – World record results on $B_s \rightarrow J/\Psi \phi$, $B_s \rightarrow \mu\mu$, $B_d \rightarrow K^* \mu\mu$ and charm physics. For some topics we are moving from exploration to precision measurements.
  – Many other analyses ongoing (not only in b and c physics)

• Some new territory already explored but SM still depressingly uncracked

• We’ll keep on looking….

• More than double the statistics in 2012

• Working hard to prepare for the future (LHCb Upgrade)
## Statistical sensitivities for LHCb Upgrade

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb(^{-1}))</th>
<th>Theory uncertainty</th>
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</thead>
<tbody>
<tr>
<td>(B^0_s) mixing</td>
<td>(2\beta_s (B^0_s \rightarrow J/\psi \phi))</td>
<td>0.10 [9]</td>
<td>0.025</td>
<td>0.008</td>
<td>(\sim 0.003)</td>
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<tr>
<td></td>
<td>(2\beta_s (B^0_s \rightarrow J/\psi f_0(980)))</td>
<td>0.17 [10]</td>
<td>0.045</td>
<td>0.014</td>
<td>(\sim 0.01)</td>
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<td></td>
<td>(A_{fs}(B^0_s))</td>
<td>(6.4 \times 10^{-3}) [18]</td>
<td>(0.6 \times 10^{-3})</td>
<td>(0.2 \times 10^{-3})</td>
<td>(0.03 \times 10^{-3})</td>
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<tr>
<td>Gluonic penguin</td>
<td>(2\beta^\text{eff}_s (B^0_s \rightarrow \phi \phi))</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(2\beta^\text{eff}_s (B^0_s \rightarrow K^{*0}K^{*0}))</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>(2\beta^\text{eff}_s (B^0_s \rightarrow \phi K^{0}_S))</td>
<td>0.17 [18]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
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<tr>
<td>Right-handed currents</td>
<td>(2\beta^\text{eff}_s (B^0_s \rightarrow \phi \gamma))</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>(\tau^\text{eff}_s (B^0_s \rightarrow \phi \gamma))</td>
<td>–</td>
<td>0.13 %</td>
<td>0.03 %</td>
<td>0.02 %</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>(S_3(B^0 \rightarrow K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4))</td>
<td>0.08 [14]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(A_{FB}(B^0 \rightarrow K^{*0}\mu^+\mu^-))</td>
<td>25 % [14]</td>
<td>8 %</td>
<td>2.5 %</td>
<td>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>0.25 [15]</td>
<td>0.08</td>
<td>0.025</td>
<td>(\sim 0.02)</td>
</tr>
<tr>
<td></td>
<td>(B(B^+ \rightarrow \pi^+\mu^+\mu^-)/B(B^+ \rightarrow K^{+}\mu^+\mu^-))</td>
<td>25 % [16]</td>
<td>8 %</td>
<td>2.5 %</td>
<td>(\sim 10%)</td>
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<td>Higgs penguin</td>
<td>(B(B^0 \rightarrow \mu^+\mu^-))</td>
<td>(1.5 \times 10^{-9}) [2]</td>
<td>(0.5 \times 10^{-9})</td>
<td>(0.15 \times 10^{-9})</td>
<td>(0.3 \times 10^{-9})</td>
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<tr>
<td></td>
<td>(B(B^0 \rightarrow \mu^+\mu^-)/B(B^0 \rightarrow \mu^-\mu^+))</td>
<td>–</td>
<td>(\sim 100%)</td>
<td>(\sim 35%)</td>
<td>(\sim 5%)</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>(\gamma (B \rightarrow D^{(<em>)}\bar{K}^{(</em>)}))</td>
<td>(\sim 20^\circ) [19]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>(\gamma (B^0 \rightarrow D_s\bar{K}))</td>
<td>–</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>(\beta (B^0 \rightarrow J/\psi K^0_S))</td>
<td>0.8° [18]</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm CP violation</td>
<td>(\Delta \Gamma)</td>
<td>(2.3 \times 10^{-3}) [18]</td>
<td>(0.40 \times 10^{-3})</td>
<td>(0.07 \times 10^{-3})</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>(\Delta A_{CP})</td>
<td>(2.1 \times 10^{-3}) [5]</td>
<td>(0.65 \times 10^{-3})</td>
<td>(0.12 \times 10^{-3})</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with 50 fb\(^{-1}\) by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.
MPA, CPV in charm and b-decays at LHCb