CP violation in $B$ mesons and $b$-baryons at LHCb

Thomas Latham
(on behalf of the LHCb Collaboration)

28th September 2017
Overview

• Introduction
  – CP violation
  – The LHCb experiment

• Recent results from LHCb
  – Determination of CKM angle $\beta$ from:
    • $B^0 \rightarrow (J/\psi \rightarrow e^+ e^-)K_S^0$
    • $B^0 \rightarrow (\psi(2S) \rightarrow \mu^+ \mu^-)K_S^0$
  – Search for CPV in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \rightarrow p\pi^-K^+K^-$

• Concluding remarks
CKM mechanism and CP violation

- Standard Model description of quark coupling to weak interaction
- CPV arises due to complex phase in the mixing matrix
- Convenient representation for b-hadron physics is the Unitarity Triangle

- CKM mechanism agrees well with experiment
- But still plenty of room for new physics
- Vital to measure CP violating observables in as many different decay processes as possible
- Look for disagreements
Manifestations of CPV

- **CPV in decay** \(|\frac{\bar{A}_f}{A_f}| \neq 1\)
  - The ratio of the amplitudes for the decay of \(b\) and \(\bar{b}\) hadrons to CP-conjugate final states is not of unit magnitude
  - Only form of CPV possible for \(B^+\) mesons and \(b\)-baryons

- **Mixing-induced CPV** \(\arg(\lambda_f) + \arg(\bar{\lambda}_f) \neq 0\)
  - The ratio of the amplitudes for decays with and without mixing is not real
  - Investigated for both \(B^0\) and \(B^0_s\) decays
  - Requires time-dependent analyses (more on this later)

- **CPV in mixing** \(|\frac{q}{p}| \neq 1\)
  - Expected to be small for the \(B\) meson system
  - Will not discuss this further today (although LHCb has made important measurements in last couple of years)

2011 + 2012 data set (3 fb$^{-1}$) used in analyses discussed today
Measurements of the angle $\beta$
$B^0 \sim \bar{B}^0$ mixing phase

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

- Neutral $B$ mesons exhibit mixing through box diagram
- Decays to $CP$ eigenstates allow to probe the mixing phase $\beta$ through the interference between decays with and without mixing
- Make comparison of direct and indirect determinations (as well as direct determinations in different decays) to probe possible new physics contributions
Time-dependent asymmetries

- The time-dependent CP asymmetry is given by:

\[ A_{CP}^f(t) = \frac{\Gamma[\bar{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\bar{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = -C_f \cos(\Delta m_d \cdot t) + S_f \sin(\Delta m_d \cdot t) \]

- \( C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \)
- \( S_f = \frac{2 \text{Im} \lambda_f}{1 + |\lambda_f|^2} \)
- \( \lambda_f = \frac{q \bar{A}_f}{p A_f} \)

- \( \frac{\bar{A}_f}{A_f} \) is the ratio of decay amplitudes
- \( \frac{q}{p} \) is related to the neutral \( B \) mixing
- In absence of CPV in decay and CPV in mixing:

\[ C_f \approx 0 \text{ and } S_f \approx -\eta_f \sin 2\beta \]

- Where \( \eta_f \) is the CP eigenvalue of the final state
Time dependent analysis

- Vertex measurements by LHCb VELO allow decay times of particles to be precisely determined
- Need also to tag the flavour of the signal at production
- Putting these two pieces of information together, can measure decay rates as a function of the decay time
- Hence allows mixing-induced CPV to be probed
Time dependent analysis

- Need also to account for effects of:
  - Decay time acceptance (due to trigger and selection requirements)
  - Experimental resolution on the measurement of the decay time
  - Rate of mis-tagging the flavour

Primary pp Collision vertex  
Decay of $b$ hadron  
Decay of $\bar{b}$ hadron  

Decay time $O(10^{-12})s$
Previous measurements

- LHCb measurement from 2015 used the decay:
  \[ B^0 \rightarrow J/\psi(\rightarrow \mu^+\mu^-)K_S^0 \]
- Its comparison with results from B factories (and other experiments) shown on right

\[ \sin(2\beta) = \sin(2\phi_1) \]

\[ S_{J/\psi K_S^0} = +0.731 \pm 0.035 \pm 0.020 \]
\[ C_{J/\psi K_S^0} = -0.038 \pm 0.032 \pm 0.005 \]

41,560 tagged signal candidates

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

cf. indirect determination (CKMfitter):
Time-dependent CP asymmetries

• Latest LHCb analysis adds two new decay modes:
  \[ B^0 \to J/\psi(\to e^+e^-)K_S^0 \]
  \[ B^0 \to \psi(2S)(\to \mu^+\mu^-)K_S^0 \]

• The fits to the \( B^0 \) candidate invariant mass spectra yield \( 10,630 \pm 140 \) and \( 7970 \pm 100 \) signal candidates, respectively

• Effective tagging efficiencies are \((5.93 \pm 0.29)\%\) and \((3.42 \pm 0.09)\%\)

\[
S_{J/\psi K_S^0} = +0.83 \pm 0.08 \pm 0.01 \\
C_{J/\psi K_S^0} = +0.12 \pm 0.07 \pm 0.02
\]

\[
S_{\psi(2S) K_S^0} = +0.84 \pm 0.10 \pm 0.01 \\
C_{\psi(2S) K_S^0} = -0.05 \pm 0.10 \pm 0.01
\]
Combination

• Combining these new measurements with the previous LHCb result produces a 20% reduction in the uncertainty
• Expected to improve precision in the World Average
• Consistent with B-factory measurements within 2σ
• Expected to further reduce the tension with the indirect determination

\[
S_{J/\psi K_S^0} = +0.75 \pm 0.04 \\
C_{J/\psi K_S^0} = -0.014 \pm 0.030
\]

\[
S_{(c\bar{c})K_S^0} = +0.760 \pm 0.034 \\
C_{(c\bar{c})K_S^0} = -0.017 \pm 0.029
\]
CPV in \( b \)-baryon decays
The search for CPV in b-baryons

\[ \Lambda_b^0 \to p\eta^- \]

\[ A_{CP}(\Lambda_b^0 \to p\pi^-) = +0.06 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)} \]
\[ A_{CP}(\Lambda_b^0 \to pK^-) = -0.10 \pm 0.08 \text{ (stat)} \pm 0.04 \text{ (syst)} \]

Consistent with CP symmetry

\[ \Lambda_b^0 (\Xi_b^0) \to K_S^0 p\pi^- \]
JHEP 04 (2014) 087

\[ A_{CP}(\Lambda_b^0 \to K_S^0 p\pi^-) = 0.22 \pm 0.13 \text{ (stat)} \pm 0.03 \text{ (syst)} \]

\[ \Lambda_b^0 (\Xi_b^0) \to \Lambda h^+ h^- \]
JHEP 05 (2016) 081

\[ A_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) = -0.53 \pm 0.23 \text{ (stat)} \pm 0.11 \text{ (syst)} \]
\[ A_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = -0.28 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ (syst)} \]

Evidence for \( \Lambda_b^0 \) decay to \( \Lambda\eta \) final state.
Observed \( \Lambda_b^0 \to \Lambda\phi \) decay but CPV consistent with zero.

\[ \Lambda_b^0 \to \Lambda \eta, \Lambda \phi \]
JHEP 09 (2015) 006

\[ \Delta A_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) = (-3.5 \pm 5.0 \pm 0.2) \times 10^{-2} \]
\[ a_{CP}^{\Lambda_b^0 \text{ odd}} = (1.2 \pm 5.0 \pm 0.7) \times 10^{-2} \]

1st observation of \( \Xi_b^- \) decay to charmless final state.
No CPV measurements performed yet.

\[ \Xi_b^- (\Omega_b^-) \to p h^- h^- \]

\[ \Lambda_b^0 (\Xi_b^0) \to p h^- h^- h^+ \]

Will discuss this analysis in more detail on the following slides...
Why charmless decays?

- Large CP asymmetries have been observed in many charmless B meson decays,
  e.g. $B^+ \rightarrow h^+ h^+ h^-$ [Phys. Rev. D 90 (2014) 112004]

- Contributions from both loop (penguin) and tree decay diagrams

- Have comparable magnitude and a relative weak phase ($= \gamma$ in SM)

- Interference can therefore give rise to CP violation in decay

- Natural to expect (large) CPV in similar decays of b-baryons as well
Search for CPV in $\Lambda_b^0 \rightarrow p\pi^-h^+h^-$

- The $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \rightarrow p\pi^-K^+K^-$ decays, observed for the first time, are analysed to search for CP violation.
- The $\Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow pK^-\pi^+, \rho\pi^-\pi^+, pK^-K^+)\pi^-$ and $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ modes are used as control channels (for signal selection and systematic studies).

$$N_{\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-} = 6646 \pm 105$$

$$N_{\Lambda_b^0 \rightarrow p\pi^-K^+K^-} = 1030 \pm 56$$
Triple-product observables

- Exploit the topology of the 4-body decay and construct observables that are scalar triple products of the final-state momenta

- For $\Lambda_b^0$ decays:
  \[ C_\hat{T} = \vec{p}_p \cdot \left( \vec{p}_{h_1^-} \times \vec{p}_{h_2^+} \right) \]

- For $\bar{\Lambda}_b^0$ decays:
  \[ \bar{C}_\hat{T} = \vec{p}_{\bar{p}} \cdot \left( \vec{p}_{h_1^+} \times \vec{p}_{h_2^-} \right) \]

- From these $C_\hat{T}$ and $\bar{C}_\hat{T}$ observables, can define asymmetries that are odd under both the $P$ and $\hat{T}$ operators
Asymmetry observables

- Divide data into 4 sub-samples depending on $\Lambda_b^0$ flavour and sign of the triple-product observable
- Determine signal yield in each sub-sample to construct the asymmetries

$$A_T(C_T) = \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)}$$

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

$CP$-violating asymmetry
$$a_{\text{CP}}^{T-\text{odd}} = \frac{1}{2} (A_T - \bar{A}_T)$$

$P$-violating asymmetry
$$a_P^{T-\text{odd}} = \frac{1}{2} (A_T + \bar{A}_T)$$
Phase-space binning schemes

- Phase space integrated asymmetries found to be compatible P and CP conservation
- To enhance the sensitivity to localised effects, also measure the asymmetries in regions of phase space:

**Scheme A:** Isolate regions of phase-space with dominant resonant contributions

**Scheme B:** Exploit contributing resonance interference as function of $|\Phi|$
Evidence of CPV in $\Lambda_b^0 \rightarrow p\pi^+\pi^−\pi^+$

- Combined significance of the 2 binning schemes determined using a permutation test:
  - 3.3 $\sigma$ deviation from CP-symmetry & 2.2 $\sigma$ deviation from P-symmetry
- This constitutes first evidence for CPV in the baryon sector
- $\Lambda_b^0 \rightarrow p\pi^+K^-K^+$ (lower purity and yield) is found to be consistent with conservation of CP and P symmetries
Branching fractions of $\Lambda_b^0/\Xi_b^0 \rightarrow ph^-h'^+h''^-$ decays

- New analysis aims to establish the signals and measure the branching fractions of whole family of these decays
  - with respect to normalisation channel: $\Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow pK^-\pi^+)\pi^-$
- There are five final states, which are analysed simultaneously to improve control of systematics from mis-ID backgrounds etc.
- The 5D phase-space makes extremely difficult the ideal procedure of evaluating per-event efficiencies (as done in many 3-body decays, e.g. recent analysis of $B_{(s)}^0 \rightarrow K_S^0 h^+ h'^-$ discussed yesterday)
- This analysis therefore aims to reduce to an absolute minimum the variation of the efficiency over the phase space
- Important consequence: must rely on hardware triggers made independent of the signal candidates – results in uniform, but reduced, efficiency
Fit results

\[ \Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^- \]

**LHCb** Preliminary

<table>
<thead>
<tr>
<th>Data</th>
<th>Fit</th>
<th>( \Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^- )</th>
<th>( \Lambda_b^0 \rightarrow pK^+\pi^-\pi^- )</th>
<th>( \Xi_b^0 \rightarrow \Lambda_b^0pK^+\pi^-\pi^- )</th>
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</table>

\[ m(p\pi^-\pi^+\pi^-) \ [\text{MeV}/c^2] \]

1809 ± 48

\[ \Lambda_b^0/\Xi_b^0 \rightarrow pK^-\pi^+\pi^- \]

**LHCb** Preliminary

<table>
<thead>
<tr>
<th>Data</th>
<th>Fit</th>
<th>( \Xi_b^0 \rightarrow pK^-\pi^+\pi^- )</th>
<th>( \Lambda_b^0 \rightarrow pK^-\pi^+\pi^- )</th>
<th>( \Lambda_b^0 \rightarrow pK^-\pi^-\pi^+ )</th>
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</table>

\[ m(pK^-\pi^+\pi^-) \ [\text{MeV}/c^2] \]

5193 ± 76

\[ 183 \pm 22 \]
Fit results

\[ \Lambda_b^0 \rightarrow pK^-K^+\pi^- \]

\[ \Xi_b^0 \rightarrow pK^-\pi^+K^- \]

444 ± 30

199 ± 21

28/09/2017

CP violation in b-hadrons at LHCb
Fit results

\[ \Lambda_b^0 / \Xi_b^0 \rightarrow pK^- K^+ K^- \]

- All decays searched for are observed except for \( \Xi_b^0 \rightarrow pK^- K^+ K^- \), for which the signal significance is 2.3\( \sigma \)

\[ \Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow pK^- \pi^+) \pi^- \]

\( 17650 \pm 140 \)
Branching fractions

- The preliminary results for absolute branching fractions are calculated using the world average values:
  \[ B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = (0.430 \pm 0.036)\% \]
  \[ B(\Lambda_c^+ \to pK^-\pi^+) = (6.46 \pm 0.24)\% \]

- In the case of the \( \Xi_b^0 \) decays, the results are a product of the BF and the currently unknown ratio of hadronisation fractions: \( f_{\Xi_b^0}/f_{\Lambda_b^0} \)

- The uncertainties are statistical, systematic and due to the two sub-BFs of the normalisation channel

\[
\begin{align*}
B(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) &= (1.90 \pm 0.06 \pm 0.10 \pm 0.16 \pm 0.07) \times 10^{-5} \\
B(\Lambda_b^0 \to pK^-\pi^+\pi^-) &= (4.55 \pm 0.08 \pm 0.20 \pm 0.39 \pm 0.17) \times 10^{-5} \\
B(\Lambda_b^0 \to pK^-K^+\pi^-) &= (0.37 \pm 0.03 \pm 0.04 \pm 0.03 \pm 0.01) \times 10^{-5} \\
B(\Lambda_b^0 \to pK^-K^+K^-) &= (1.14 \pm 0.03 \pm 0.07 \pm 0.10 \pm 0.05) \times 10^{-5}
\end{align*}
\]
Concluding remarks

- **Wide spectrum of CP-violation measurements** ongoing at LHCb

- Run 1 measurements of CKM angle $\beta$ made in 3 "golden modes"
  - Reduced uncertainty by 20% with the addition of two new modes

- Observation of $CP$-violation in $b$-baryons still elusive but first evidence now obtained from $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays
  - Many other decay modes with newly established signals being studied

- Run 2 data sample being taken already exceeds size of Run 1 – look out for updates soon
  - Many measurements also of CKM phases $\gamma$ and $\beta_s$ ongoing that I was not able to cover today

- Looking further forward, the **LHCb upgrade** will bring unprecedented precision in these areas
  - Excellent prospects for making precision tests of the Standard Model explanation of CP violation
Backup Slides
CKM mechanism and CP violation

• Standard Model description of quark coupling to weak interaction

• CPV arises due to complex phase in the mixing matrix

• Convenient representation for $b$-hadron physics is the Unitarity Triangle

• Angles and side lengths can be measured through various $B$-decay processes
The LHCb detector

LHCb $\sigma(pp \rightarrow H_b X)$ @ 7 TeV = $(72.0 \pm 0.3 \pm 6.8)$ µb
LHCb $\sigma(pp \rightarrow H_b X)$ @ 13 TeV = $(154.3 \pm 1.5 \pm 14.3)$ µb

Kaon/pion separation

- Most particle identification information comes from the Ring Imaging Cherenkov detectors.
- Three different radiators provide separation over a wide momentum range.

\[ \cos \theta = \frac{1}{\beta n} \]
Trigger categories

Trigger On Signal
- Particle from the signal decay fires a trigger line.
- Triggered by HCAL deposits.

Trigger Independent of Signal
- Particle from the rest of the event fires a trigger line.
- Triggered mostly by HCAL deposits or muons.

Trigger Efficiencies:
- ~30% efficient for multi-body hadronic
- ~90% efficient for di-muons
$K_S^0$ reconstruction

- $K_S^0$ decays to $\pi^+\pi^-$ divided into two categories:
  - **Long**: pion tracks have hits in the vertex detector (VELO)
  - **Downstream**: pion tracks have no VELO hits
Time-dependent decay rates

- For an initially pure flavour eigenstate, time evolution proceeds according to:

\[
\frac{d\Gamma[B_{d,s}^0(t) \to f]}{dt} \propto e^{-\Gamma t} \left[ \left( |A_f|^2 + |\bar{A}_f|^2 \right) \cosh(\frac{\Delta \Gamma_{d,s}}{2} t) + \left( |A_f|^2 - |\bar{A}_f|^2 \right) \cos(\Delta m_{d,s} t) \right] \\
\frac{d\Gamma[\bar{B}_{d,s}^0(t) \to f]}{dt} \propto e^{-\Gamma t} \left[ \left( |A_f|^2 + |\bar{A}_f|^2 \right) \cosh(\frac{\Delta \Gamma_{d,s}}{2} t) - \left( |A_f|^2 - |\bar{A}_f|^2 \right) \cos(\Delta m_{d,s} t) \right]
\]

- The time-dependent CP asymmetry is therefore:

\[
A_{CP}(t) = \frac{\Gamma[\bar{B}_{d,s}^0(t) \to f] - \Gamma[B_{d,s}^0(t) \to f]}{\Gamma[\bar{B}_{d,s}^0(t) \to f] + \Gamma[B_{d,s}^0(t) \to f]} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh(\frac{\Delta \Gamma_{d,s}}{2} t) + A_f^{\Delta \Gamma_{d,s}} \sinh(\frac{\Delta \Gamma_{d,s}}{2} t)}
\]

\[
C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \quad S_f = \frac{2\text{Im}\lambda_f}{1 + |\lambda_f|^2} \quad \lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f} \quad \frac{q}{p} \bar{A}_f \quad |A_f|^2 = \frac{2\text{Re}\lambda_f}{1 + |\lambda_f|^2}
\]

- \[|C_f|^2 + |S_f|^2 + |A_f^{\Delta \Gamma}|^2 = 1\]
- \[
\frac{q}{p} \bar{A}_f \quad \text{is related to the neutral } B \text{ mixing}
\]
- \[
\frac{\bar{A}_f}{A_f} \quad \text{is the ratio of decay amplitudes}
\]
\( B^0 \rightarrow (c\bar{c})K_S^0 \) invariant mass distributions

![Graphs showing mass distributions for \( B^0 \rightarrow J/\psi K_S^0 \) and \( B^0 \rightarrow \psi(2S)K_S^0 \) processes as measured by LHCb.](image-url)
$B^0 \to (c\bar{c})K_S^0$ decay time distributions

\begin{align*}
\text{LHCb} \\
B^0 \to J/\psi K_S^0 \\
\text{LHCb} \\
B^0 \to \psi(2S)K_S^0
\end{align*}

Candidates / (0.15 ps)

Decay time [ps]
\( B^0 \to (c \bar{c}) K^0_s \) tagging performance and external inputs

<table>
<thead>
<tr>
<th>Tagger</th>
<th>( B^0 \to J/\psi K^0_s )</th>
<th>( B^0 \to \psi(2S) K^0_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>3.60(13)</td>
<td>2.46(5)</td>
</tr>
<tr>
<td>SS</td>
<td>2.40(28)</td>
<td>1.07(8)</td>
</tr>
<tr>
<td>OS + SS</td>
<td>5.93(29)</td>
<td>3.42(9)</td>
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</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value and uncertainty</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A^7_{Pb} (J/\psi) )</td>
<td>(-0.0100 \pm 0.0084 \pm 0.0005)</td>
<td>[23]</td>
</tr>
<tr>
<td>( A^8_{Pb} (J/\psi) )</td>
<td>(-0.0077 \pm 0.0054 \pm 0.0004)</td>
<td>[23]</td>
</tr>
<tr>
<td>( A^7_{Pb} (\psi(2S)) )</td>
<td>(-0.0143 \pm 0.0077 \pm 0.0005)</td>
<td>[23]</td>
</tr>
<tr>
<td>( A^8_{Pb} (\psi(2S)) )</td>
<td>(-0.0138 \pm 0.0051 \pm 0.0003)</td>
<td>[23]</td>
</tr>
<tr>
<td>( \Delta m [\text{ps}^{-1}] )</td>
<td>(0.5065 \pm 0.0016 \pm 0.0011)</td>
<td>[6]</td>
</tr>
<tr>
<td>( \tau [\text{ps}] )</td>
<td>(1.520 \pm 0.004)</td>
<td>[6]</td>
</tr>
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</table>
$B^0 \rightarrow (c\bar{c})K_S^0$ systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$B^0 \rightarrow J/\psi K_S^0$</th>
<th></th>
<th>$B^0 \rightarrow \psi(2S)K_S^0$</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>$\sigma_S$</td>
<td>$\sigma_C$</td>
<td>$\sigma_S$</td>
<td>$\sigma_C$</td>
</tr>
<tr>
<td>$\Delta \Gamma$</td>
<td>0.003</td>
<td>0.007</td>
<td>0.007</td>
<td>0.003</td>
</tr>
<tr>
<td>$\Delta m$</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Production asymmetry</td>
<td>0.004</td>
<td>0.009</td>
<td>0.007</td>
<td>0.005</td>
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<tr>
<td>Tagging calibration</td>
<td>0.002</td>
<td>0.005</td>
<td>0.005</td>
<td>0.002</td>
</tr>
<tr>
<td>Decay-time bias</td>
<td>0.006</td>
<td>0.006</td>
<td>0.006</td>
<td>0.004</td>
</tr>
<tr>
<td>$\sigma_t$ scaling</td>
<td>0.003</td>
<td>0.005</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Decay-time efficiency</td>
<td>0.006</td>
<td>0.004</td>
<td>0.006</td>
<td>0.004</td>
</tr>
<tr>
<td>Total</td>
<td>0.011</td>
<td>0.016</td>
<td>0.014</td>
<td>0.010</td>
</tr>
</tbody>
</table>
Outlook for $b$-baryons

• Following establishment of signals in the other $ph^-h^+h^-$ final states, CPV is now being studied

• Analysis of $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ (and other modes) to be updated to include Run 2 data

• Exciting new prospects from recent first observation of $\Xi^-_b \to pK^-K^-$ [PRL 118 (2017) 071801]

• Very rich structure in these decays – possibility for amplitude analyses
  – See e.g. recent analysis of $\Lambda^0_b \to D^0p\pi^-$ [arXiv:1701.07873]

• Open question is whether CPV effects (once they are observed) can be related back to fundamental CKM parameters
### Yields and efficiencies

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Signal yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$</td>
<td>1809 $\pm$ 48</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$</td>
<td>5193 $\pm$ 76</td>
</tr>
<tr>
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<td>444 $\pm$ 30</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow pK^-K^+K^-$</td>
<td>1706 $\pm$ 46</td>
</tr>
<tr>
<td>$\Xi_b^0 \rightarrow pK^-\pi^+\pi^-$</td>
<td>183 $\pm$ 22</td>
</tr>
<tr>
<td>$\Xi_b^0 \rightarrow pK^-\pi^+K^-$</td>
<td>199 $\pm$ 21</td>
</tr>
<tr>
<td>$\Xi_b^0 \rightarrow pK^-K^+K^-$</td>
<td>27 $\pm$ 14</td>
</tr>
</tbody>
</table>

#### 2011

<table>
<thead>
<tr>
<th>Decays</th>
<th>Acceptance</th>
<th>Ratios of efficiencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$</td>
<td>1.050 $\pm$ 0.004</td>
<td>0.425 $\pm$ 0.009</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$</td>
<td>1.004 $\pm$ 0.004</td>
<td>0.432 $\pm$ 0.009</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow pK^-K^+\pi^-$</td>
<td>0.970 $\pm$ 0.004</td>
<td>0.468 $\pm$ 0.010</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow pK^-K^+K^-$</td>
<td>0.916 $\pm$ 0.003</td>
<td>0.452 $\pm$ 0.010</td>
</tr>
<tr>
<td>$\Xi_b^0 \rightarrow pK^-\pi^+\pi^-$</td>
<td>1.009 $\pm$ 0.004</td>
<td>0.424 $\pm$ 0.009</td>
</tr>
<tr>
<td>$\Xi_b^0 \rightarrow pK^-\pi^+K^-$</td>
<td>0.969 $\pm$ 0.004</td>
<td>0.450 $\pm$ 0.010</td>
</tr>
<tr>
<td>$\Xi_b^0 \rightarrow pK^-K^+K^-$</td>
<td>0.922 $\pm$ 0.003</td>
<td>0.429 $\pm$ 0.009</td>
</tr>
</tbody>
</table>

#### 2012

<table>
<thead>
<tr>
<th>Decays</th>
<th>Acceptance</th>
<th>Ratios of efficiencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$</td>
<td>1.070 $\pm$ 0.003</td>
<td>0.433 $\pm$ 0.011</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$</td>
<td>1.020 $\pm$ 0.003</td>
<td>0.438 $\pm$ 0.011</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow pK^-K^+\pi^-$</td>
<td>0.978 $\pm$ 0.003</td>
<td>0.462 $\pm$ 0.012</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow pK^-K^+K^-$</td>
<td>0.928 $\pm$ 0.003</td>
<td>0.445 $\pm$ 0.012</td>
</tr>
<tr>
<td>$\Xi_b^0 \rightarrow pK^-\pi^+\pi^-$</td>
<td>1.019 $\pm$ 0.003</td>
<td>0.431 $\pm$ 0.011</td>
</tr>
<tr>
<td>$\Xi_b^0 \rightarrow pK^-\pi^+K^-$</td>
<td>0.979 $\pm$ 0.003</td>
<td>0.434 $\pm$ 0.011</td>
</tr>
<tr>
<td>$\Xi_b^0 \rightarrow pK^-K^+K^-$</td>
<td>0.929 $\pm$ 0.003</td>
<td>0.425 $\pm$ 0.011</td>
</tr>
</tbody>
</table>
Table 16: 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. Note that the current sensitivities do not include new results presented at ICHEP 2012 or CKM2012.

<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>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$</td>
<td>0.10 [138]</td>
<td>0.025</td>
<td>0.008</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$</td>
<td>0.17 [214]</td>
<td>0.045</td>
<td>0.014</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$a_{s1}$</td>
<td>$6.4 \times 10^{-3}$ [43]</td>
<td>$0.6 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-3}$</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gluonic penguins</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \phi)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow K^{*0} \bar{K}^{*0})$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi K_S^0)$</td>
<td>0.17 [43]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \gamma)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{\text{eff}} (B_s^0 \rightarrow \phi \gamma) / \tau_{\bar{B}_s^0}$</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguins</td>
<td>$S_3 (B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.08 [67]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB} (B^0 \rightarrow K^{*0} \mu^+ \mu^-)$</td>
<td>25% [67]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>$A_1 (K\mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.25 [76]</td>
<td>0.08</td>
<td>0.025</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/B(B_s^0 \rightarrow K^+ \mu^+ \mu^-)$</td>
<td>25% [85]</td>
<td>8%</td>
<td>2.5%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$B(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>$1.5 \times 10^{-9}$ [13]</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$B(B_s^0 \rightarrow \mu^+ \mu^-)/B(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>–</td>
<td>$\sim 100%$</td>
<td>$\sim 35%$</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle angles</td>
<td>$\gamma (B \rightarrow D^{(<em>)} K^{(</em>)})$</td>
<td>$\sim 10-12^\circ$ [244, 258]</td>
<td>$4^\circ$</td>
<td>$0.9^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B_s^0 \rightarrow D_s K)$</td>
<td>–</td>
<td>11$^\circ$</td>
<td>$2.0^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \rightarrow J/\psi K_S^0)$</td>
<td>$0.8^\circ$ [43]</td>
<td>$0.6^\circ$</td>
<td>$0.2^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_{\Gamma}$</td>
<td>$2.3 \times 10^{-3}$ [43]</td>
<td>$0.40 \times 10^{-3}$</td>
<td>$0.07 \times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$</td>
<td>$2.1 \times 10^{-3}$ [18]</td>
<td>$0.65 \times 10^{-3}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>