Opportunities for Run II
(for CP violation measurements in B decays)

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Implications of LHCb Measurements
and Future Prospects

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Outline

• For each of four main areas:
  – (i) $a_{sl}^{d,s}$ from semileptonic decays; (ii) $\gamma$ from $B \rightarrow DK$;
    (iii) $2\beta_{(s)}$ from $b \rightarrow c\bar{c}s$; (iv) $\gamma$ and $2\beta_{(s)}$ from charmless decays

consider

  – current status
  – prospects to reduce experimental uncertainty
  – other aspects: assumptions in the analyses; data-driven ways to reduce “theory uncertainty”
Run I and Run II

- **Run I**
  - 2011: 1/fb recorded at $\sqrt{s} = 7$ TeV
  - 2012: 2/fb recorded at $\sqrt{s} = 8$ TeV
  - L0Hadron: typically 1:1 TOS:TIS for $B \rightarrow DX$ decays

- **Some key measurements not yet on full data set, e.g.**
  - 1/fb: $a_{sl}^s$, $\gamma$ (GLW/ADS), $\sin(2\beta)$, $B_s \rightarrow K^+K^-$
  - 3/fb: $a_{sl}^d$, $\gamma$ (GGSZ), $2\beta_s$, $B_s \rightarrow \phi\phi$

- **Improvement is not just $\sqrt{\int L dt}$, nor $\sqrt{\int L dt \times \sigma}$**
  - better S/B separation, better flavour tagging, etc.
  - but in future stocks could go down as well as up ...

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Examples

• $2\beta_s$ (aka $\phi_s$) from $B_s \rightarrow J/\psi\phi$
  - Signal yield: $27,500 \rightarrow 95,000$
  - Tagging ($\epsilon D^2$): $3.1\% \rightarrow 3.7\%$
  - Stat. error: $0.09 \rightarrow 0.049$

• $\gamma$ from $B \rightarrow DK \ GGSZ$
  - $1/fb$ ($LHCb$-PAPER-2012-027) → $3/fb$ ($LHCb$-PAPER-2014-041)
  - Signal yield: $650 \rightarrow 2250$
  - Stat. error ($r_B$): $0.04 \rightarrow 0.02$
Run I and Run II

- **Run I**
  - 2011: 1/fb recorded at $\sqrt{s} = 7$ TeV
  - 2012: 2/fb recorded at $\sqrt{s} = 8$ TeV
  - L0Hadron: typically 1:1 TOS:TIS for $B \to DX$ decays

- **Run II**
  - Expect 5-6/fb to be recorded at $\sqrt{s} = 13$ TeV
  - Trigger settings under discussion

Large increase in yields is coming, but … not immediately and not equally for all channels
$a_{s_{l}}^{d,s}$ from semileptonic decays

$$a_{s_{l}}^{d} = (-0.02 \pm 0.19 \pm 0.30)\%$$
$a_{sl}^{d,s}$ from semileptonic decays

• Prospects for reduction of uncertainties
  - Statistical:
    • $a_{sl}^s$ update to 3/fb, use more $D_s$ decays
  - Systematic:
    • largest contribution due to detection asymmetries
    • related to size of control samples → expect reduction

• Other aspects:
  - assumptions that SL decays are (i) flavour-specific & (ii) CP conserving; also CPT assumed to be conserved (see e.g. arXiv:1407.1269)
    • shouldn’t these be experimentally tested? [n.b. very hard to test (ii) @ LHCb]
  - contribution to D0 inclusive dimuon result if $\Delta \Gamma_d \neq 0$; important therefore to measure it (LHCb-PAPER-2013-065; 1/fb)
\( \gamma \) from \( B \to DK \)

- Sensitivity to \( \gamma \) from numerous channels
  - \( B^+ \to DK^+ (D \to K_S hh) \)
  - \( B^+ \to DK^+ (D \to hh') \)
  - \( B_s \to D_s K \)
  - \( B^0 \to DK^{*0} (D \to hh') \)
    - \( B^0 \to DK\pi (D \to hh') \)
  - \( B^+ \to DK^+ (D \to K_S K\pi) \)
  - \( B^+ \to DK^+ (D \to K_3\pi, 4h, hh'\pi^0) \)
  - \( B^0 \to DK^{*0} (D \to K_S hh') \)
  - \( B^+ \to DK^+\pi\pi (D \to hh', K_S hh', \text{etc.}) \)
  - \( B^+ \to D^*K^+ (D \to hh', K_S hh', \text{etc.}) \) ... and many, many more

Colour code: \(3/fb; 1/fb; \text{not yet}\)
Which modes add most?

- Could save time & effort if we knew a priori which modes give the most $\gamma$ sensitivity
- No golden rule, but we want
  - potentially large CP violation (large $r_B$)
  - large yield
    - high product branching fraction x efficiency [in practice: few final state particles]
  - reduced reliance on flavour tagging
  - enough observables to reduce ambiguities
- Several modes seem to have good potential, e.g.
  - $B^0 \rightarrow DK\pi$ Dalitz plot analysis
  - $B^+ \rightarrow DK^+ (D \rightarrow \pi\pi\pi^0)$ [n.b. $B(D \rightarrow \pi\pi\pi^0) \sim 10 \times B(D \rightarrow \pi\pi)$]
Prospects for $\gamma$ sensitivity

• Still much to come from Run I
  - Official projection is that we reach $7^\circ$ sensitivity
• Run II data-doubling time will be years, not months
  - Will need to squeeze the most out of the data
• Other aspects:
  - Systematic uncertainties generally small
    • Must consider correlations between analyses in combination
  - Negligible theoretical uncertainty
  - Combination already considering sub-$1^\circ$ level effects
    • e.g. charm mixing & CP violation (see, e.g., arXiv:1307.4384)
2β(s) from $b \to c\bar{c}s$

$$\sin(2\beta) \equiv \sin(2\phi_1)$$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value (68% CL)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar ($\chi_{c0}$ $K_S$)</td>
<td>$0.69 \pm 0.03 \pm 0.01$</td>
<td>PRD 79 (2009) 072009</td>
</tr>
<tr>
<td>BaBar J/ψ (hadronic) $K_S$</td>
<td>$0.69 \pm 0.04 \pm 0.07$</td>
<td>PRD 69 (2004) 052001</td>
</tr>
<tr>
<td>Belle</td>
<td>$0.67 \pm 0.02 \pm 0.01$</td>
<td>PRL 108 (2012) 171801</td>
</tr>
<tr>
<td>ALEPH</td>
<td>$0.84 \pm 0.02 \pm 0.16$</td>
<td>PLB 492, 259 (2006)</td>
</tr>
<tr>
<td>OPAL</td>
<td>$3.20 \pm 0.90 \pm 0.50$</td>
<td>EPJ C5, 379 (1998)</td>
</tr>
<tr>
<td>CDF</td>
<td>$0.79 \pm 0.41$</td>
<td>PRD 61, 072005 (2000)</td>
</tr>
<tr>
<td>LHCb</td>
<td>$0.73 \pm 0.07 \pm 0.04$</td>
<td>PLB 724 (2013) 24</td>
</tr>
<tr>
<td>Belle5S</td>
<td>$0.57 \pm 0.58 \pm 0.06$</td>
<td>PRL 108 (2012) 171801</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>$0.68 \pm 0.02$</td>
<td><strong>HFAG</strong></td>
</tr>
</tbody>
</table>

3/fb update on sin(2β) from $B^0 \to J/\psi K_S$ will be close to world-leading

LHCb 3/fb results dominate world average of $\phi_s$ from $B_s \to J/\psi \{\phi,\pi\pi\}$
Can we do (even) better on $2\beta_{(s)}$ ?

Many channels studied for $\sin(2\beta)$, not only $B^0 \to J/\psi K_S$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\text{BaBar}$ N(BB)=465M</th>
<th>$\text{Belle}$ N(BB)=772M</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K_S (\eta_{CP}=-1)$</td>
<td>$0.657 \pm 0.036 \pm 0.012$</td>
<td>$0.670 \pm 0.029 \pm 0.013$</td>
<td>$0.665 \pm 0.024$ (0.023 stat-only)</td>
</tr>
<tr>
<td>$J/\psi K_L (\eta_{CP}=+1)$</td>
<td>$0.694 \pm 0.061 \pm 0.031$</td>
<td>$0.642 \pm 0.047 \pm 0.021$</td>
<td>$0.663 \pm 0.041$ (0.037 stat-only)</td>
</tr>
<tr>
<td>$J/\psi K^0$</td>
<td>$0.666 \pm 0.031 \pm 0.013$</td>
<td>-</td>
<td>$0.665 \pm 0.022$ (0.019 stat-only)</td>
</tr>
<tr>
<td>$\psi(2S)K_S (\eta_{CP}=-1)$</td>
<td>$0.897 \pm 0.100 \pm 0.036$</td>
<td>$0.738 \pm 0.079 \pm 0.036$</td>
<td>$0.807 \pm 0.067$ (0.062 stat-only)</td>
</tr>
<tr>
<td>$\psi(nS)K^0$</td>
<td>-</td>
<td>-</td>
<td>$0.676 \pm 0.021$ (0.018 stat-only)</td>
</tr>
<tr>
<td>$\chi_{c1} K_S (\eta_{CP}=-1)$</td>
<td>$0.614 \pm 0.160 \pm 0.040$</td>
<td>$0.640 \pm 0.117 \pm 0.040$</td>
<td>$0.632 \pm 0.099$ (0.094 stat-only)</td>
</tr>
<tr>
<td>$\eta_c K_S (\eta_{CP}=-1)$</td>
<td>$0.925 \pm 0.160 \pm 0.057$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$J/\psi K^0 (K^0 \to K_S \pi^0) (</td>
<td>\eta_{CP}</td>
<td>=1-2</td>
<td>A_L</td>
</tr>
<tr>
<td><strong>All charmonium</strong></td>
<td>$0.687 \pm 0.028 \pm 0.012$</td>
<td>$0.667 \pm 0.023 \pm 0.012$</td>
<td>$0.677 \pm 0.020$ (0.018 stat-only)</td>
</tr>
</tbody>
</table>

😊 rating indicates favourability at LHCb

How about $\phi_s$?
- Can (should) add $\psi(2S)\phi$, $\chi_{c1} \phi$, $\eta_c \phi$, $J/\psi \eta'$, etc. but gain will be marginal
- More to gain in $B_s \to J/\psi KK$ at high $m(KK)$? [Also $J/\psi \to ee$ can be added]

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(and, always, trying to squeeze more out of the tagging)
Other aspects related to $2\beta_{(s)}$

- $B_s \to J/\psi$ KK analysis now very sophisticated
  - KK S-wave handled model-independently
  - Different CP violation effects allowed in each polarisation amplitude

- Assumptions of $\Delta\Gamma_d = 0$ ($\sin(2\beta)$ analysis) and CPT conservation (both) can be tested in dedicated analyses

- Only(?) remaining concern is possible penguin pollution
  - Study $b \to c\bar{c}d$ modes related by flavour symmetries ($B^0 \to J/\psi \rho^0; J/\psi \omega, B_s \to J/\psi K_S, J/\psi K^{*0}$)
  - Related: exploit U-spin relation between $B^0 \to D^+D^-$ and $B_s \to D_s^+D_s^-$

How can we quantify effects of flavour-symmetry breaking?
Aside on \( b \to c \bar{c} d \)

\[
\sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_{1 \text{eff}}) \]

Currently no LHCb results on this plot, but will add results on \( B^0 \to J/\psi \rho^0 \) (LHCb-PAPER-2014-058) and expect to be competitive for \( D(*)D(*) \)

In addition, should get best results on CP violation in decay in \( B^+ \to J/\psi \pi^+ \), \( \bar{D}^0D^+ \) and \( B_s \to J/\psi K^{*0} \)

A lot still to do!
**sin(2\beta_{eff}) from b → qqs decays**

$$sin(2\beta_{eff}) \equiv sin(2\phi_{1}^{eff})$$

Also no LHCb results on this plot (yet). Modes studied in $B^0 \rightarrow K_S hh$ Dalitz plot analyses are accessible in high yields:

- $K_S \pi^+\pi^-$
- $K_S K^+K^-$

Sensitivity generally better for $B_s$ modes (more convenient final states; better flavour-tagging; $\Delta \Gamma_s \neq 0$)

**Done:** $B_s \rightarrow K^+K^- (1/fb)$, $\phi\phi (3/fb)$

**To come:** $B_s \rightarrow K^{*0}K^{*0}$, $K_SK\pi$
Flavour symmetries in $b \to q\bar{q}s$ decays

- Possibility to study both $B^0$ and $B_s$ decays opens many opportunities for studies based on flavour symmetries
  - e.g. relation between $B_s \to K^+K^-$ and $B^0 \to \pi^+\pi^-$


How can we control the maximum allowed U-spin breaking ($\kappa$)?

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Will be important for many analyses
Hadronic effects in $b \to q\bar{q}s$ decays

- Further challenges from hadronic effects in three-body decays
  - Striking CP violation effects observed
  - What is best approach to understand their origin? Model-independent or model-dependent approach?
  - Interpretation in terms of resonant contributions ($\phi$, $\rho$, $K^*$, etc.) needs model-dependent Dalitz plot fits – very challenging!

Possibility for similar analyses to search for CP violation in $b$ baryon decays – even more challenging!
Summary

• Over 200 papers published on Run I data …
  – … but still many important analyses to be done
• Run II data will allow significant improvements in precision for almost all observables (for CP violation in B decays)
  – Very few channels with limiting systematics
  – Some limitations in interpretation (e.g. flavour symmetry breaking effects)
• Opportunities to improve beyond $\sqrt{(\int L dt \times \sigma)}$ in most modes
  – but not guaranteed … plenty of hard work ahead
The infamous table

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb\(^{-1}\) recorded during Run 2) and for the LHCb Upgrade (50 fb\(^{-1}\)). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

<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^0_s) mixing</td>
<td>(\phi_s(B^0_s \to J/\psi \phi))  \text{(rad)}</td>
<td>0.050</td>
<td>0.025</td>
<td>0.009</td>
<td>(\sim 0.003)</td>
</tr>
<tr>
<td>(A_{s}(B^0_s)) (10^{-3})</td>
<td></td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic</td>
<td>(\phi^{\text{eff}}_s(B^0_s \to \phi \phi)) \text{(rad)}</td>
<td>0.15</td>
<td>0.10</td>
<td>0.023</td>
<td>0.02</td>
</tr>
<tr>
<td>penguin</td>
<td>(\phi^{\text{eff}}_s(B^0_s \to K^{*0}K^{*0})) \text{(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^{\text{eff}}(B^0 \to \phi K^0_s)) \text{(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^{\text{eff}}_s(B^0_s \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^{\text{eff}}(B^0_s \to \phi \gamma)/\tau_{BP})</td>
<td>5%</td>
<td>3.2%</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak</td>
<td>(S_3(B^0 \to K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4))</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td>penguin</td>
<td>(q^2 A_{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/c^4))</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</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</td>
<td>(B(B^0_s \to \mu^+ \mu^-) \times 10^{-9})</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td>penguin</td>
<td>(B(B^0 \to \mu^+ \mu^-)/B(B^0 \to \mu^+ \mu^-))</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>(\sim 5%)</td>
</tr>
<tr>
<td>Unitarity</td>
<td>(\gamma(B \to D(s)K(s)))</td>
<td>7°</td>
<td>4°</td>
<td>1.1°</td>
<td>negligible</td>
</tr>
<tr>
<td>triangle</td>
<td>(\gamma(B^0 \to D^\pm K^\pm))</td>
<td>17°</td>
<td>11°</td>
<td>2.4°</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>(\beta(B^0 \to J/\psi K^0_s))</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^-) \times 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} \times 10^{-3})</td>
<td>0.8</td>
<td>0.5</td>
<td>0.12</td>
<td>–</td>
</tr>
</tbody>
</table>

☺☺ – exceeded Run I expectation; ☺ – matched expectation; ☾ – on track

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