Prospects for CP Violation studies at LHCb

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On behalf of the LHCb Collaboration

Lake Louise Winter Institute
Chateau Lake Louise, Canada

18th – 25th February 2008
What is the point of LHCb?

- **Single arm spectrometer**
  - B/$\bar{B}$ production correlated and peaks in the forward-backward direction

- **Produced B mesons are highly boosted**
  - Average B momentum $\sim 80$ GeV
  - Typical lifetime resolution 40fs ($\sim 3\%$)
  - Typical mass resolution 14-18 MeV

- **LHCb has access to all flavours of B hadrons**

- **Excellent particle identification**
  - Kaon ID. eff. 88%, with pion mis-ID of 3%
  - Effective Kaon–pion separation in momentum range of 2–100 GeV

- **Expect to collect 2fb$^{-1}$ of data in a nominal year of running**
## Status of the unitarity triangle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha (^{\circ})$</td>
<td>$87.5^{+6.2}_{-5.3}$</td>
</tr>
<tr>
<td>$\sin(2\beta)$</td>
<td>$0.688 \pm 0.025$</td>
</tr>
<tr>
<td>$\gamma (^{\circ})$</td>
<td>$76.8^{+30.4}_{-31.5}$</td>
</tr>
<tr>
<td>$\phi_s$ (rad)</td>
<td>$-0.79 \pm 0.56^{+0.01}_{-0.14}$</td>
</tr>
</tbody>
</table>

Plot and precisions taken from the
CKMFitter Summer 2007 update
Measurements of the CKM angle $\gamma$

- $B^0 \rightarrow hh$
- $B^\pm \rightarrow D^0 K^\pm$
- $B^0_s \rightarrow D_s K^\pm$
Measuring $\gamma$ from $B^0 \rightarrow h \bar{h}$

Tree diagram

Due to non-negligible penguin diagrams, $B \rightarrow h \bar{h}$ decays are potentially sensitive to New Physics

Example of penguin diagrams

Major advantage of LHCb: the particle identification system allows the different $B \rightarrow h \bar{h}$ mass peaks to be separated

Ref: CERN-LHCb-2007-059
Measuring $\gamma$ from $B^0 \rightarrow hh$ (2)

- Extract $\gamma$ from time dependent CP asymmetries:

  $$A_{CP}(t) = \frac{A_{dir} \cos(\Delta m t) + A_{mix} \sin(\Delta m t)}{\cosh(\Delta \Gamma t / 2) + A_{\Delta \Gamma} \sinh(\Delta \Gamma t / 2)}$$

- Reconstruction performance:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield (2fb$^{-1}$)</th>
<th>B/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow KK$</td>
<td>36k</td>
<td>0.06</td>
</tr>
<tr>
<td>$B_d \rightarrow \pi\pi$</td>
<td>36k</td>
<td>0.46</td>
</tr>
</tbody>
</table>

- Sensitivity to CP violation parameters (2fb$^{-1}$):

  $$\begin{align*}
  \sigma(A_{dir}) & = 0.043 \\
  \sigma(A_{mix}) & = 0.037 \\
  \sigma(A_{dir}^{KK}) & = 0.042 \\
  \sigma(A_{mix}^{KK}) & = 0.044
  \end{align*}$$

  - $A_{mix}$ and $A_{dir}$ depend on the penguin/tree amplitude ratio $d e^{i \theta}$
    - In principle $d e^{i \theta}$ is different for each mode!
  - Invoke U-spin symmetry (Fleischer):
    - Assume $d_{\pi\pi} = d_{KK}$ and $\theta_{\pi\pi} = \theta_{KK}$
    - Can solve for $\gamma$, with $\beta$ and $\phi_s$ as external inputs

Fits allow for 20% U-spin breaking

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Measuring $\gamma$ from $B^{\pm} \rightarrow D^{0}K^{\pm}$ (ADS+GLW)

- The idea: combining colour suppressed B decays with Cabibbo favoured D decays (and vice versa) increases the sensitivity to CP parameters since the interference effects become of order 1.

- Tree level decays, so unaffected by New Physics

Extract $\gamma$ by measuring the relative rates of these B decays

- The measured rates depend on the weak phase ($\gamma$), strong phases in B and D decays, relative magnitudes of B and D decay rates.

- Gain extra information by including decays where the D goes to a CP eigenstate: $D \rightarrow K\pi\pi$ and $D \rightarrow \pi\pi$

- Can also gain extra information by including 4 body D decays: $D \rightarrow K\pi\pi\pi$

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Measuring $\gamma$ from $B^{\pm} \to D^{0}K^{\pm}$ (2)

<table>
<thead>
<tr>
<th>Decay</th>
<th>Signal Yield (2fb$^{-1}$)</th>
<th>Background Yield (2fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^{\pm} \to D(K\pi)K$, favoured</td>
<td>56k</td>
<td>35k</td>
</tr>
<tr>
<td>$B^{\pm} \to D(K\pi)K$, suppressed</td>
<td>0.71k</td>
<td>1.5k</td>
</tr>
<tr>
<td>$B^{\pm} \to D(K\pi\pi)K$, favoured</td>
<td>62k</td>
<td>40k</td>
</tr>
<tr>
<td>$B^{\pm} \to D(K\pi\pi)K$, suppressed</td>
<td>0.76k</td>
<td>2.4k</td>
</tr>
<tr>
<td>$B^{\pm} \to D(hh)K$</td>
<td>7.8k</td>
<td>14k</td>
</tr>
</tbody>
</table>

- Can achieve a precision of 5°-13° on $\gamma$ in 2fb$^{-1}$, depending on the strong phases in the D decays.

Also under study for a global analysis:
- $B^{\pm} \to DK^{\pm}$, with $D \to K_{S}\pi\pi$
- $B^{\pm} \to DK^{\pm}$, with $D \to KK\pi\pi$
- $B^{\pm} \to D^{*}K^{\pm}$, with $D \to KK,K\pi,\pi\pi$
- $B^{0} \to DK^{*0}$, with $D \to KK,K\pi,\pi\pi$

**BOTTOM LINE: EXPECT A PRECISION OF $\sim$5° WITH 2fb$^{-1}$ OF DATA**

Ref: CERN-LHCb-2006-066, CERN-LHCb-2007-043

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Measuring $\gamma$ from $B_s \rightarrow D_s K$ & $B_d \rightarrow D\pi$

- Tree level decays, so not affected by New Physics
- Extract $\gamma$, strong phase difference $\Delta$, amplitude ratio $|\lambda|$ (~0.37) from time dependent asymmetries
- Use lifetime difference ($\Delta \Gamma_s$) between $B^0$ and $\bar{B}^0$ to resolve some ambiguities in extracted value of $\gamma$
  - include $B_s \rightarrow D_s \pi$ events in a simultaneous fit to constrain $\Delta \Gamma_s$ and $\Delta m_s$

With 2 fb$^{-1}$ of data:

<table>
<thead>
<tr>
<th>$\gamma + \phi_s$</th>
<th>10.3$^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_s$</td>
<td>0.007 ps$^{-1}$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
</tbody>
</table>
**Measuring $\gamma$ from $B_s \to D_s K$ & $B_d \to D\pi$ (2)**

- Can perform similar extraction from $B_d \to D^{(*)}\pi$ decay modes; also **tree level decays**
- Because there is no substantial lifetime difference in $B_d$ system, such an extraction suffers from an eightfold ambiguity on $\gamma$
- Invoke U-spin symmetry (Fleischer) to resolve this ambiguity
  - The channels $B_d \to D^{(*)}\pi$ and $B_s \to D_s K$ are related through the exchange of the $d$ and $s$ quarks
  - Hence assume that the strong phases and amplitudes are the same for the channels

Can make an unambiguous extraction with $2\text{fb}^{-1}$ of data, depending on the value of the strong phases

- Work in progress: global analysis of all $B_h \to D_h(K,\pi)$, including excited $D, K$ states
- Expect an unambiguous extraction with $\sigma_\gamma < 10^\circ$ in $2\text{fb}^{-1}$

Ref: CERN-LHCb-2005-036
CERN-LHCb-2007-041
CERN-LHCb-2007-44
Measuring $\phi_s$
**B_s mixing phase with b \rightarrow \bar{c}c\bar{s}**

- $\phi_s$ is predicted to be very small in the Standard Model
  - $\text{SM } \phi_s = -0.037 \pm 0.002 \text{ rad}$
- Can receive sizeable New Physics Contributions
- Golden mode is $B_s \rightarrow J/\psi \phi$
  - Yield = 130k, $B/S = 0.12$ in $2\text{fb}^{-1}$

**Measure $\phi_s$ from time dependant decay rate asymmetries**

\[
A_{CP}(t) = -\frac{\eta_f \sin \phi_s \sin(\Delta m_s t)}{\cosh\left(\frac{\Delta \Gamma_s t}{2}\right) - \eta_f \cos \phi_s \sinh\left(\frac{\Delta \Gamma_s t}{2}\right)}
\]
**Bs mixing phase with b→c̅cs (2)**

**Bs→J/ψφ is not a pure CP mode**

- Need angular analysis to disentangle CP even ($\eta_f = -1$) and CP odd ($\eta_f = +1$) contributions
- Current analysis is based on separation in one angle; 3-angle based separation is under study

**PRECISSIONS**

<table>
<thead>
<tr>
<th>Data sample</th>
<th>$\sigma(\phi_s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5fb$^{-1}$</td>
<td>0.046</td>
</tr>
<tr>
<td>2fb$^{-1}$</td>
<td>0.023</td>
</tr>
<tr>
<td>10fb$^{-1}$</td>
<td>0.009</td>
</tr>
</tbody>
</table>

**BOTTOM LINE:** AFTER 10fb$^{-1}$, WILL HAVE $>3\sigma$ EVIDENCE OF NON-ZERO $\phi_s$, EVEN IF ONLY SM

**New physics in $B_s$ mixing**

The New Physics in $B_s$ mixing can be parameterized as:

$$M_{12} = (1 + h_s \exp(2i\sigma_s)) M_{12}^{SM}$$

LHCb can exclude significant areas of phase space with early data (first few months of running)

After LHCb measurement of $\phi_s$ with $\sigma(\phi_s) = \pm 0.1$ ($\sim 0.2$ fb$^{-1}$)

**Diagram:**
- 2006 (including $\Delta m_s$ measurement)
- 2009

From hep-ph/0604112

 Courtesy Z. Ligeti
CP violation in $b \to s\bar{s}s$ penguin decays

$B_s \to \phi\phi$

- CP violation <1% in SM because mixing and penguin phases cancel
- But New Physics can affect mixing and decays differently
  - $\Delta\phi_{NP} \neq 0$
  - Yield = 3.1k (2fb$^{-1}$, assuming B.R. = 1.4×10$^{-5}$)
  - $B/S < 0.8$ at 90% C.L.

After 10fb$^{-1}$: $\sigma_{stat}(\Delta\phi_{NP}) = 0.05$

Also: use $B_s \to J/\psi\phi$ to disentangle New Physics contributions to mixing and decays

Ref: CERN-LHCb-2007-047
CERN-LHCb-2007-130
Other measurements: \( \alpha, \beta \)
## Roundup of some other measurements

<table>
<thead>
<tr>
<th>Measurement Channel</th>
<th>Precision after 2fb$^{-1}$</th>
<th>Precision after 10fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>B$^0 \rightarrow \pi^+\pi^-\pi^0$</td>
<td>8.5°</td>
</tr>
<tr>
<td>Sin(2$\beta$)</td>
<td>B$^0 \rightarrow J/\psi K_s$</td>
<td>0.020*</td>
</tr>
</tbody>
</table>

*Compare to 0.019 expected from B factories after 2ab$^{-1}$*
So where does all that leave us?

LHCb will see first collisions in the autumn of 2008

- Possible early significant measurement of $\phi_s$ if New Physics contributions are large!
- Will achieve a precision of ~few degrees on $\gamma$ with first year of nominal running