THE PHYSICS PROSPECTS AND STATUS OF THE LHCb EXPERIMENT

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This paper summarises the B-physics prospects of the LHCb experiment. The focus is on the uniqueness of LHCb over and above the B-factories and the Tevatron experiments: the measurement of the unitarity angle $\gamma$ using a number of complementary methods, the measurement of the $B_s^0$ mixing phase $\phi_s$ in tree and penguin decay modes, and the expected observation of the rare decay mode $B_s^0 \to \mu^+\mu^-$ below Standard Model predictions.

Keywords: LHCb experiment; CP-violation; gamma measurement.

PACS numbers: 11.25.Hf, 123.1K

1. The LHCb Experiment

The LHCb detector, shown schematically in Fig. 1, is a single-arm forward spectrometer designed to study CP violation in B-hadron decays at the LHC. LHCb covers a polar angular aperture between approximately 10 and 250 mrad (300 mrad) in the non-bending (bending) plane and exploits the sharply peaked forward-backward $b\bar{b}$ production cross section.

LHCb operates at a tuned LHC luminosity of nominally $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$. This results in an unprecedented source of B hadrons, around $10^{12}$ $b\bar{b}$ pairs per 2 fb$^{-1}$ of integrated luminosity corresponding to one year ($10^7$ seconds) of data-taking. A detailed description of the individual detector components and technologies can be found in $^1$ and references therein. Commissioning of the LHCb detector is now well underway; vital experimental attributes of the experiment include:

- **The Vertex Locator (VELO)** provides an impact parameter resolution of 30$\mu$m and is crucial to all time-dependent CP violation studies.
- **The tracking system** provides an excellent B mass resolution, e.g. $\sim$14 MeV$/c^2$ for the $B_s^0 \to D_s^+K$ decay mode.
- **Two RICH detectors** provide $\pi/K$ separation over the momentum range
Fig. 1. A schematic of the LHCb spectrometer.

1–100 GeV/c, essential in reducing backgrounds in selected final states and for providing an efficient flavour tag (using kaons) of B or $\bar{B}$.

A number of B-physics measurements with LHCb will now be highlighted.

2. Measurement of $\gamma$

The LHCb experiment will make a number of complementary measurements of the CKM angle $\gamma$ in both $B^0$ and $B^0_s$ decay modes. Since new physics effects are expected to manifest themselves in loop diagrams, the comparison of measurements in both trees and loops is vital. Also important is to use methods with different experimental and theoretical systematics. In LHCb the angle $\gamma$ can be measured in a variety of different ways:

- $\gamma$ can be measured without theoretical uncertainty via time-dependent decay asymmetries in $B^0_s \rightarrow D_s K$ combined with the asymmetry in $B^0_s \rightarrow J/\psi \phi^2$. $B^0_s \rightarrow D_s K$ is a $b \rightarrow c$ transition and $B^0_s \rightarrow D_s K$ is a $b \rightarrow u$ transition (Cabibbo suppressed) and the two decays interfere via $B^0_s$ mixing. Since tree decays dominate, this is a “Standard Model (SM) measurement”, not affected by new physics in loop diagrams. All possible charge conjugate states give a total of four time-dependent decay rates to be measured. A total of 6200 events are expected in 2 fb$^{-1}$ of LHCb data-taking which gives a precision in $\gamma$ of $\sim 10^\circ$, which is statistics limited.

- $\gamma$ can be measured via time-independent decay rates in $B^{\pm} \rightarrow D^0 K^{\pm}$: This is a direct CP violation process in which a $b \rightarrow c$ transition interferes with $b \rightarrow u$. Again the tree-level dominates so this is a SM measurement, there is no penguin pollution. The method involves selecting modes where $D^0$ and $\bar{D}^0$ decay to the same final state $f$, where $b \rightarrow u \rightarrow f$ is then doubly Cabibbo and colour suppressed. This is a rate-counting exercise with no flavour tagging nor proper time analysis. The ADS method uses four possible decay rates for each $D^0$ into the $K^\pm \pi^\mp$ charged state. LHCb expect
a total of 400 events into the suppressed modes. Considering the D^0 decay modes into the CP eigenstates \( \pi^+\pi^- \), \( K^+K^- \), the GLW method\(^6\), adds an additional 7.8k events. After 2 fb\(^{-1}\) of LHCb data-taking, a precision in \( \sigma(\gamma) \) of \( 5-13^\circ \) is expected, the range is the result of the (as yet) unknown B and D^0 decay strong phase differences.

- Time-dependent CP asymmetries in \( B^0_d \rightarrow \pi^+\pi^- \) and \( B^0_s \rightarrow K^+K^- \) decays allow a measurement of \( \gamma \) to \( \sim 5^\circ \). Assuming the validity of U-spin symmetry\(^7\), this measurement is sensitive to new physics in penguin loops.

The combined error on \( \gamma \) after 2 fb\(^{-1}\) of LHCb data-taking from tree processes alone is expected to be \( \sim 4^\circ \).

### 3. \( B^0_s \rightarrow J/\psi \phi \) and \( B^0_s \rightarrow \phi \phi \)

The \( B^0_s \) mixing process introduces a small CP-violating weak phase of \( \phi_s \) whose value, \(-0.042 \pm 0.001 \) rad, is predicted to be theoretically clean in the SM\(^8\). \( \phi_s \) has not yet been measured with any accuracy and could be much larger than the SM prediction if new physics contributes to \( B^0 \rightarrow B^\pm \) transitions. LHCb will measure \( \phi_s \) in the tree decay process \( B^0_s \rightarrow J/\psi \phi \) through the interference of the direct decay with that which proceeds via the mixing process. Hence a time-dependent asymmetry will be measured in the decay rates:

\[
A_{CP} = \frac{N(B^0_s \rightarrow J/\psi \phi) - N(B^0_s \rightarrow J/\psi \phi)}{N(B^0_s \rightarrow J/\psi \phi) + N(B^0_s \rightarrow J/\psi \phi)}. \tag{1}
\]

The flavour tagging efficiency in LHCb is around 7\%, and the very good proper time resolution of 36.0 fs for this process resolves the \( B^0_s \) oscillations. The channel is experimentally easy since the decays \( J/\psi \rightarrow \mu^+\mu^- \) and \( \phi \rightarrow K^+K^- \) result in a dimuon trigger plus four charged tracks. The LHCb yield for the channel \( B^0_s \rightarrow J/\psi \phi \) in 2 fb\(^{-1}\) of data is 131k events with a background/signal of 0.12.

Since \( B^0_s \rightarrow J/\psi \phi \) is a vector-vector final state, an angular analysis is required to separate the mixture of CP-even and CP-odd states. The LHCb sensitivity for 2 fb\(^{-1}\) is 0.021 rad, which is a factor two below the SM value. Significant regions of new physics amplitudes and phases can be excluded with the very first data.

If new physics effects are realised, deviations from SM predictions can also be expected in the flavour-changing neutral-current gluonic penguin \( B^0_s \rightarrow \phi \phi \). The technique is the same as the tree process, namely the interference of direct and mixed amplitudes. The CP violation expected in the SM is less than 1\%\(^9\), hence the observation of any CP violation in \( B^0_s \rightarrow \phi \phi \) is a signature for new physics. Again, the decay to two vector particles requires an angular analysis to extract the CP asymmetries and a time-dependent analysis will be performed\(^10\). LHCb expect 4000 signal events in 2 fb\(^{-1}\) of data. The LHCb sensitivity for \( \phi_s \) in the \( B^0_s \rightarrow \phi \phi \) channel is 0.10 rad and 0.04 rad in 2 and 10 fb\(^{-1}\), respectively, getting down to the SM value in five years of data-taking.
4. **$B_s^0 \rightarrow \mu^+\mu^-$**

$B_s^0 \rightarrow \mu^+\mu^-$ is a very rare loop decay process with a branching ratio of $3.5 \times 10^{-9}$ in the SM. The rate can be strongly enhanced in SUSY models\(^1\) and hence is a very sensitive probe to new physics. For LHCb the main issue is background rejection of inclusive $b \rightarrow \mu$ decays. The current 90% confidence limit from CDF and D0 with 1 fb\(^{-1}\) of data is $\sim 20$ times the SM prediction\(^2\). The LHCb expectation is the observation of around 20 events after 2 fb\(^{-1}\) which would be a $3\sigma$ evidence for a SM signal.

5. **Performance summary of LHCb and outlook**

A full description of the LHCb physics performance can be found in Ref.\(^1\). A summary of benchmark channels for one year of operation at a luminosity of $2 \times 10^{32}$ cm\(^{-2}\) s\(^{-1}\) is shown in Table 1. The current status of the unitarity triangle is shown in Fig. 2(left)\(^13\) and the outlook for LHCb’s contribution to the knowledge of the unitarity triangle after five years of operation is shown in Fig. 2(right). The latter prediction assumes lattice QCD improvements to the 1.5% level, $\sin(2\beta)$ will be measured to 0.01, $\gamma$ to 2.4° and $\alpha$ to 4.5°.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Channel</th>
<th>Event</th>
<th>Sensitivity 1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>$B_s^0 \rightarrow J/\psi K_s^0$</td>
<td>240k</td>
<td>$\sigma(\sin 2\beta) \sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B_s^0 \rightarrow \phi K_s^0$</td>
<td>0.8k</td>
<td>$\sigma(\sin 2\beta) \sim 0.32$</td>
</tr>
<tr>
<td>$\phi$s</td>
<td>$B_s^0 \rightarrow J/\psi\phi$</td>
<td>131k</td>
<td>$\sigma(\phi_s) \sim 0.021$ rad</td>
</tr>
<tr>
<td></td>
<td>$B_s^0 \rightarrow \phi\phi$</td>
<td>4k</td>
<td>$\sigma(\phi_s) \sim 0.10$ rad</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$B^\pm \rightarrow D^0 K^\pm$ (2-body D decay)</td>
<td>8.2k</td>
<td>$\sigma(\gamma) \sim 5 - 13^\circ$</td>
</tr>
<tr>
<td></td>
<td>$B_d^0 \rightarrow \pi^+\pi^-$, $B_s^0 \rightarrow K^+\bar{K}^-$</td>
<td>26k, 37k</td>
<td>$\sigma(\gamma) \sim 5 - 10^\circ$</td>
</tr>
<tr>
<td></td>
<td>$B_d^0 \rightarrow D^0 K^{*0}$</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B_d^0 \rightarrow D^0 K^{*0}$</td>
<td>3400</td>
<td>$\sigma(\gamma) \sim 6 - 12^\circ$</td>
</tr>
<tr>
<td></td>
<td>$B_d^0 \rightarrow D^0_{CP} K^{*0}$</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>$\gamma + \phi_s$</td>
<td>$B_d^0 \rightarrow D_s K$</td>
<td>6.2k</td>
<td>$\sigma(\gamma + \phi_s) \sim 10^\circ$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$B^0 \rightarrow \pi\rho$</td>
<td>14k</td>
<td>$\sigma(\alpha) \sim 10^\circ$</td>
</tr>
<tr>
<td>Rare decays</td>
<td>$B_s^0 \rightarrow \rho^+\rho^0, \rho^+\rho^-, \rho^0\rho^0$</td>
<td>9k, 2k, 1k</td>
<td>3$\sigma$ SM value</td>
</tr>
<tr>
<td>Charm</td>
<td>$D^{*+} \rightarrow D^0(K^+\pi^\pm)\pi^\mp$</td>
<td>50M</td>
<td></td>
</tr>
</tbody>
</table>

In summary, the LHCb experiment will perform a high-statistics study of CP violation with unprecedented precision in many different and complementary chan-
nels, and will provide a sensitive test of the Standard Model and physics beyond. The experiment combines excellent vertexing and particle identification with a flexible trigger. LHCb will take B-physics a significant step further than the B-factories and the Tevatron, with access to all b-hadron species. The experiment will be ready for data-taking in 2008.

References