Prospects for measuring CP–violating asymmetries with LHCb

J.F. Libby

The University of Oxford and CERN

Abstract

The motivation for and a description of the LHCb detector will be presented. Specific examples of CP–violating asymmetry measurements which utilise the unique capabilities of LHCb will be given.

(Proceedings of a talk presented at BEACH 2000 in Valencia on the 30th July 2000.
Submitted to Nuclear Physics B.)

1 Introduction

The LHC will provide pp collisions at a centre-of-mass energy of 14 TeV. One year of running at this energy and an average luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ will yield $\sim 10^{12}$ $b\bar{b}$ pairs. Many of these will form neutral B-mesons (both B_d^0 and B_s^0) in which CP-violating asymmetries are expected to be observed. To harvest these prodigious statistics a dedicated B-physics experiment, LHCb, will be constructed. This paper will motivate and describe the features of LHCb which have been optimised for B-physics measurements: (i) efficient triggering on many different final states, (ii) excellent proper time resolution and (iii) good particle identification over a wide range of momentum. This will be followed by some specific examples of CP-violating asymmetry measurements which can be made using LHCb; these measurements will be more difficult if not impossible at the general purpose LHC experiments [1].

2 The LHCb detector

Figure 1: A plan view of the LHCb detector.

A brief overview of the detector and choice of luminosity will be given before more details of the trigger, vertex detector and Ring Imaging CHerenkov (RICH) detectors are presented. Further information on the LHCb detector can be found in Reference [2].

Figure 1 gives a plan view of the LHCb detector; all major sub-systems and the overall dimensions of the experiment are shown. The detector is a forward spectrometer which has a polar angle acceptance of 10–300 mrad in one hemisphere about the interaction region. The choice of a forward geometry exploits the peaking of correlated $b\bar{b}$ production at small angles to the beam direction. This leads to large numbers of events where a CP-violating decay and the accompanying B-decay, required for flavour tagging, are both within the acceptance. Furthermore, the forward geometry allows for a vertex detector with silicon planes perpendicular to the beam direction placed in Roman Pots; these can be brought close to beam providing excellent resolution of primary and secondary vertices in B-decays.

In addition, the detector contains two RICH detectors which are used for particle identification. There is electromagnetic and hadronic calorimetry, which combined with a 5 station muon tracking system, provides triggers on not only high transverse momentum (p_t) leptons but high p_t photons and hadrons as well.

The working luminosity at the LHCb interaction point will be $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ which is a factor 50 below the LHC design value. At this reduced luminosity the rate of single interactions per LHC bunch crossing is maximised; single interaction events are easy to reconstruct.

2.1 The LHCb trigger

Table 1: The LHCb trigger efficiency (ϵ) for reconstructed and correctly flavour tagged events in several channels of interest.

Channel	Level-0 ϵ (%)				Level-1 ϵ (%)	Level-2 ϵ (%)	Total ϵ (%)
	μ	electron	hadron	all			
$B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_s^0 + \text{tag}$	17	63	17	72	42	81	24
$B_d^0 \rightarrow J/\psi(e^+e^-)K_s^0 + \text{tag}$	87	6	16	88	50	81	36
$B_s^0 \rightarrow D_s^+K^- + \text{tag}$	15	9	45	54	56	92	28
$B_d^0 \rightarrow \bar{D}^0 K^{*0}$	8	3	31	37	59	95	21
$B_d^0 \rightarrow \pi^+\pi^- + \text{tag}$	14	8	70	76	48	83	30

The level-3 trigger has an efficiency of $\sim 100\%$ for events that can be reconstructed and tagged in these channels.

One of the primary challenges for LHCb is the trigger. At the LHC the $b\bar{b}$ cross section is ~ 160 times smaller than that for minimum bias events and the time between LHC bunch crossing is only 25 ns. LHCb uses a multi-level pipelined trigger to select the B-decays of most interest; the 4 levels are described below.

The level-0 trigger identifies high p_t muons, hadrons, electrons and photons as well as vetoing multiple interactions. The level-0 acceptance rate is 1 MHz and has a latency of 4 μs .

The level-1 trigger is a vertex trigger. Initially, high impact parameter tracks, in a 2-D projection, are searched for. These candidates are then used to find 3-D secondary vertices. The level-1 trigger has a latency of 500 μs and a suppression factor of 25.

The level-2 trigger adds momentum information from the tracking stations; this removes low p tracks which have been multiply scattered thus faking a secondary vertex. The level-3 trigger combines information from the whole detector, including the RICHes, to identify the decays of interest. Algorithms are run to classify events into different streams such as charged two-body and dilepton decays. Level-2 and 3 provide suppression such that rate at which events are stored is 200 Hz.

Table 1 summarises the trigger performance in several channels of interest to LHCb.

2.2 The LHCb Vertex Locator (VELO)

The LHCb VELO consists of silicon planes mounted in Roman pots within the vacuum tank of the beam pipe. There are 17 stations of silicon planes interspersed over approximately $\sim 1\text{m}$ in z about the interaction region. Each station contains two discs: one with r -strip detectors and one with ϕ -strip detectors. The silicon planes will be within 1 cm of the beam during data taking.

Figure 2: The difference in standard deviations (σ) between pion and kaon hypotheses for true pions is plotted against the logarithm of the pions momentum.

The VELO will provide a proper time resolution of ~ 40 ps. This allows $\Delta M_s/\Gamma_s$ to be measured up to 75 with one year of data taking. Furthermore, excellent proper time resolution reduces the dilution of CP-violating asymmetries in the B_s^0 system.

2.3 The LHCb RICH system

In the study CP-violating B-decays hadron identification is important for two reasons. Firstly, many decays of interest have a topologically identical background. For example, the decay $B_s^0 \rightarrow D_s K$, which is sensitive to the CKM-angle γ , is swamped by background from $B_s^0 \rightarrow D_s \pi$. The ability to differentiate between pions and kaons provided by a RICH detector leads to a suppression of the background to a low level. Such hadrons from B-decays are often of high momentum thus the RICH system has been designed to give π/K separation up to momenta of 100 GeV/ c .

Secondly, a $K^\pm$ can be used to flavour tag the the B_d^0 or B_s^0 at production. The $K^\pm$ arises from the decay chain $b \rightarrow c \rightarrow s$ of the accompanying B-hadron. Such kaons are typically of low momenta which motivates particle identification capability down to momenta of 1 GeV/ c .

The two RICH detectors give π/K separation over the range 1 to 100 GeV/ c by using 3 different radiators: aerogel (RICH1), C_4F_{10} (RICH 1) and CF_4 (RICH2). The emitted Cherenkov photons are focused onto a detector plane of pixellated Hybrid Photo-Diodes (HPDs).

The combined performance of the RICH system is illustrated in Figure 2 where the variation of the difference in standard deviations between pion and kaon hypotheses with momentum is given.

3 Examples of the physics potential of LHCb

When the LHC begins operation not all parameters of the unitarity triangle will be well measured. In particular, the angles α and γ will either be unmeasured or known with large statistical uncertainty. The examples given here present measurements of CP-violating

Figure 3: The difference in the likelihood from its minimum value when α is fixed and the other parameters are fitted.

asymmetries that probe these two angles. Such measurements, combined with others not discussed here, will allow the over-constraining of the unitarity triangle at the LHC.

For further information on the topics discussed below and others the reader is referred to [3] and the references therein.

3.1 The measurement of α

The measurement of the time-dependent asymmetry of $B_d^0 \rightarrow \pi^+ \pi^-$ can be used to determine α . LHCb expects to reconstruct and tag 4900 events per year with a signal to two-body background ratio of 15. This sample yields a sensitivity to α of between 2 to 5°. However, it is expected that the systematic error due to uncertainties on the interfering Penguin process will compromise the one year statistical sensitivity.

The channel $B_d^0 \rightarrow \pi^+ \pi^- \pi^0$ provides such an alternative measure of α . The decays of interest are those in which $B_d^0 \rightarrow \rho \pi \rightarrow 3\pi$. The additional interferences due to the intermediate ρ allows the time dependent variation of the Dalitz plot to be used extract not only α but the real and imaginary parts of the tree and penguin amplitudes as well.

LHCb have performed studies on the selection of such events and preliminary fitting studies. These studies show that LHCb can reconstruct around 1300 $B_d^0 \rightarrow \rho \pi$ events a year which gives an expected accuracy of between 3 to 6° on α . Furthermore, the interferences in the decay allow the value of α to be determined unambiguously as the interferences give sensitivity to both $\sin 2\alpha$ and $\cos 2\alpha$. These lift the ambiguity between the true solution α and $\pi/2 - \alpha$ as illustrated in Figure 3.

3.2 The measurement of γ using $B_d^0 \rightarrow D^{*-} \pi^+$

The four decays B_d^0 or $\overline{B_d^0} \rightarrow D^{*\mp} \pi^\pm$ can be combined to measure the quantity $-2\beta - \gamma$; fixing β from other measurements allows the extraction of γ . This is a theoretically clean mode which suffers from no Penguin pollution. High statistics are required because the asymmetry is expected to be very small $\sim 1\%$; the LHCb hadron trigger allows these large numbers of events to be accumulated. LHCb has studied methods for inclusive and exclusive reconstruction which yield 80k and 260k respectively. The expected sensitivity to γ given these statistics is shown in Figure 4.

There is a systemic error arising from $|\xi| = |A(\overline{B_d^0} \rightarrow D^{*+} \pi^-)|/|A(B_d^0 \rightarrow D^{*+} \pi^-)|$, where A is the amplitude for the process. $|\xi|$ is expected to be known to 10% or better.

The channel $B_s^0 \rightarrow D_s K$ can also be used to measure γ .

Figure 4: The sensitivity to γ for 1 and 5 year event samples of $B_d^0 \rightarrow D^{*-}\pi^+$ for a 0 or 10% systematic uncertainty on $|\xi|$.

3.3 New strategies for extracting CKM angles

In recent years there have been several studies which have proposed new strategies invoking U-spin symmetry (invariance of the strong interaction under interchange of d and s quarks) to combine decay modes of the B_d^0 and the B_s^0 . Preliminary studies show very promising results in several of these channels. In particular combining $B_s^0 \rightarrow K^+K^-$ and $B_d^0 \rightarrow \pi^+\pi^-$, which exploits the particle identification capabilities of LHCb, and combining $B_{d(s)}^0 \rightarrow D_{d(s)}^+ D_{d(s)}^-$ give expected errors of a few degrees on γ for one year of data taking.

A procedure which does not use U-spin symmetry is the combination of the charged and neutral decays of $B_d \rightarrow \pi K$ to extract γ . LHCb studies suggest that with one year of data taking yields ambiguous solutions of γ with errors between 2° to 7° .

4 Conclusion

The detector features of LHCb which have been optimised for B-physics at multi-TeV pp collisions have been presented. Specific examples of channels which will allow the precise determination of the CKM-angles α and γ have been given. The physics capabilities of LHCb will allow the over-constraint of the unitarity triangle during the LHC era.

References

- [1] N. Ellis, M. Smizanska and P. Arce in these proceedings.
- [2] The LHCb Collaboration, Technical Proposal, CERN/LHCC 98-4.
- [3] P. Ball *et al* , B-Decays in 'Proceedings of the workshop on Standard Model Physics (and more) at the LHC', CERN 2000-04