Review of CP Violation Studies
with B-Mesons at LHC

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Abstract
The Large Hadron Collider (LHC) proposed at CERN will be the ultimate source of B-mesons. With the large number of B-mesons expected at LHC, a real precision test of CP violation in B-meson decays will become possible. There are already several efforts made to explore this possibility and a summary of those activities is presented.

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1 Introduction

CP violation has been with us for more than 30 years [1] and its origin still remains one of the unsolved problems in particle physics [2]. The standard model with three families of the left-handed quark doublet [3] can explain observed CP violation in $K_L$ decays through the complex Cabibbo-Kobayashi-Maskawa quark mass mixing matrix [4]. However, it cannot be excluded for the moment that CP violation is generated by a mechanism beyond the standard model [5].

In the neutral kaon system, continuous experimental efforts have been made to measure the isospin dependence of CP violation in the $K_L \to 2\pi$ decays predicted by the standard model. The expected signal is very small and such a dependence is not yet experimentally established [6]. Two new experiments are in preparation.

Due to the complication introduced by the strong interaction at low energies, theoretical predictions for CP violation cannot be made very accurately in the kaon system. On the other hand, it is now generally accepted that such a difficulty is much smaller for particular decays in the $B$-meson system and the standard model can make accurate predictions once the four parameters of the CKM matrix become known [7]. Therefore, it is worthwhile to measure the effects of CP violation in the $B$-meson system with an accuracy of a few %. Another advantage of the $B$-meson is that it can decay into many different final states. The standard model predicts a definite pattern of CP violation for different final states. With a large number of $B$-mesons, one can study such a pattern [8]. A good example is CP violation in $B_s$ decaying into $J/\psi\phi$. While the standard model expects negligible CP violation, a superweak model predicts a sizable effect [9].

The standard model predictions for CP violation in the $B$-meson decays are best illustrated by the unitarity triangle. Three sides of the triangle are obtained from $b \to c + W^-$ and $b \to u + W^-$ decays and $B^0$-$\overline{B}^0$ oscillations and will be well measured by CLEO and four LEP experiments. The three angles, often referred as $\alpha$, $\beta$ and $\gamma$ can be measured from CP asymmetries in the $B$-meson decays. CP violation in the $B$-meson decays could be seen first by BaBar at SLAC, BELL at KEK, HERAB at DESY and possibly CDF at FNAL [10] before LHC.

The goal of the CP violation study at LHC is the “precision” test. Using a large number of $\sim 10^{10}$ to $> 10^{12}$ $B$-mesons expected at LHC, $\alpha$ and $\beta$ can be measured to an accuracy of $\leq 0.01$. Measurements of $\gamma$, of the mass difference between the two mass eigenstates of the $B_s$-meson system through $B_s$-$\overline{B}_s$ oscillations and of the rare $B$-meson decays [11] will be also unique contributions from LHC. In this article, predicted experimental capabilities of proposed LHC detectors are summarised.
2 General Consideration

The b-quark cross sections are estimated to be $\sim 1 \mu b$ in fixed target mode and $\sim 500 \mu b$ in collider mode at LHC. $B_s$-mesons are also produced. The fractions of the b-quark production in the p-p interactions are $\sim 0.0025\%$ in fixed target mode and $\sim 0.5\%$ in collider mode. The large b-quark cross section and $\sigma_{b}/\sigma_{\text{total}}$ ratio are clear advantages for working with collider mode. It may be noted that the current fixed target charm experiments operate with $\sigma_{c}/\sigma_{\text{total}}$ approximately $0.5\%$.

At LHC, the detector has to cope with an event rate of 40 MHz with an even higher interaction rate. The trigger, in particular the first-level trigger, must be fast and very selective. An experiment working in the fixed target mode can have some advantages in the trigger.

Due to the large b-quark mass, b-quark decays produce particles ($\mu$, e and hadrons) with large momenta. In the p-p interaction, this translates into the production of particles with a large transverse momentum ($P_T$) respect to the beam axis. Muons can be identified fast and easily and the number of muons in one event is small. Therefore, a large $P_T$ muon trigger is a simple and effective first-level trigger. On the other hand, the trigger is sensitive only to the semileptonic decays of the b-quark and to final states with $J/\psi$. This results in a low trigger efficiency.

The trigger efficiency will be roughly doubled if one can use the large $P_T$ electron (and positron) in the first-level trigger. This is more difficult than using muons due to many sources of background such as $\pi^0$ Dalitz decays and photon conversions in the detector material. The small event multiplicity in fixed target mode could be an advantage in this respect [12].

Large $P_T$ hadrons can be used effectively for the trigger in fixed target mode. It is well known that the average $P_T$ of pions in normal p-p interaction events increases with the centre of mass energy. Therefore, the large $P_T$ hadron trigger is not as effective in collider mode [12].

Another characteristic of b-quark decays is the displaced secondary vertex. In fixed target mode, the average flight-length of a b-hadron is a few cm. If the production target is point-like, the primary vertex is a priori known and a very fast trigger for selecting events containing tracks with a large impact parameter can be designed [12]. In collider mode, the position of the primary vertex is not known well due to the bunch length of the proton beam. Thus, the primary vertex must be reconstructed first before selecting events containing a track with a large impact parameter.

With a fixed target experiment using an extracted beam [14], the charged B-meson becomes “visible” by placing the vertex detector very closed to the production target. This could be useful for studying such decays as $B^+ \rightarrow \tau^+\nu_{\tau}$ and $B_s \rightarrow \mu^+\mu^-$ where the background is a serious problem.

It is important to note that one can no longer record all the events associated
with the B-meson, and particular B-meson decay modes of interest must be se-
lected. This requires the online reconstruction of events in the third-level trigger
with all the detector information.

The ultimate limitation of an experiment may come from radiation damage.
It is very conceivable that LHC will produce more B-mesons than an experiment
can really use due to the radiation damage to the detector.

3 General Purpose Detectors

ATLAS [15] and CMS [16] are two general purpose collider detectors designed
to perform high $P_T$ physics such as studies of the top quark and search for the
Higgs and supersymmetric particles in the p-p interactions at LHC in the central
region. The b-quark is an important tool for high $P_T$ physics.

With the increasing interest in b-physics itself, the two collaborations started
to investigate the capabilities of their detectors to study b-physics such as CP
violation in the B-meson decays. Those studies are also influencing the design of
the detectors, in particular the vertex detectors.

It is expected to take several years for LHC to reach its design luminosity of
$L \approx 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ which is required to fully exploit LHC for high $P_T$ physics. Thus, b-physics will be an important physics programme for ATLAS and CMS
during the first few years of the LHC operation. Once LHC achieves the design lu-
minosity, b-physics will become exceedingly difficult due to the large background.

Both ATLAS and CMS have an excellent muon detection capability and the
muon is used in the first-level trigger. ATLAS uses a single muon with $P_T \geq 6$
GeV. For the $B \rightarrow J/\psi K_S$ decay mode, the trigger muon can be generated by the
muons from the $J/\psi$ decay or from the semileptonic decay of the partner b-quark
which is used as the tag.

The CMS first-level trigger consists of a single muon with $P_T \geq 10$ GeV or
two muons with $P_T \geq 3 \sim 5$ GeV. The double muon trigger is very effective for
B-meson decay final states with $J/\psi$. The single muon trigger is mainly sensitive
to the semileptonic decay of the partner b-quark used for the tag.

The excellent detection capability for the electron allows ATLAS to recon-
struct $J/\psi \rightarrow e^+e^-$. Due to the strong magnetic field of the detector (4 T), CMS
has difficulty to use the electron channel.

Both experiments have improved their vertex detectors by placing their first
plane much closer to the beam than the original designs shown in the letters of in-
tent. The new designs provide a much better impact parameter resolution which
reduces the background in the reconstructed B-mesons and improves the eigen-
time resolution of the B-meson. However, the radiation damage while operating
at the nominal LHC luminosity becomes a serious concern.

Table summarizes the expected performance for measuring $\sin 2\alpha$ and $\sin 2\beta$
by ATLAS and CMS using the CP asymmetries obtained from the decay time

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
B-meson & $\sin 2\alpha$ & $\sin 2\beta$ \\
\hline
$J/\psi$ & 0.2 & 0.4 \\
$\psi$ & 0.1 & 0.3 \\
\hline
\end{tabular}
\caption{Expected CP asymmetries for B-meson decays.}
\end{table}
Table 1: Expected performances of the general purpose detectors at LHC for sin 2\(\alpha\) and sin 2\(\beta\) using the time integrated method.

| No.(b\(\bar{b}\))/10\(^7\) sec | 5 \times 10^{12} |
|---------------------------------|------------------|
| **Measurement**                 |                  |
| sin 2\(\alpha\) from \(\pi^+\pi^-\) | sin 2\(\beta\) from \(J/\psi K_S\) |
| **Experiment**                  |                  |
| ATLAS                           | CMS              |
| ATLAS                           | CMS              |
| **No.(reconstructed “final state”+tag)** |                  |
| **\(\mu\)-tag**                |                  |
| 3070                            | 3400             |
| \(J/\psi \rightarrow \mu^+\mu^-\) |                  |
| 3847                            | 9200             |
| \(J/\psi \rightarrow e^+e^-\)   |                  |
| 6041                            | -                |
| **\(e\)-tag**                  |                  |
| -                               | -                |
| \(J/\psi \rightarrow \mu^+\mu^-\) |                  |
| 4322                            | -                |
| **total**                       |                  |
| 3070                            | 3400             |
| 14210                           | 9200             |
| **background/signal**           |                  |
| 1.67                            | 0.84             |
| ~ 0.1                           | ~ 0.1            |
| **stat. information**           |                  |
| 0.71                            | 0.47             |
| 0.62                            | 0.47             |
| \(\sigma_{\text{statistical}}\) |                  |
| 0.08                            | 0.09             |
| 0.028                           | 0.047            |

*Including the statistical fluctuation in the background.

integrated rates. It is assumed that LHC will run with an average luminosity of \(10^{33}\) for \(10^7\) s, i.e. roughly one year. The quoted errors are only statistical. It shows that sin 2\(\beta\) can be measured very well. For the measurement of sin 2\(\alpha\), the large amount of remaining background is a worry. The background comes mainly from other two-body decay modes of b-hadrons such as B \(\rightarrow\) K\(\pi\) and \(B_s\) \(\rightarrow\) KK. The momentum resolution is not sufficient to distinguish them from the B \(\rightarrow\) \(\pi^+\pi^-\) decay.

One way to separate the background in ATLAS and CMS, which have no special kaon and pion identification capabilities, is to study the decay time distribution. The background events are expected to decay (almost) purely exponentially. With the absence of the penguin diagram, the decay time distribution for \(\pi^+\pi^-\) events is given by

\[
e^{-\Gamma t} (1 \pm \sin 2\beta \times \sin \Delta m t)
\]

where \(\Delta m\) and \(\Gamma\) are the mass difference between the two weak eigenstates and the decay width of the neutral B-mesons, respectively. Another advantage of studying the decay time distribution is that the errors on both sin 2\(\alpha\) and sin 2\(\beta\) can be reduced by \(~ 20\%\) due to the increased statistical sensitivity of the method [17].
4 Dedicated Detectors

4.1 Past

Three different approaches to perform B-physics in a dedicated way, COBEX [18], GAJET [12] and LHB [14], were initiated. COBEX proposed to work in collider mode and GAJET and LHB in fixed target mode. An internal gas-jet target was considered for GAJET while LHB considered extracting the halo of the LHC beam parasitically using a bent crystal. All three experiments were designed to run for many years in different luminosity conditions of LHC.

All three detectors were forward spectrometers equipped with a Si vertex detector very close to (or in) the beam, large aperture magnet(s) with a tracking system, a particle identification system capable of the π/K/p separation over all the necessary kinematic range, electromagnetic (and hadronic for GAJET and LHB) calorimeter(s) and a muon system.

Compared with the two fixed target experiments, COBEX benefited from the larger b-quark production cross section in collider mode. GAJET emphasised its simple and effective impact parameter trigger strategy based on the point-like target geometry combined with the large $P_T$ lepton and hadron triggers. LHB deployed a vertex detector system close to the production target where most of the B-mesons decay.

General advantages of a dedicated detector compared to a general purpose detector are the following:

- The forward spectrometer geometry allows a more efficient muon $P_T$ trigger with a lower threshold value.
- The vertex detector system close to the beam provides a better vertex resolution. This is important in particular for studying $B_s$-$\bar{B_s}$ oscillations and CP violation in $B_s$ decays.
- The particle identification system reduces the background in the $B\rightarrow \pi^+\pi^-$ decay mode generated by other two-body decay modes of b-hadrons to a negligible amount. It also reduces the combinatorial background and the many-body decay modes of B- and $B_s$-mesons can be reconstructed. This allows measurements of the third angle of the unitary triangle, $\gamma$, CP asymmetries expected to be very small in the standard model and CP asymmetries in charged B-meson decays.

Table 2 summarises the performances of the three dedicated experiments. Dedicated experiments indeed do much better in the difficult decay mode $B\rightarrow \pi^+\pi^-$ than general purpose experiments not only statistically but also in the reduction of the background.
Table 2: Expected performances for past proposed dedicated experiments at LHC.

| Experiment | COBEX  | GAJET  | LHB    |
|------------|--------|--------|--------|
| No.($b\bar{b}$)/$10^7$ sec | $4 \times 10^{12}$ | $2 \times 10^{10}$ | $7.7 \times 10^9$ |

First-level trigger

| High $P_T$ | COBEX | GAJET | LHB |
|------------|--------|-------|-----|
| Large impact parameter | $\mu$ (only at low $\mathcal{L}$) | $\mu$, $e$, hadron yes | $\mu$, $e$ |
| Tagging method | $\mu$ ($K^\pm$) | $\mu$, $e$, $K^\pm$ | $\mu$, $e$, $K^\pm$, $B^\pm$ |

| $\sin 2\alpha$ from $\pi^+\pi^-$ | COBEX | GAJET | LHB |
|-----------------------------------|--------|-------|-----|
| No. (reconstructed $\pi^+\pi^-+tag$) | 30000  | 4500  | 3200 |
| background/signal | $<0.16$ | 0.3 | $<0.1$ |
| $\sigma_{\sin 2\alpha}$ statistical | 0.015  | 0.04  | 0.07 |

| $\sin 2\beta$ from $J/\psi K_S$ | COBEX | GAJET | LHB |
|-----------------------------------|--------|-------|-----|
| No. (reconstructed $J/\psi K_S+tag$) | 270000 | 10350 | 13000 |
| $\sigma_{\sin 2\beta}$ statistical | 0.007  | 0.03  | 0.02 |

| Final states useful to measure $\gamma$ | COBEX | GAJET | LHB |
|---------------------------------------|--------|-------|-----|
| $B_s \to D_s K$ /branching ratio | $\ast 1.8 \times 10^8$ | $\ast 8.3 \times 10^7$ | $\ast 2.8 \times 10^7$ |
| $B^+ \to D^{0}K^+$ /branching ratio | - | - | $\ast 1.2 \times 10^8$ |
| $B^0 \to D^{0}K^{*0}$ /branching ratio | - | $\ast 1.9 \times 10^8$ | - |

*Relevant branching fractions must be multiplied to obtain the actual number of reconstructed events.*
4.2 Current Status and Future

Although the LHC committee (LHCC) has repeatedly confirmed the necessity of a dedicated B-physics experiment as one of the baseline LHC experiments along with ATLAS, CMS and ALICE, none of the above three experiments was recommended for submitting a technical proposal. Instead, LHCC requested the submission of a new letter of intent by a joint collaboration based on the collider mode with a newly designed forward spectrometer with a vertex detector system placed in the Roman pot [19]. A collaboration containing most of the members of the original three groups and many other institutes was formed to do this task. The collaboration is in the process of optimising the detector and the trigger strategy and intends to submit the letter of intent by the end of February 1995. A performance even better and more solid than that claimed by the originally proposed dedicated experiments is expected.

5 Conclusions

There are already active efforts to plan to measure CP violation in B-meson decays at LHC. The two general purpose experiments, ATLAS and CMS will study CP violation during the initial period of LHC running with less luminosity than the design one. They can measure $\sin 2\beta$ using the $B \rightarrow J/\psi K_S$ decay mode well and contribute to the $\sin 2\alpha$ measurement. They have an excellent mass resolution and a good B-meson decay vertex resolution. Their limitation is in the particle identification.

A dedicated B-physics detector at LHC will tackle the problem of CP violation in the B-meson decay for many years and try to measure the angles of the unitarity triangle with a precision of $\lesssim 0.01$. It will have a more efficient trigger for the $b$-quark events than the general purpose detectors. The capability of identifying pions, kaons and protons will ensure clean reconstruction of many different B-meson decay modes which is important to study CP violation in a complete way.

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