B PHYSICS AT LHC

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CP violation is one of the few remaining open questions in the Standard Model. Although there is increasing evidence that CP violation phenomena can be well accommodated in the framework of the Standard Model, it is not excluded that there exists a sizable contribution from new physics, or even that CP violation is entirely due to new physics. A better insight into this problem can be obtained by studying CP violation in B-meson decays in detail. The ultimate opportunity of doing such studies is offered by LHC, in particular with the LHCb detector which is designed for this purpose.

1 Introduction

The Standard Model can so far describe the world of elementary particles successfully and consistently. The theory has been tested up to the quantum correction level and all the precision tests performed at both high and low energies show no sign of deviation from the Standard Model predictions, except a few intriguing experimental results in the neutrino sector.

Along with mass generation and the Higgs particle, CP violation is one of the few remaining aspects of the Standard Model which are not yet thoroughly tested. Although CP violation is firmly established in neutral kaon decays, theoretical uncertainties due to the strong interaction prevent a real precision test being made. CP violation in the neutral B-meson decays is close to being established, [1] however it will still take some time to provide enough statistics to make a meaningful test of the Standard Model prediction.

CP violation is one of the three necessary conditions to generate matter-antimatter asymmetry in the universe. [2] The Standard Model, however, does not seem to be capable of generating a sufficient amount of CP violation to explain the observed dominance of matter in our universe. [3] This calls for new sources of CP violation beyond the Standard Model. Furthermore, various examples of physics beyond the Standard Model widely discussed now introduce new sources of CP violation. CP violation is therefore a highly interesting place to look for evidence for new physics.

In the Standard Model, CP violation is described in the framework of the 3×3 complex unitary mass-mixing matrix (CKM-matrix), [4] which can be described by four independent parameters. One of the four parameters can be chosen to be the well established Cabibbo angle. [5] The current errors on $|V_{\rm ub}|$ and $|V_{\rm cb}|$ will be progressively reduced in coming years using the data from BABAR and BELLE. The value of $|V_{\rm td}|$ is indirectly determined from the $\rm B^0$-$\rm \overline{B}^0$ oscillation frequency assuming that the oscillation is fully generated by the Standard Model box diagram. Already now, the error is totally dominated by the theoretical uncertainties in the decay constant $f_{\rm B_d}$ and the B parameter $B_{\rm B_d}$. Once the $\rm B_s^0$-$\rm \overline{B}_s^0$ oscillation frequency will be measured by CDF, [6] the ratio $|V_{\rm td}/V_{\rm ts}|$ can be determined with a small theoretical error. Therefore, the four parameters of the CKM matrix will be well determined with a small theoretical uncertainty within the frame work of the Standard Model.

Within the framework of the Standard Model, the CP asymmetry between $\rm B^0$ and $\rm \overline{B}^0$ decaying into $\rm J/\psi K_S$ measures $\sin 2\phi_1$, where ϕ_1 is the phase of $V_{\rm td}$, with a small theoretical uncertainty. Similarly, the CP asymmetry between $\rm B_s^0$ and $\rm \overline{B}_s^0$ decaying into $\rm J/\psi\phi$ measures $\sin 2\delta\phi_3$ where $\delta\phi_3$ is the phase of $V_{\rm ts}$. By 2006, the CP asymmetry in $\rm J/\psi K_S$ could be measured with an error of ~ 0.1 by combining the measurements from BABAR, BELLE, CDF and D0. The CP asymmetry in $\rm J/\psi\phi$ could be measured only by CDF with a significantly larger error. Since the phases of $V_{\rm td}$ and $V_{\rm ts}$ can be given by the four CKM parameters determined from the $|V_{\rm ub}|$, $|V_{\rm cb}|$ and $|V_{\rm td}/V_{\rm ts}|$ measurements as described before, the consistency of the CKM description can be tested.

Any inconsistency would be a clear sign of new physics. If this indeed the case, the next step is to isolate the contribution from the Standard Model and that from new physics in order to understand the nature of new physics. Even if no inconsistency emerges at this point, we cannot exclude a possibility that a numerical accident conceals the contribution from new physics due to the limited statistics of the measurements.

In the presence of new physics, only the processes dominated by the tree diagrams should be considered to extract the CKM elements. Thus, $|V_{\rm ub}|$ and $|V_{\rm cb}|$ can be extracted but not $|V_{\rm ts}|$ and $|V_{\rm td}|$ since B-$\rm \overline{B}$ oscillations could receive a sizable contribution from new physics in the box diagram. The CP asymmetry in $\rm J/\psi K_S$, where the decay is dominated by the tree diagram, would mea-

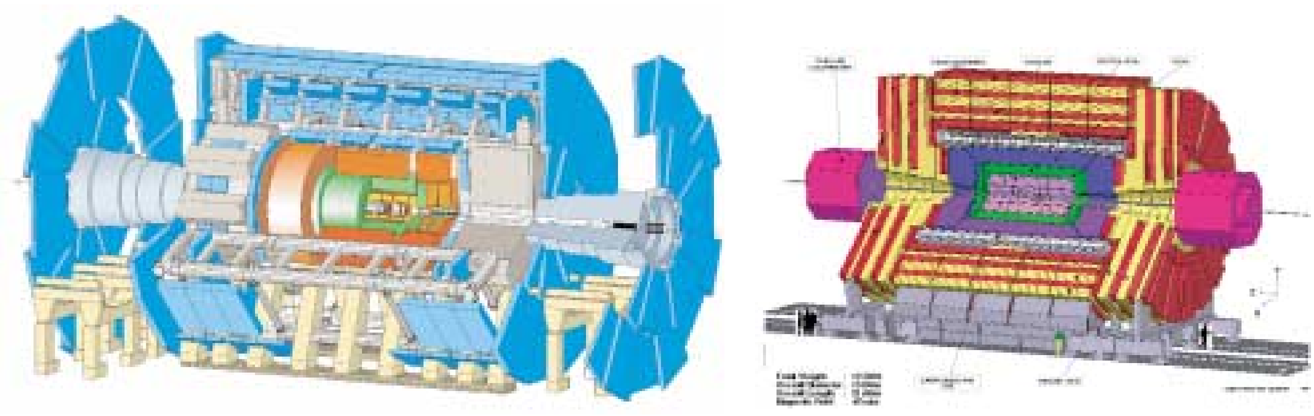


Figure 1: ATLAS and CMS detectors

sure $\phi_1 + \phi^{\rm d}_{\rm NP}$ where $\phi^{\rm d}_{\rm NP}$ is the phase of the new physics process contributing to the $\rm B^0$-$\rm \overline{B}^0$ oscillations. If we measure CP asymmetries in $\rm B^0$ and $\rm \overline{B}^0$ decaying into $\rm D^{*\pm}\pi^{\mp}$, we would be able to extract $\phi_3 + \phi_1 + \phi^{\rm d}_{\rm NP}$ where ϕ_3 is the phase of $V_{\rm ub}$. By combining them, ϕ_3 could then be obtained. Since $|V_{\rm ub}|$ is known, we can extract all the four parameters of the CKM matrix even in the presence of new physics. This analysis could be reinforced by measuring the CP asymmetries in $\rm B^0_s$ and $\rm \overline{B}^0_s$ decaying into $\rm J/\psi\phi$ and $\rm B^0_s$ and $\rm \overline{B}^0_s$ decaying into $\rm D^{\pm}_s K^{\mp}$, which would also allow ϕ_3 to be extracted even in the presence of new physics.

For the decay modes where the penguin diagrams are expected to play an important role, new physics can also contribute in the loop. Therefore, separating the Standard Model contribution and that from new physics to CP violation is more difficult using decay modes such as $\rm B_d \to \pi\pi$, $\rm B_d \to \rho\pi$, $\rm B_d \to K\pi$ and $\rm B_s \to KK$. On the other hand, they will give us additional handle to test the consistency of the Standard Model description in CP violation. In addition, rare decays such as $\rm B_s \to \mu^+\mu^-$ are clearly sensitive to new physics.

The LHC offers the opportunity to study those decay modes with high statistics. In proton-proton collisions at 14 TeV, the $\rm b\overline{b}$ cross section is expected to be of the order of 500 μb which leads, even for a modest luminosity of 2×10^{32} cm^{-2}s^{-1}, to about 10^{12} $\rm b\overline{b}$ pairs in a standard (10^7 s) year of running. Moreover, a sizable fraction of the inelastic interactions consists of events with a $\rm b\overline{b}$ pair ($\approx 5 \times 10^{-3}$). Another advantage is that many different kinds of b-hadrons, i.e. $\rm B_u$, $\rm B_d$, $\rm B_s$, $\rm B_c$ and b-baryons, are produced in pp interactions. Therefore, it is natural that the study of CP violation in B meson decays will be carried out by the experiments at LHC[7] when it becomes operational in 2006.

2 General Purpose Detectors at LHC

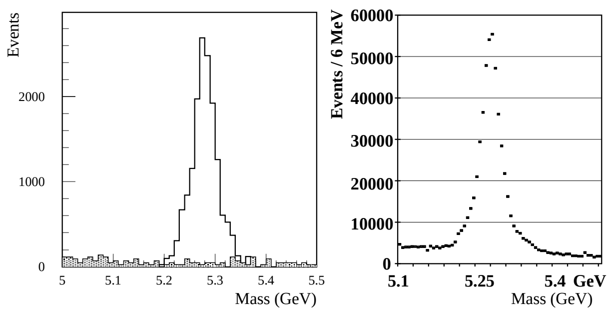
ATLAS and CMS, shown in Figure 1, are two general purpose collider detectors designed to perform high-$p_{\rm T}$ physics such as to study the top quark and to search for the Higgs and supersymmetric particles in pp interactions at LHC in the central region. The b quark is an important tool for high-$p_{\rm T}$ physics. With the increasing interest in physics of the B-meson itself, the two collaborations include the study of B-meson decays as a part of their physics programme.

It is expected to take several years for LHC to reach its design luminosity of 10^{34} cm^{-2}s^{-1} which is required to fully exploit LHC for high-$p_{\rm T}$ physics. Thus, the physics of b-quarks will be important for ATLAS and CMS during the first few years of the LHC operation. Once LHC achieves the design luminosity, b-quark physics will become exceedingly difficult due to the large background since many pp interactions occur in one bunch crossing.

A single high $p_{\rm T}$ muon is used for the first level trigger in the ATLAS experiment. CMS uses both muons and electrons for the first level trigger: either a single high $p_{\rm T}$ muon or electron, or di-lepton (ee, $\mu\mu$ and eμ) with lower $p_{\rm T}$ thresholds are required. Those trigger requirements are sensitive to the B-meson decay final states with leptons, such as $\rm K^*\ell^+\ell^-$, $\rm J/\psi(\ell^+\ell^-)K_S$ and $\ell\nu X$(semileptonic decay). The leptons from the semileptonic decays provide a good flavour tag.

Both experiments plan to have their vertex detectors close to the beam for the B physics programme at low luminosity. A proper time resolution of ~ 60 fs is expected for the fully reconstructed B-mesons.

They can collect a large number of the $\rm B_d \to J/\psi K_S$ decays. The reconstructed signals are expected to be very clean as seen from Figure 2. Similarly, a large sample of the $\rm B_s \to J/\psi\phi$ can be reconstructed.



(a) ATLAS (b) CMS

Figure 2: Reconstructed invariant mass distribution for $\mathrm{B_d} \rightarrow \mathrm{J}/\psi\mathrm{K_S}$ decays with the ATLAS and CMS detectors.

However, reconstruction of hadronic final states will be very difficult. Firstly, the triggers of the both experiments are not sensitive to the hadronic final state. Therefore, those decays are collected only through the semileptonic decay of the accompanying b hadrons and event statistics will be limited. Secondly, background is very high due to the lack of an adequate K/π identification capability. For example, the $\mathrm{B_s} \rightarrow \mathrm{D_s K}$ decay signal is totally washed out by the $\mathrm{B_s} \rightarrow \mathrm{D_s}\pi$ decay signal. Since the two decay topologies are identical, a good vertex resolution does not help and the invariant mass resolutions of ATLAS and CMS are not sufficient to separate the two decay modes kinematically. Particle identification is also important for reconstructing $\mathrm{B_d} \rightarrow \pi^+\pi^-$ decays. Without particle identification, other two-body b-hadron decays such as $\mathrm{B_d} \rightarrow \pi^\pm\mathrm{K}^\mp$ and $\mathrm{B_s} \rightarrow \mathrm{K}^+\mathrm{K}^-$ cannot be distinguished from $\mathrm{B_d} \rightarrow \pi^+\pi^-$ decays from the invariant mass distribution.

It is clear that a dedicated experiment to study CP violation in B-meson decays with particle identification capability is necessary.

3 The LHCb Experiment

The LHCb experiment shown in Figure 3 is a forward spectrometer dedicated to the study of CP violating B-meson decays at the LHC. Some of the reasons for choosing the forward geometry are as follows:

- The B-meson production angles are peaked in the forward and backward direction with respect to the beam direction. The produced b and $\overline{\mathrm{b}}$ are typically correlated in one unit of rapidity. Therefore, the geometric efficiency is high for detecting all the decay particles from one b-hadron together with a decay particle from the accompanying hadron to be used as a flavour tag.

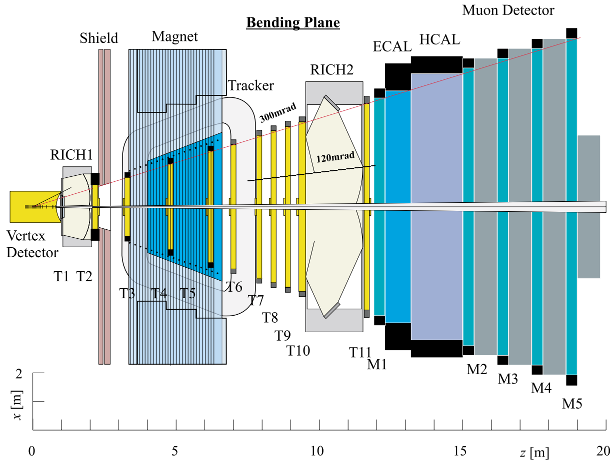


Figure 3: Top View of the LHCb detector.

- A particle identification system of a manageable size covering all of the necessary momentum region can be built based on Ring Imaging Cherenkov Counters (RICH).

- An efficient early level trigger can be designed based on muons, electrons and hadrons with large transverse momenta. In the forward direction, longitudinal momenta of particles are large. Threshold values for a p_T-cut can therefore be decided on the basis of background suppression rather than detector requirements.

- The large Lorentz boost of accepted B-mesons (corresponding to about 7 mm mean decay distance) allows proper-time measurements to be made with a few percent uncertainty. This is crucial for studying CP violation and oscillations with $\mathrm{B_s}$-mesons because of the expected high oscillation frequency.

- Forward planar detector systems, quite similar to those used in fixed target experiments, are less complicated, easier to install, maintain and upgrade.

Its efficient trigger allows the LHCb experiment to exploit fully its physics potential at a much lower luminosity (2×10^{32} cm^{-2}s^{-1}) than the LHC nominal luminosity. This matches well with the expected machine condition in the start-up period of the LHC. Working at a lower luminosity also eases the problem of radiation damage. The experiment can operate in conditions corresponding to the LHC design luminosity as well, by locally reducing the luminosity at the LHCb interaction region.

As seen from Figure 3, the detector consists of a micro-vertex detector system at the intersection point (placed in Roman pots), a tracking system, aerogel and

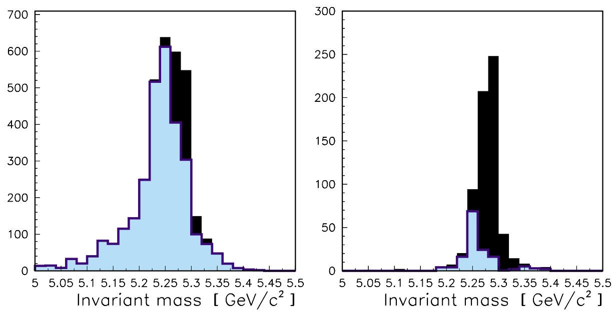


Figure 4: Simulated invariant mass distribution for $B_s \to D_s\pi$ reconstructed with the LHCb spectrometer without applying particle identification (left) and with information from the RICH detectors (right). Background contribution is indicated by the lighter colour.

gas RICH counters, a large-gap dipole magnet, electromagnetic and hadronic calorimeters and a muon system. It has an excellent proper time resolution of ~ 30 fs for a fully reconstructed B meson and a very good invariant mass resolution of 17 MeV/c^2 for $B^0 \to \pi^+\pi^-$ decays.

One of the most crucial components of the LHCb detector is the RICH system. It consists of two detectors with three different radiators in order to cover the required momentum range, 1 to ~ 100 GeV/c. The power of the RICH system is demonstrated in Figure 4 where the invariant mass distributions for reconstructed $B_s \to D_s^{\pm}K^{\mp}$ decays are shown with and without RICH information.

Triggering is another important issue.[8] The first level decision is based on high-p_T hadrons or electrons found in the calorimeter system, or muons found in the muon system. It provides a modest reduction of minimum bias events by ~ 10. The high-p_T hadron trigger significantly increases the yield of final states without leptons. At the next level, data from the micro-vertex detector are used to select events with multiple vertices.

After a positive decision of the vertex trigger, data are read out to an event buffer. Hereafter, all the detector information is in principle available for the trigger decision. Due to the large b-hadron production rate, not all the events with b-hadrons can be recorded. Therefore, the b-hadron final states are reconstructed to select the decay modes of interest.

4 Summary

Becoming operational in 2006, the three experiments at LHC will seek for a sign of new physics through examining the consistency of the CKM description for CP violation. This is done in two ways:
1) Reducing significantly the errors of the CP asymmetries well established by by BABAR, BELLE, CDF and D0 by that time: Examples are

- CP asymmetry in B^0 and $\overline{B}^0$ decaying into $J/\psi K_S$ will be measured with an error of < 0.01 by combining all three experiments.
- Collecting $\sim$ 5k cleanly reconstructed and flavour tagged $B_d \to \pi^+\pi^-$ decays by LHCb in one year.
- Collecting $\sim$ 1000 cleanly reconstructed and flavour tagged $B_d \to \rho^+\pi^-$ decays by LHCb in one year.

2) Establishing new CP asymmetries which are not possible by BABAR, BELLE, CDF and D0: for example

- CP asymmetry in B_s^0 and $\overline{B}_s^0$ decaying into $J/\psi\phi$ will be measured with an error of ~ 0.01 by combining all three experiments.
- CP asymmetry measurement in B_s^0 and $\overline{B}_s^0$ decaying into $D_s^{\pm}K^{\mp}$ with 2.4 k reconstructed and flavour tagged events by LHCb in one year.
- Collecting $\sim$ 340 k well reconstructed and flavour tagged $B_d \to D^*\pi$ decays by LHCb in one year.

LHCb equipped with particle identification will play the key role for these studies. From those measurements, we will be able to make a model independent test of whether observed CP violation is due to the Standard Model. If indeed there exists new physics contributing in CP violation, those measurements will allow us to separate the contribution from the Standard Model and that from new physics unambiguously.

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