REVIEW OF FUTURE CP-VIOLATION EXPERIMENTS IN B-MESON DECAYS

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Experimental prospects for studying CP violation in B-meson decays are reviewed. Comparisons are made for various options: experiments at e^+e^- storage rings operating at the $\Upsilon(4S)$ energy, HERA and the Tevatron will produce results in the near future. They will have a good chance to discover CP violation in B-meson decays. On a longer time scale, experiments at the LHC will aim at much more accurate measurements to make a precision test of the Standard Model in CP violation. There exists also a proposal to build a dedicated experiment to study heavy flavour physics at the Tevatron.

1 Introduction

The Standard Model has so far been very successful in describing the world of elementary particles in a consistent way. The validity of the theory has been tested up to the quantum correction level and all the precision measurements 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 untested areas of the Standard Model. Since the discovery in 1964 [1], the neutral kaon system remains the only place where CP violation is observed. Although the effect can be accommodated within the Standard Model, it is not excluded that a mechanism beyond the Standard Model is responsible.

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.

In the Standard Model, CP violation is described in the framework of the 3×3 unitary mass-mixing matrix (CKM-matrix) [4]. Such a matrix can have a nontrivial phase which satisfies a condition [5], $\mathrm{Im}(V_{ij}V_{lk}V^*_{ik}V^*_{lj}) \neq 0$, necessary to generate CP violation where V_{ij} is an element of the CKM matrix.

The CKM matrix is uniquely defined by four parameters. One of the most commonly used parameterizations was introduced by Wolfenstein [6], with parameters λ, A, ρ and η. CP violation requires $\eta \neq 0$. The parameter λ is the sine of the Cabibbo angle [7] and is measured to be ~ 0.22 from kaon and hyperon decays. Given λ, A can be obtained from $|V_{\mathrm{cb}}|$ measured in B-meson decays produced by the $\mathrm{b} \rightarrow \mathrm{c} + \mathrm{W}$ process. For ρ and η, a combination of $|V_{\mathrm{ub}}|$ and $|V_{\mathrm{td}}|$ is needed. Currently, both elements are obtained using B-mesons: $|V_{\mathrm{ub}}|$ is determined from B-meson decays produced by the $\mathrm{b} \rightarrow \mathrm{u} + \mathrm{W}$ process and $|V_{\mathrm{td}}|$ is obtained from the frequency of B^0-$\overline{\mathrm{B}}^0$ oscillations. With current uncertainties on $|V_{\mathrm{ub}}|$ and $|V_{\mathrm{td}}|$, $\eta = 0$ is not excluded [a]. Determinations of $|V_{\mathrm{ub}}|$ and $|V_{\mathrm{td}}|$ will continue to improve with more experimental data and better theoretical understanding in the future.

It has to be noted that the element $|V_{\mathrm{td}}|$ could also be measured from the rare $\mathrm{K}^+ \rightarrow \pi^+\nu\overline{\nu}$ decays [8]. The CP violating decay $\mathrm{K_L} \rightarrow \pi^0\nu\overline{\nu}$ [8] is dominated by the contribution from the interplay between the decays and oscillations, and the branching fraction is proportional to η. Its theoretical uncertainty is considered to be small.

As a first step, "first generation" of CP violation experiments in the B-meson systems will become operational around the turn of the century. If the Standard Model is largely responsible for the observed CP violation in the neutral kaon system, they will discover CP violation in $\mathrm{B_d} \rightarrow \mathrm{J}/\psi\,\mathrm{K_S}$ decays [9]. A consistency test can then be made by comparing the observed CP asymmetry with the Standard Model prediction. If they disagree, this would mean a sign of new physics and opens up a wide rage of questions which have to be answered by "second generation" of experiments which can measure CP violation in many more decay channels with much higher precision.

Even if they agree, this could well be due to a numerical accident generated by new physics. New physics naturally introduces additional flavour-changing neutral currents. They can affect the oscillations of K^0-$\overline{\mathrm{K}}^0$, B^0-$\overline{\mathrm{B}}^0$ and B^0_s-$\overline{\mathrm{B}}^0_\mathrm{s}$, B-meson decay amplitudes dominated by the penguin and box diagrams and CP violation in K- and B-meson (and possibly D-meson) systems. Therefore, η and ρ extracted from the processes involving B^0-$\overline{\mathrm{B}}^0$ and K^0-$\overline{\mathrm{K}}^0$ oscillations no longer correspond to the

[a] A non-zero value of η ($\eta > 0$) is only obtained if the CP violation parameter in the neutral kaon system, ϵ, is taken into account.

real values. Thus, experiments are needed which measure enough different CP asymmetries with high precision so that a real consistency test can be done.

In addition, collection of data which help further understanding of B-meson decays has to be continued to improve the precision on the CKM matrix elements.

For the B-meson system, “second generation” CP experiments with the following capabilities are then needed:

- Being able to measure $\mathrm{B_s^0}$-$\mathrm{\overline{B}_s^0}$ oscillations even if the oscillation frequency is far beyond what is expected from the Standard Model.

- Being able to measure CP asymmetries in many different decay modes, including those of $\mathrm{B_s}$-mesons, where the Standard Model predictions have little theoretical uncertainty: some examples are $\mathrm{B_d} \to \mathrm{J}/\psi\,\mathrm{K_S}$, $\mathrm{B_d} \to \mathrm{D}^*\pi$, $\mathrm{B_d} \to \rho\pi$, $\mathrm{B_d} \to \phi\mathrm{K_S}$, $\mathrm{B_s} \to \mathrm{J}/\psi\phi$, $\mathrm{B_s} \to \mathrm{D_sK}$, $\mathrm{B_s} \to \mathrm{K^+K^-}$.

- Being able to study very rare decay modes generated by the penguin and box diagrams, such as $\mathrm{B_s} \to \mu\mu$, at least down to the level expected by the Standard Model.

In the following, experimental prospects to pursue such studies are reviewed.

2 Future Experiments

2.1 Experiments before 2005

CESR is the only $\mathrm{e^+e^-}$ collider currently working at $\Upsilon(4\mathrm{S})$ studying decays of B-mesons. The machine luminosity has been constantly improved and has now reached a level of $4 \times 10^{32}\mathrm{cm^{-2}s^{-1}}$ with a final goal of $1.7 \times 10^{33}\mathrm{cm^{-2}s^{-1}}$ by the turn of the century [10]. There even exists an idea to increase its luminosity beyond $10^{34}\mathrm{cm^{-2}s^{-1}}$ by constructing an additional ring. This may allow them to observe $\mathrm{B_d} \to \pi^0\pi^0$ decays which provides a crucial information to understand the effect of gluonic penguin diagrams in the study of CP violation for $\mathrm{B_d} \to \pi^+\pi^-$ decays.

The current detector at CESR, CLEO, is undergoing a major upgrade [10] (Figure 1) replacing the vertex detector and drift chamber. The upgrade also includes installation of a Ring Imaging Cherenkov Counter which will allow clean separation of $\mathrm{B_d} \to \mathrm{K}^\pm\pi^\mp$ and $\mathrm{B_d} \to \pi^+\pi^-$ decays.

CLEO will stay as a front-runner of B physics for some time. By accumulating statistics, they look for CP violation in decay amplitudes. However, they cannot observe CP violation generated by the interplay between the decays and oscillations such as $\mathrm{B^0}$ and $\mathrm{\overline{B}^0} \to \mathrm{J}/\psi\mathrm{K_S}$ as explained later. For this purpose, asymmetric $\mathrm{e^+e^-}$

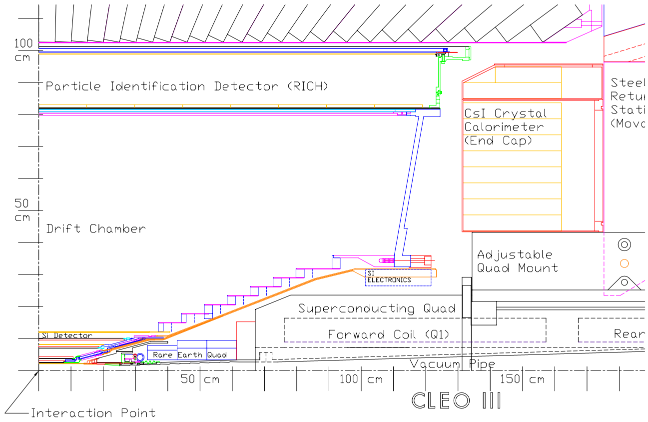

Figure 1: Upgrade plan for the CLEO detector.

colliders are being constructed, KEKB at KEK [11] and PEP-II at SLAC [12].

Table 1 summarises some parameters of the two $\mathrm{e^+e^-}$ B-meson factories. KEKB is being constructed in the existing TRISTAN tunnel and PEP-II in the PEP tunnel. Two beams with moderately different energies collide in both machines producing the $\Upsilon(4\mathrm{S})$ boosted. This is essential for the CP violation study. At the $\Upsilon(4\mathrm{S})$, $\mathrm{B^0}$-$\mathrm{\overline{B}^0}$ are produced in a state with an orbital angular momentum of one. Due to quantum coherency of this state, one can show that the difference in the decay time between the two $\mathrm{B_d}$-mesons must be measured in order to obtain a visible signal of CP violation. With a stationary $\Upsilon(4\mathrm{S})$, only the sum of the decay times can be measured since the production points of $\mathrm{B_d}$-mesons given by the $\mathrm{e^+e^-}$ collision points are not well defined compared with the average flight path of $\mathrm{B_d}$-mesons. With a boosted $\Upsilon(4\mathrm{S})$, measuring the decay time difference becomes possible as illustrated in Figure 2.

In the PEP-II design, the two beams collide head-on. Then the two beams are separated by dipole magnets in order to avoid parasitic collisions. Separation has to be done quickly in order to increase the number of bunches, which leads to high luminosity. For quick separation of the beams after the collision, the dipoles have to be placed very close to the interaction point,

Table 1: List of some machine parameters for PEP-II and KEKB.

Machine	PEP-II	KEKB
$E_\mathrm{H}/E_\mathrm{L}$ [GeV]	9/3.1	8/3.5
$\mathcal{L}$ [$\mathrm{cm^{-2}s^{-1}}$]	3×10^{33}	10^{34}
Bunch spacing [m]	1.26	0.6
Crossing angle	0°	±11 mrad

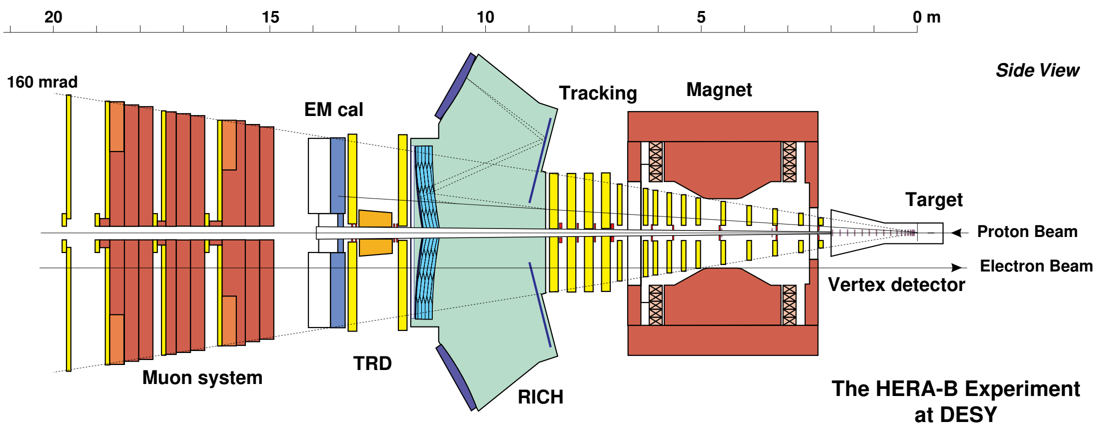

Figure 3: A schematic view of the HERA-B detector.

which makes the detector design difficult. In the KEK design, the two beams collide with a small angle. In this scheme, the beams are automatically separated after the collision. Therefore, no dipole is needed close to the interaction point and the bunch spacing can be reduced, i.e. the number of bunches can be increased. However, crossing bunches with a finite angle may introduce an instability of the beams which limits the luminosity.

Both machines have only one interaction region with a detector in order to obtain the highest luminosities.

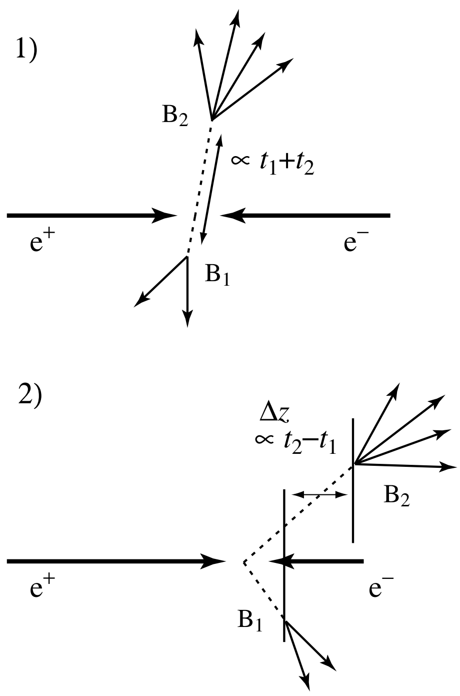

Figure 2: Illustration of $\Upsilon(4S) \to B^0\overline{B}^0$ followed by decays of the two B mesons for 1) a symmetric collider and 2) an asymmetric collider.

BELLE [11] is placed at KEKB and BaBar [12] at PEP-II. They are equipped with Si strip vertex detectors and high performance particle-identification devices. They expect to start taking data in Spring 1999.

The HERA-B experiment [13] (Figure 3) uses the halo of the HERA proton beam and internal targets placed inside the beam pipe. It runs parasitically to the other HERA experiments. The internal targets are made of eight thin metal wires (~ 50 μm diameter). Since it is a fixed target experiment, B-mesons are boosted with an average decay length of $\sim$6 mm. The collaboration plans to start taking data with the full detector sometime in 1999.

The CDF experiment has already demonstrated its potential by reconstructing the largest sample of $B_d \to J/\psi K_S$ decays [14] (Figure 4) used to measure a CP asymmetry [b]. Both CDF [16] and D0 [17] are upgrading their detector which will enhance their capability for studying CP violation in B-meson decays in the next run starting in 2000. In particular, D0 will introduce a magnet.

Some of the experimental conditions for those three different approaches are listed in Table 2. For all the experiments, the micro-vertex detector is a crucial part of the spectrometer. It is essential for reducing the background and measuring the B-meson decay time. The second point is particularly important for BaBar and BELLE to observe CP violation.

In addition to lepton identification, the capability to separate kaons from pions introduced by BaBar, BELLE, CLEO and HERA-B is another important point. This can be seen for the reconstruction of the $B_d \to \pi^+\pi^-$ decay. Dangerous backgrounds in this channel are $B_d \to K^\pm\pi^\mp$ (also $B_s \to K^\pm\pi^\mp$ and K^+K^- for hadron machines). Since they are real two-body B-meson decays,

[b]OPAL [15] also gives a measurement of CP asymmetry in $B_d \to J/\psi K_S$. For both cases, measured asymmetries are compatible with zero.

Table 2: Experimental conditions for e^+e^- machines, HERA and the Tevatron.

Machines	e^+e^- CESR	e^+e^- KEKB	e^+e^- PEP-II	HERA	Tevatron
Experiments	CLEO-III	BELLE	BaBar	HERA-B	CDF, D0
Reactions	$e^+ + e^-$ at $\Upsilon(4S)$			p + Metal wires at $\sqrt{s}$ =40 GeV	$p + \overline{p}$ at $\sqrt{s}$ =1.8 TeV
$\sigma_{b\overline{b}}$	~1 nb			~760 nb	~60 μb
$\sigma_{b\overline{b}}/\sigma_{\mathrm{hadronic}}$	$\sim 2 \times 10^{-1}$			$\sim 10^{-6}$	$\sim 10^{-3}$
b-hadrons	B_u, B_d			B_u, B_d, B_s, B_c, all b-baryons	B_u, B_d, B_s, B_c, all b-baryons
In one event	only $B\overline{B}$			many other particles	many other particles
Geometry of detector	central symmetric	central, slightly asymmetric		very forward fixed target	central symmetric
Particle ID	p/K/π/μ/e			p/K/π/μ/e	hadron/μ/e

the micro-vertex detectors will not help to remove them, and the mass resolutions of spectrometers are not sufficient to separate those channels using invariant masses with different mass hypotheses. Furthermore, the efficiency for the flavour tag can be increased by using the kaon tag.

BaBar, BELLE and CLEO are equipped with electromagnetic calorimeters made of CsI crystals. Their excellent energy resolution and clean environment at the $\Upsilon(4S)$ decays allow the experiments to enhance the decay channels to be investigated by including final states with multi π^0's.

Among the future experiments, CP violation studies in the B_s-meson system are unique for those at hadron machines. Good decay time resolutions and the large number of produced B_s mesons allow them to have better sensitivities in detecting B_s^0-$\overline{B}_s^0$ oscillations than those achieved by the LEP experiments. However, their expected sensitivities still do not cover the whole range of the oscillation frequencies allowed by the Standard Model.

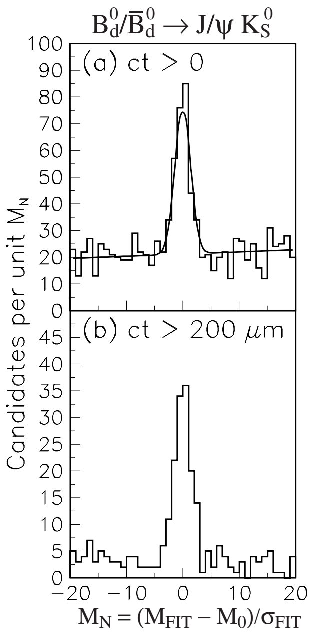

Figure 4: Invariant mass distribution for $J/\psi\, K_S$ measured by the CDF experiment with different cuts on the flight distance.

2.2 Experiments after 2005

The $b\overline{b}$ cross section for proton-proton collisiona at LHC ($\sqrt{s} = 14\ TeV$) is expected to be $\sim 500\ \mu b$ [18]. Even with a modest luminosity of 10^{32} to 10^{33} $cm^{-2}s^{-1}$, more than 10^{11} B-mesons will be produced in 10^7 seconds. The cross section ratio, $\sigma_{b\overline{b}}/\sigma_{\mathrm{inelastic}}$ is predicted to be $\sim 5 \times 10^{-3}$, which is similar to $\sigma_{c\overline{c}}/\sigma_{\mathrm{inelastic}}$ in the current fixed target charm experiments. Therefore, LHC is a promising machine for studying CP violation in B-meson decays with

Table 3: Comparison of ATLAS, CMS and LHCb.

Experiment	general purpose detectors ATLAS	CMS	dedicated experiment LHCb
Reactions	p + p at $\sqrt{s}$ =14 TeV		
$\sigma_{b\overline{b}}$	$\sim$500 μb		
$\sigma_{b\overline{b}}/\sigma_{\mathrm{hadronic}}$	$\sim 5 \times 10^{-3}$		
$\mathcal{L}$ for B physics	10^{33} cm^{-2}s^{-1}		2×10^{32} cm^{-2}s^{-1}
Acceptance	central region $\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2.4$	forward region $1.6 < \eta < 5.3$
Early level trigger with a reduction factor > 100	high-p_{t} μ	high-p_{t} μ or e	medium-p_{t} μ, e or hadrons followed by secondary vertex trigger
Particle ID	hadron/μ/e		p/K/π/μ/e

high statistics.

Three experiments are under construction for proton-proton collisions at LHC. ATLAS [19] and CMS [20] are two general-purpose experiments designed to look for Higgs and supersymmetric particles: LHCb [21] is a dedicated experiment for the CP violation study. Experimental conditions for the three experiments are summarised in Table 3. All the detectors are naturally equipped with high performance vertex detectors.

Since ATLAS and CMS are designed to look for particles produced in a very hard collision, detectors cover the central region. For the initial phase of the LHC operation where the machine luminosity is $\sim 10^{33}$ cm^{-2}s^{-1}, they intend to do physics with B-mesons. The b-quark events are triggered by the high transverse momentum (p_{t}) lepton trigger by reducing the threshold value.

LHCb chose the forward geometry mainly due to the following reasons:

- The b-quark production is peaked in the forward region where both b and $\overline{\mathrm{b}}$ fly in the same direction. Therefore, a single arm spectrometer with a modest angular coverage of up to ~ 300 mrad can detect the decay products of both b-hadrons for 10 to 20% of $\mathrm{b\overline{b}}$ events. This keeps the cost of the detector low.

- B-hadrons produced in the forward direction are on average faster than those in the central region. Their average momentum is about 80 GeV/c, corresponding to a mean decay length of $\sim$7 mm. Therefore, a good decay time resolution can be obtained for reconstructed B-mesons.

- In the forward region, momenta are mainly carried by the longitudinal components. Therefore, the threshold value for the p_{t} trigger can be set low for electrons, muons and hadrons; around 1.5 GeV/c. This makes the p_{t} trigger more efficient than in the central region.

- The detector can be built in an open geometry which allows easy installation and maintenance.

As already demonstrated by CDF, general purpose collider experiments can reconstruct well B-meson final states containing lepton pairs, such as $\mathrm{J}/\psi\,\mathrm{K_S}$, $\mathrm{J}/\psi\phi$ and $\ell^+\ell^-$. As an example, Figure 5 shows the simulated invariant mass distribution for reconstructed $\mathrm{B_d} \to \mathrm{J}/\psi\,\mathrm{K_S}$ decays with the CMS detector.

An especially good mass resolution and particle identification become essential for the reconstruction of hadronic final states. As an example, Figure 6 shows the reconstructed $\mathrm{B_s} \to \mathrm{D_s K}$ decay with and without particle identification for the LHCb experiment. The major background $\mathrm{B_s} \to \mathrm{D_s}\pi$ decay can be successfully eliminated by the RICH and excellent mass resolution, although its branching fraction is about 15 times larger than that of $\mathrm{B_s} \to \mathrm{D_s K}$. This is estimated by taking into account the Cabibbo suppression and form factor difference.

The importance of K/π separation can be also demonstrated in the $\mathrm{B_d} \to \pi^+\pi^-$ decays. As discussed previously, the major background comes from other two body decay modes of the B-meson. Figure 7 shows the simulated $\pi^+\pi^-$ invariant mass distributions of reconstructed $\mathrm{B_d}$ mesons for ATLAS. The contribution from the real $\mathrm{B_d} \to \pi^+\pi^-$ decays shown as the crossed his-

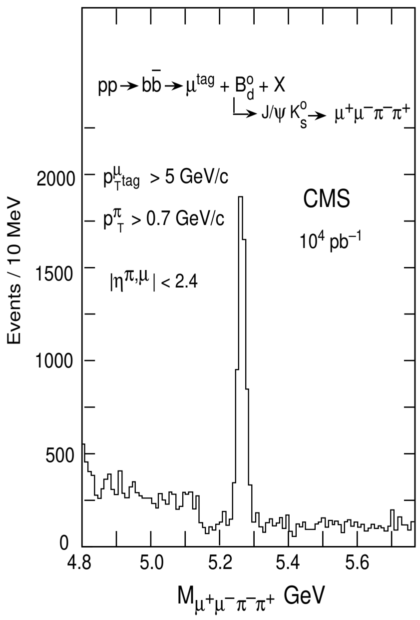

Figure 5: Simulated invariant mass distribution of $B_d \to J/\psi K_S$ decays for the CMS detector.

togram is completely buried in the background. The background peaking at the B_d-meson mass is due to other two-body B-meson decays and the combinatorial background is flat under the mass peak.

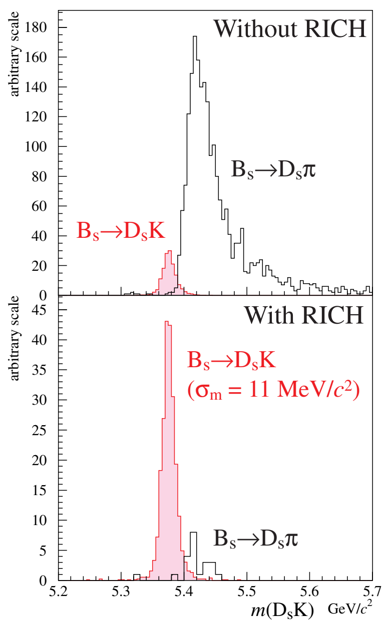

Figure 6: Simulated $D_s(KK\pi)K$ invariant mass distributions for reconstructed $B_s \to D_sK$ decays in LHCb. The shaded histogram is the true $B_s \to D_sK$ decays. The background channel, $B_s \to D_s\pi$, is assumed to have 15 times larger branching fraction than that of the signal.

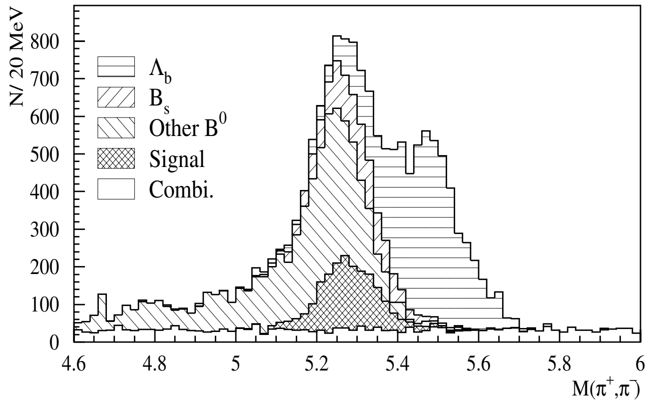

Figure 7: Simulated $\pi^+\pi^-$ invariant mass distributions of reconstructed $B_d \to \pi^+\pi^-$ decays for ATLAS with various background contributions.

In some two-body decay modes like $B_d \to K^\pm\pi^\mp$, a CP violation effect from the decay amplitudes is expected. The size of CP asymmetry could be as large as $\sim$0.01. Expected statistical accuracies of CP asymmetry measurements in this decay mode by the LHC experiments are of the same order. Therefore, this effect is not negligible. Furthermore, a discovery of CP violation in $B_d \to K^\pm\pi^\pm$ decays by itself is very important. Such studies are clearly only possible with the LHCb detector which can separate kaons from pions in all the necessary momentum range.

An excellent decay time resolution is essential for B_s-meson studies. ATLAS and CMS will improve the sensitivities to observe B_s^0-$\overline{B}_s^0$ oscillations compared to CDF, D0 and HERA-B, for example. However, LHCb having expected decay time resolution of 43 fs and 86k reconstructed and initial flavour tagged $B_s \to D_s\pi$ decays is needed to observe B_s^0-$\overline{B}_s^0$ oscillations even if the oscillation frequency is well above the Standard Model expectation.

BTeV [22] (Figure 8) is a dedicated heavy flavour experiment being proposed at the Tevatron. The experiment is based on a forward spectrometer, similar to

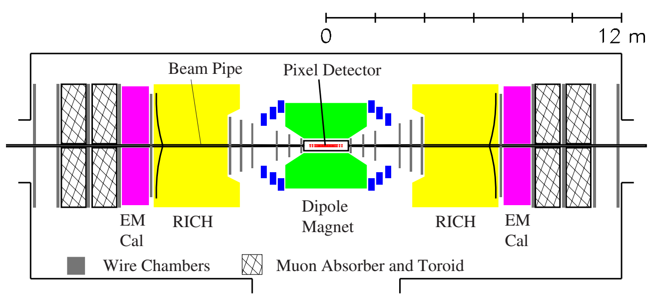

Figure 8: A schematic view of the BTeV detector.

LHCb, but with a double arm configuration. In its detector design, a dipole magnet is at the interaction region and a vertex detector with Si pixels is placed inside the magnetic field. This vertex detector is used in the very first level of the trigger in order to select events with detached vertices. The spectrometer is also equipped with tracking chambers, RICH's, electromagnetic calorimeters and muon systems. BTeV's physics goal and capability is very similar to that of LHCb. In addition, they intend to focus on charm physics as well.

3 Conclusions

CP violation will stay as one of the most important subjects of elementary particle physics for sometime. Together with continuous strong theoretical interests, the experimental programme already laid down beyond 2005 will keep the field very active and competitive.

In addition to the well established experimental programme in the kaon system, CP violation experiments in B-meson systems are rapidly developing. The clean environment of e^+e^- machines and the very high statistics available at hadron machines provide complementary physics programmes in the B-meson systems.

We are all hoping to see within the next ten years a sign of new physics which will explain why we have not annihilated soon after the big bang.

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