



Fermilab

FERMILAB-Conf-03/028-E February 2003

Future of B Physics at CDF and DØ

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Contribution to Panel Discussion on
“The Future of Hadron B Experiments”

Abstract

In this contribution to the panel discussion on “The Future of Hadron B Experiments” held at the 8th International Conference on B Physics at Hadron Machines (Beauty 2002) at Santiago de Compostela, Spain, June 17-21, 2002, we explore the physics potential for B physics at CDF and DØ in five years and beyond. After a brief introduction to precision flavour physics, we concentrate our discussion on the future of CP violation by evaluating the prospects for measuring the CKM angles β , γ and α at the Tevatron Collider experiments CDF and DØ by the end of Run II.

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Introduction

This report contains my contribution to the panel discussion on “The Future of Hadron B Experiments” held at the 8th International Conference on B Physics at Hadron Machines (Beauty 2002) at Santiago de Compostela, Spain, June 17-21, 2002. The panel was chaired by Fred Gilman, also current chair of HEPAP, who charged the panel members to evaluate the physics potential for B physics at Hadron Machines in five years and beyond [1]. In my contribution, I discussed the future of B physics at the two Tevatron Collider experiments CDF and DØ at the end of Run II. More information about B physics prospects at the Tevatron in Run II and beyond can be found in Ref. [2].

Since the official start of the Fermilab Tevatron Run II in March 2001, much work has gone into commissioning the CDF and DØ detectors. Both experiments were taking physics data and presenting first physics results at the time of this conference in summer of 2002 [3]. The goal for the first phase of Run II (Run IIa) is to collect a data sample of about 2 fb^{-1} until 2004. After a short shutdown of about 6 months, Fermilab’s current plan foresees a high-luminosity running period of the Tevatron with an integrated luminosity of possibly $\sim 10 \text{ fb}^{-1}$ delivered until the turn-on of the LHC in 2007. The most important upgrades for CDF and DØ consist of replacing their silicon vertex detectors by more radiation tolerant devices to allow for collecting $10\text{-}15 \text{ fb}^{-1}$ of $p\bar{p}$ collision data.

Toward Precision Flavour Physics

In the 1990’s, particle physics was dominated by a decade of precision electroweak physics with measurements from LEP, SLD, the Tevatron and various fixed target experiments. The progress made in that decade can be summarized in the constraints on the Higgs boson mass as known in 1999. In the famous M_W versus M_{top} plane, the Tevatron and LEP measurements on M_W , the CDF and DØ results on M_{top} as well as constraints from various indirect measurements are displayed in Figure 1(a). As indicated, the Standard Model (SM) prefers a light Higgs Boson mass. Ten years earlier, in 1989, the top quark was not yet discovered and the W boson mass was only known with a precision of about $1.5 \text{ GeV}/c^2$. Enormous progress has been made in this decade of precision electroweak physics.

With the turn-on of the e^+e^- B factories in 1999, the physics community started to talk about particle physics moving from a decade of precision electroweak physics toward a decade of precision flavour physics. A lot of progress in understanding flavour physics has already been achieved in the past 4-5 years. In 1998, we had no information on CP violation in the B system which was discovered in 2001 [4], and the constraints from $|V_{ub}|$, B mixing and CP violation in the kaon system were quite coarse. Much progress has been made since then as can be seen in Figure 1(b) showing the constraints on the position of the apex of the unitarity triangle from $|V_{ub}|$, B mixing, ϵ_K and $\sin 2\beta$. This plot has been taken from the 2002 Review of Particle Properties [5].

According to the chair of this panel on “The Future of Hadron B Experiments”, Fred Gilman, for the first time there exist now two independent tests of the CKM mechanism

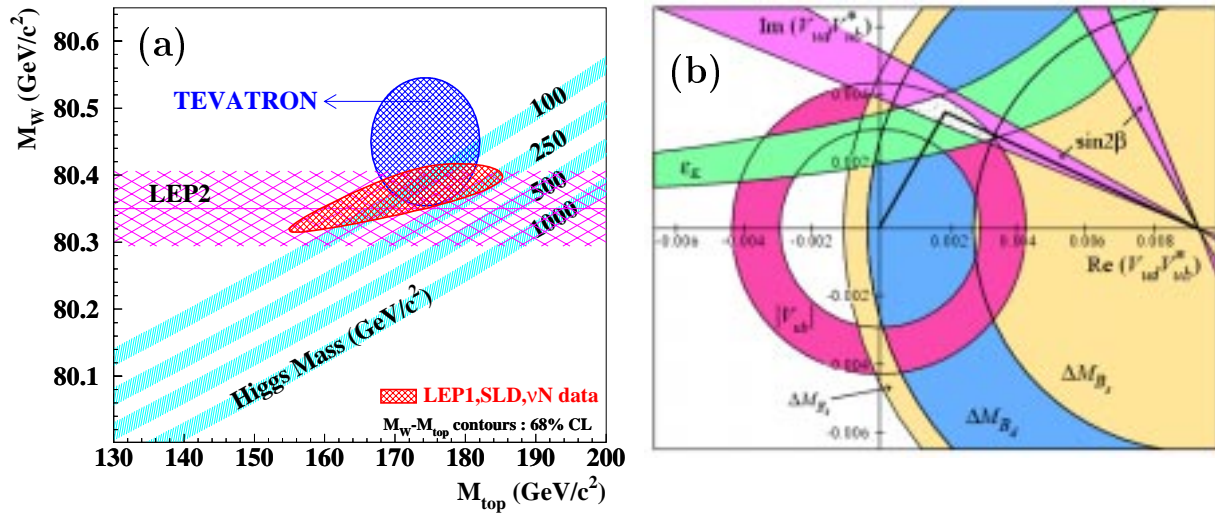


Figure 1: (a) Constraints on the Higgs boson mass as of 1999 from measurements of M_W and M_{top} from the Tevatron, LEP 2 and indirect results. (b) Constraints on the position of the apex of the unitarity triangle from $|V_{ub}|$, B mixing, ϵ and $\sin 2\beta$ as of 2002 (from Ref. [5]).

in the Standard Model [1]. Rate measurements of $|V_{ub}|$ as well as B^0 and B_S^0 mixing constrain the position of the apex of the unitarity triangle as illustrated in Figure 2(a). The second independent test comes from CP violation in the kaon system (ϵ_K) and the B system ($\sin 2\beta$) as displayed in Figure 2(b). Both tests through rate measurements and CP violation are in striking agreement as illustrated in Figures 2 and 1(b).

A Look into the Future

When the “wise (wo)man” is asked to have a look into the future of B physics at hadron machines, (s)he might do two things. First, (s)he might take a step back and recommend

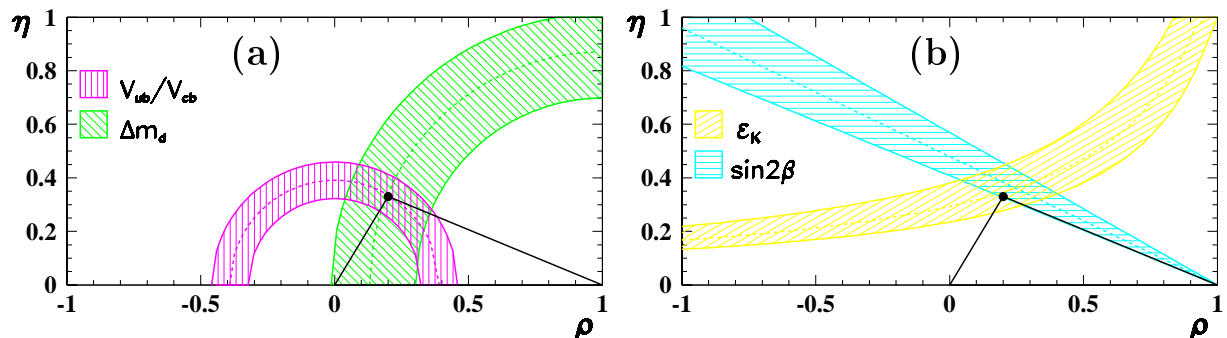


Figure 2: Illustration of the two independent tests of the CKM unitarity triangle through (a) rate measurements ($|V_{ub}|$ and B mixing) and (b) CP violation (ϵ_K and $\sin 2\beta$).

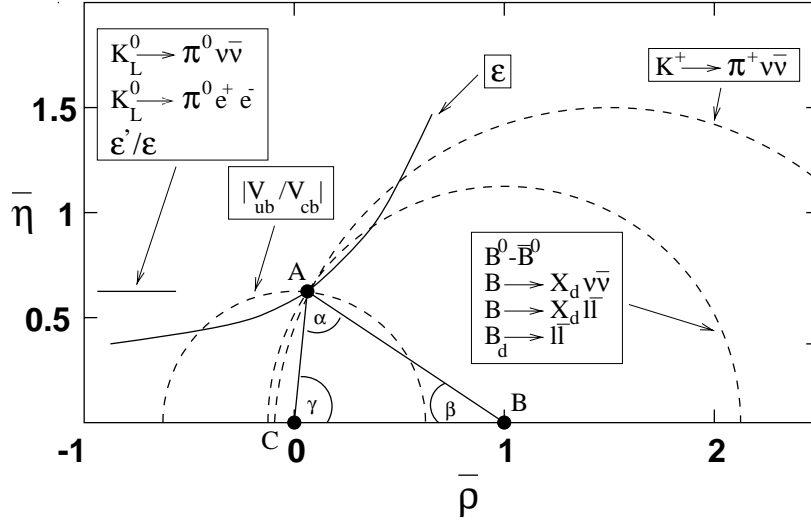


Figure 3: An ideal CKM unitarity triangle indicating the different constraints from K decays and B physics (from Ref. [6]).

to get a “grand view”. For the topic of this panel discussion, the “grand picture” is presented in Figure 3 taken from Ref. [6]. In this diagram an ideal view of the CKM unitarity triangle is given indicating the different constraints from K decays (ϵ_K , ϵ'/ϵ , $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$) as well as B physics ($|V_{ub}|$, B mixing, rare decays and CP violation in form of the angles α , β and γ). The second advice the wise (wo)man might offer is to look at your older friends. If you want to know how you’ll appear in five years from now, look at your older friends and see what they are right now. The older friend of B physics is kaon physics. Currently, the virtue of kaon experiments is to test the Standard Model by measuring modes that are theoretically clean such as $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. Thus, the goal of B physics in five years and beyond should be to test the SM by concentrating on theoretically clean modes. These will also allow to find new physics in an unambiguous way. In the remainder of this paper, we will therefore focus on testing CP violation through theoretically clean B decay modes.

The Future of CP Violation

In the following, we assume a data sample of 15 fb^{-1} for the quoted prospects which would correspond to the luminosity that can possibly be reached by the end of the Tevatron Run II. We will mainly concentrate on prospects determined at CDF as they were more accessible than prospects from DØ.

The Angle β from $B^0 \rightarrow J/\psi K_S^0$

CDF’s most important B physics goal in Run II is the study of CP violation in the B system. The golden decay $B^0 \rightarrow J/\psi K_S^0$ is the mode which all experiments will use to

obtain precision measurements of $\sin 2\beta$. For Run IIa with 2 fb^{-1} of data, CDF expects $\sim 20,000$ fully reconstructed $B^0 \rightarrow J/\psi K_S^0$ decays. With an expected effective tagging efficiency of $\varepsilon \mathcal{D}^2 \sim 9.1\%$, CDF will measure $\sin 2\beta$ with an uncertainty of about 0.05. DØ expects a similar precision. The systematic uncertainty on $\sin 2\beta$ is dominated by the uncertainty on the dilution which is determined by large control samples of $J/\psi K$ data. Thus this uncertainty scales with statistics. Since we do not see a limiting systematic uncertainty, the precision on $\sin 2\beta$ will scale with the integrated luminosity resulting in an uncertainty of 0.02 in 15 fb^{-1} competitive with expected measurements at the $e^+e^- B$ factories.

***CP* Asymmetry in $B_S^0 \rightarrow J/\psi\phi$**

While the *CP* asymmetry in $B^0 \rightarrow J/\psi K_S^0$ measures the weak phase of the CKM matrix element V_{td} , *CP* asymmetry in $B_S^0 \rightarrow J/\psi\phi$ measures the weak phase of the CKM matrix element V_{ts} . The latter *CP* asymmetry is expected to be very small in the Standard Model, on the order of a few percent. In the context of testing the Standard Model, this mode has the same fundamental importance as measuring $\sin 2\beta$ but is most accessible at a hadron collider. An observation of a large *CP* asymmetry would be a clear signal of new physics.

In Run I, CDF's yield of $J/\psi\phi$ was about 40% of $J/\psi K_S^0$ which results in an expectation of about 8000 $J/\psi\phi$ events in Run IIa. The magnitude of the *CP* asymmetry in $B_S^0 \rightarrow J/\psi\phi$ is modulated by the frequency of B_S^0 mixing. This requires to resolve B_S^0 oscillations. There is an additional complication in this decay mode, if the $J/\psi\phi$ final state is not a pure *CP* eigenstate. In this case, an angular analysis is necessary to determine the mixture of *CP* even and *CP* odd states in this decay channel. With 15 fb^{-1} of data in Run II, CDF expects a resolution of 0.03-0.06 on the *CP* asymmetry in $B_S^0 \rightarrow J/\psi\phi$ for $\Delta m_S \sim 20 \text{ ps}^{-1}$ depending on the *CP* content of the final state.

***CP* Asymmetry in $B_S^0 \rightarrow J/\psi\eta^{(\prime)}$**

Measuring the *CP* asymmetry in $B_S^0 \rightarrow J/\psi\eta^{(\prime)}$ decays is very similar to measuring it in $B_S^0 \rightarrow J/\psi\phi$ with two differences. First, the $J/\psi\eta$ and $J/\psi\eta'$ final states are *CP* eigenstates. Therefore no angular analysis is needed and no degradation of the *CP* asymmetry occurs. Second, the presence of photons in the final state makes these modes more difficult to detect at CDF since the CDF calorimeter was not designed to measure low energy photons with good resolution. However, CDF is capable of detecting these signals as shown in Figure 4. Here, in the invariant diphoton mass spectrum clear signals of $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ are observed in CDF Run I data.

Scaling from the expected number of $B^+ \rightarrow J/\psi K^+$ events, the rate of B^0 to B_S^0 production and the expected relative branching ratios, CDF expects about 8000 $B_S^0 \rightarrow J/\psi\eta$ events in Run II. Studies of J/ψ events in Run I indicate that a mass resolution of $40 \text{ MeV}/c^2$ and a signal-to-background ratio of 1:2 appears achievable. For $\Delta m_S \sim 20 \text{ ps}^{-1}$ and a proper time resolution of $\sigma_t \sim 0.045 \text{ ps}$, CDF expects to measure the *CP* asymmetry in $B_S^0 \rightarrow J/\psi\eta$ with an uncertainty on the order of 0.1.

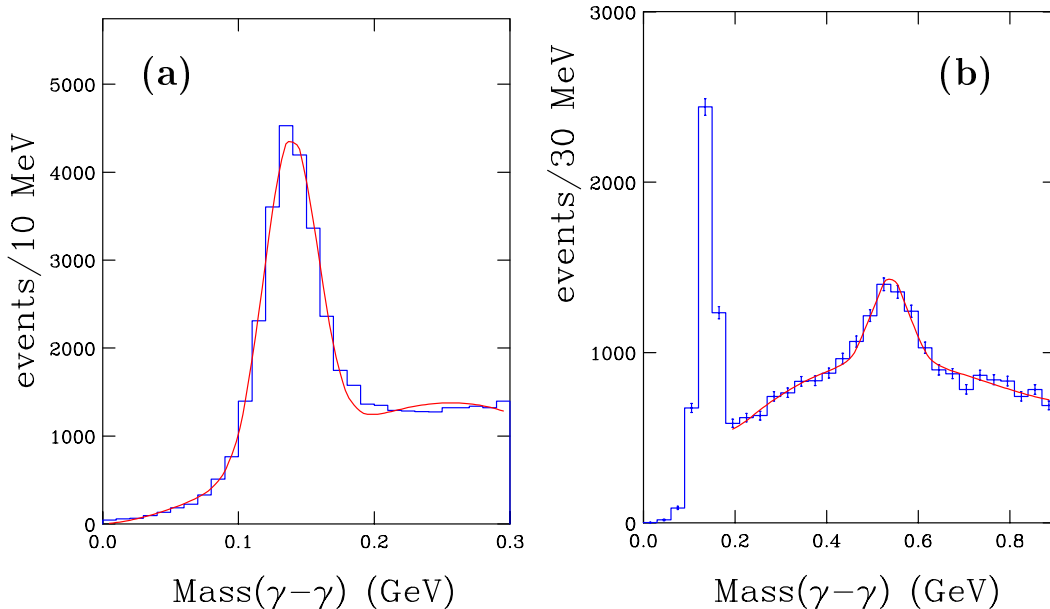


Figure 4: Invariant diphoton mass distribution showing (a) $\pi^0 \rightarrow \gamma\gamma$ and (b) $\eta \rightarrow \gamma\gamma$ signals in CDF Run I data.

The Angle γ from $B_S^0 \rightarrow D_S^- K^+$

A good candidate to determine the CKM angle γ is the decay mode $B_S^0 \rightarrow D_S^- K^+$ measuring $\sin \gamma$. In this mode, CP violation occurs via interference of the quark level processes $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$ through direct and mixed decays. Since B_S^0 oscillations are expected to have a small CP violating phase, the relative weak phase of this decay is $e^{i\gamma}$. Penguin contributions are expected to be small but there is a strong phase δ present which cannot be reliably calculated with present theoretical techniques and needs to be extracted from data. The time dependent decay rates for all four processes $B_S^0/\bar{B}_S^0 \rightarrow D_S^\mp K^\pm$ are fitted with a two-fold ambiguity in δ and γ .

The reduction of backgrounds, in particular physics backgrounds from the Cabibbo allowed process $B_S^0 \rightarrow D_S^- \pi^+$, is the primary challenge for CDF in extracting the $B_S^0 \rightarrow D_S^- K^+$ signal. Exploiting the $D_S^- K^+$ invariant mass as well as dE/dx information of the final state particles, studies at CDF show that a signal-to-background ratio of 1/6 can be achieved and a signal of 850 $B_S^0 \rightarrow D_S^- K^+$ events can be expected in 2 fb^{-1} . Thus, an initial measurement of γ should be possible at CDF in the beginning of Run II. Within the first 2 fb^{-1} of data, the expected error on $\sin(\gamma \pm \delta)$ is 0.4 to 0.7 depending on the assumed background levels. By the end of Run II, an uncertainty near 0.2 for γ may be achievable.

The Angle γ from $B^- \rightarrow D^0 K^-$

In a similar manner, the angle γ can be determined from the decays $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow \bar{D}^0 K^-$ with $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$. The advantage is that these modes are self-tagging

and no time-dependent measurement is necessary. One needs to just measure branching fractions of these decays. However, the decay $B^- \rightarrow \bar{D}^0 K^-$ is particularly problematic due to the small expected branching ratio. All these decay modes have significant physics and combinatoric backgrounds that must be reduced to acceptable levels to make this method feasible. CDF expects to collect a small sample of about 100 signal candidates with the two-track hadronic trigger in 2 fb^{-1} . There is optimism that the physics background can be brought down to the same level as the signal, but there could be considerable combinatoric background. If the combinatoric background can also be reduced to a level comparable to the signal, CDF would be in the position to measure γ with an uncertainty in the order of $10\text{-}20^\circ$ in 2 fb^{-1} . At this point it is not clear whether this can be scaled to a 5° measurement on γ with 15 fb^{-1} at the end of Run II.

The Angle α

To date, there are only two methods considered to be clean extractions of the CP phase α from B decays. Each method has its own particular difficulties. Originally it was suggested to use the time dependent CP asymmetry in $B^0 \rightarrow \pi^+ \pi^-$ to obtain α . In order to remove the ‘‘penguin pollution’’, it is necessary to perform an isospin analysis of $B \rightarrow \pi\pi$ decays [7] including the decay mode $B^0 \rightarrow \pi^0 \pi^0$ which is difficult to measure. The second method is the Dalitz-plot analysis of $B^0 \rightarrow \rho\pi \rightarrow \pi^+ \pi^- \pi^0$ decays [8]. The problem here is to understand the continuum background and the correct description of $\rho \rightarrow \pi\pi$ decays.

In a recent paper by London and Datta [9], a new method to measure the CP phase α has been suggested using decays $B^0/B_S^0 \rightarrow K^{(*)} \bar{K}^{(*)}$. Because the branching ratios for $B \rightarrow K^{(*)} \bar{K}^{(*)}$ are rather small, $\mathcal{O}(10^{-6})$, and because B_S^0 decays are involved, this method is most appropriate for hadron colliders, in particular since no π^0 detection is needed. The basic idea is to consider the pure $b \rightarrow d$ penguin decays $B^0 \rightarrow K^0 \bar{K}^0$ and $B^0 \rightarrow K^* \bar{K}^*$ and relate their time dependent decay rate to the corresponding B_S^0 decay modes into $K^0 \bar{K}^0$ and $K^* \bar{K}^*$ assuming U -spin symmetry. Using a double ratio in which the $SU(3)$ -breaking effects largely cancel, the theoretical uncertainties are estimated to be at most 5% [9]. The potential weakness of this method is an up to 16-fold ambiguity in extracting α which can be reduced by considering other $K^{(*)} \bar{K}^{(*)}$ final states. This constitutes a promising method for a potentially clean measurement of α . CDF expects to collect about 100-200 $B \rightarrow K^{(*)} \bar{K}^{(*)}$ decays with its hadronic track trigger in 1 fb^{-1} .

Conclusion

In this contribution to the panel discussion on ‘‘The Future of Hadron B Experiments’’ held at the Beauty 2002 conference, we made an attempt to discuss the question ‘‘Quo vadis, B physics?’’, where is B physics going in five years and beyond by representing the B physics prospects at CDF and $D\mathcal{O}$. There exists a long laundry list of modes to measure at the B factories, the Tevatron and 3rd generation B experiments (BTeV, LHCb). In the kaon system two clean tests of the Standard Model have been identified, $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, but it is not clear which are the ‘‘smoking gun modes’’ in the B system.

Precision measurements of $\sin 2\beta$, $B_S^0 \rightarrow J/\psi\phi$ and possibly $B \rightarrow K^{(*)}\bar{K}^{(*)}$ decays are likely good candidates.

Going back to looking at the “grand picture”, the relation of the CKM matrix to the quark mass hierarchy, flavour physics, the Higgs mechanism and electroweak symmetry breaking, it would be desirable to have a well defined path with clean Standard Model tests to be performed in the B system. Since this path is not obvious at this point, the only answer can be to continue strengthening the planned experimental efforts (Run IIb, BTeV, LHCb) to ask questions to nature by doing experiments in order to test the flavour sector of the Standard Model until it breaks. Let me conclude with a quote from Woody Allen which does not only relate to the lack of access to divine counseling but also to the funding situation in US high energy physics: *“If only God would give me some clear sign! Like making a large deposit in my name at a Swiss bank.”*

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