

**FUTURE PROSPECTS FOR CP VIOLATION IN HADRON
MACHINES**

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ABSTRACT

The capabilities of future CP violation experiments in hadron machines are reviewed. Special emphasis is put on the CDF experiment in the Run II of the Tevatron, due to start taking data in 2001, and on LHCb and BTeV, on a longer time scale.

1 Introduction

While the first statistically significant observation of CP violation in the B meson system will most likely take place in one of the e^+e^- b -factory experiments (BaBar, Belle), this talk will try to prove that the contribution from experiments in hadron colliders will be dominant in the future, starting in 2001.

Figure 1 shows the standard CP violation triangle. The angle β is the most easily accessible, in particular through the asymmetry in the decays

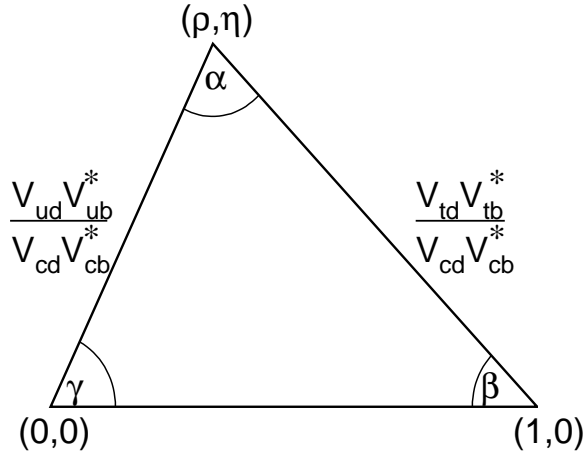


Figure 1: *The standard CP violation triangle.*

$B^0/\overline{B}^0 \rightarrow J/\Psi K_S$. First determinations by CDF ¹⁾, OPAL ²⁾ and ALEPH ³⁾ have recently become available. When combined, they give a two-standard deviation measurement of $\sin 2\beta$:

$$\sin 2\beta = 0.78 \pm 0.37 . \quad (1)$$

The combination is totally dominated by the CDF result. By summer 2000, the electro-positron colliders should get a measurement with an uncertainty about ± 0.15 ⁴⁾. The task is substantially more involved for the other two angles, α and γ . It is not obvious when will BaBar or Belle be able to obtain a measurement.

Hadronic uncertainties diminish the usefulness of a determination of the length of the side of the triangle opposite β . The length of the side opposite γ , can be obtained from the determination of Δm_s , the frequency of the oscillations in the $B_s^0 - \overline{B}_s^0$ system. The current limit from LEP is ⁵⁾:

$$x_s = \frac{\Delta m_s}{\Gamma_s} > 21.8 . \quad (2)$$

Standard Model expectations for x_s are in the range 20–30 ⁶⁾. When the determination of x_s will become available, it will be possible to combine it

with x_d , the similar parameter in the B_d system, now measured to be ⁵⁾

$$x_d = \frac{\Delta m_d}{\Gamma_d} = 0.717 \pm 0.026 , \quad (3)$$

in order to obtain the length of the side of the triangle opposite γ through the relation:

$$\frac{\Delta m_d}{\Delta m_s} \simeq \frac{|V_{td}|}{|V_{ts}|} \simeq \frac{|V_{td}|}{|V_{cb}|} . \quad (4)$$

Since the lepton machines are only scheduled to run at the energy of the $\Upsilon(4S)$ resonance, no B_s mesons will be produced. Therefore, x_s will only be determined in hadron machine experiments.

The standard CP triangle in fig. 1 is the only one obtained from the standard Wolfenstein parametrization of the CKM matrix ⁷⁾. However, one should remember that this is just an expansion of the complete matrix in powers of λ , the sinus of the Cabibbo angle, valid up to order $\mathcal{O}(\lambda^3)$. If one proceeds with the expansion up to λ^4 , one encounters a new imaginary contribution to V_{ts} , which gives rise to a new unitarity triangle. A new angle, $\delta\gamma$, appears, which in the Standard Model is proportional to λ^2 , and, therefore, very small, of order $\mathcal{O}(10^{-2})$. It is easily accessible through the decay $B_s \rightarrow J/\Psi\phi$, the B_s equivalent to the ‘‘golden channel’’ $B_d \rightarrow J/\Psi K_S$. Again, this is not possible in the lepton machines, which do not produce B_s .

The experimental program in the coming years has two clear goals:

- First, to observe for the first time CP violation in the B system. As explained above, this will most likely be achieved by BaBar and/or Belle, followed by HERA-B at DESY, CDF and D0.
- Then, to test whether CP violation is generated by the Standard Model. Here, all the experiments mentioned before will contribute but, most probably, the second-generation dedicated experiments, LHCb and BTeV, will be needed.

In the remaining of the talk, the capabilities of the experiments foreseen in future hadron colliders will be reviewed. Section 2 will cover the near future: CDF and D0 at the Fermilab Tevatron, scheduled to start physics data-taking in spring 2001. The more distant future, from 2005 on, will be covered in Section 3. ATLAS, CMS and LHCb are approved to take data at CERN’s LHC, while BTeV, if approved, will run at the Tevatron. Special emphasis will

be put in the two dedicated b -experiments, LHCb and BTeV. Finally, section 4 will give a short summary of the talk.

2 The Near Future: CDF and D0

2.1 The detector upgrades

The upgraded Tevatron at Fermilab is scheduled to start collider physics operation in spring 2001 with two upgraded detectors, CDF and D0. The luminosity delivered in the first two years of operation is expected to reach about 2 fb^{-1} , which is equivalent to a production of about 10^{11} b pairs per year. The challenge in a hadron collider experiments is not producing the b pairs, but rather triggering on them, selecting them and getting rid of the background. CDF has proven to be able to do all this with their recent determination ¹⁾

$$\sin 2\beta = 0.79^{+0.41}_{-0.44} \quad (5)$$

using the J/Ψ channel.

Both CDF and D0 are undergoing substantial upgrades ^{8, 9)}. Among other improvements, CDF is getting a new, longer, vertex detector, that will provide 3D coordinates in a larger acceptance region. A new time-of-flight system will allow kaon identification at low momentum, and can, therefore, be used for kaon tagging: using the kaon charge to decide on the flavor of the decaying b hadron. More importantly, a new pipelined, deadtimeless trigger system will allow purely hadronic events (no leptons) to be triggered efficiently. This will vastly increase the physics capabilities of CDF, as it will be shown later. The new all-hadron trigger requires two high transverse momentum tracks at level 1 and, using vertex detector information, finds their vertex at level 2 and requires the decay length to be positive.

D0 upgrades are not less important. The detector will have for the first time a solenoidal coil, with a 2 Tesla field that, together, with the new scintillating-fiber central tracking system, will provide precise momentum measurements for all charged tracks. Furthermore, a new four-layer vertex detector will also be added. These changes should allow D0 to reconstruct and tag B decays using standard displaced vertex techniques.

A comparison between the b -physics capabilities of CDF and D0 shows a clear advantage for the former, due, in particular, to its unique all-hadron

trigger. In order to trigger on hadronic B decays, D0 has to rely on semileptonic decays of the opposite-side B hadron, therefore paying the price of the 10% semileptonic branching ratio.

2.2 B_s oscillations

As mentioned in the introduction, the measurement of the mass difference of the two B_s states, Δm_s , is needed in order to determine the length of the side of the standard CKM triangle opposite the angle γ . The mass difference is obtained from the difference between mixed and unmixed B_s decays as a function of proper time:

$$\frac{N_{unmixed}(t) - N_{mixed}(t)}{N_{unmixed}(t) + N_{mixed}(t)} = D \cdot \cos(\Delta m_s t) , \quad (6)$$

where D is the so-called dilution factor, explained later. In order to be able to perform the measurement one needs to determine:

- The proper decay time. Hence good decay length resolution is needed.
- The B_s flavor at production time (tagging). The dilution factor D in the previous equation is $D = 1 - 2p_{mistag}$, where p_{mistag} is the probability of getting the flavor wrong.
- The B_s flavor at decay time, using, for instance, flavor-specific decays.

CDF has studied the flavor-specific decay channel $B_s^0 \rightarrow D_s^- \pi^+$ or $B_s^0 \rightarrow D_s^- \pi^+ \pi^- \pi^+$ with $D_s^- \rightarrow \phi \pi^-, K^{*0} K^-$. As one can see, there are no leptons and, therefore, the purely hadronic trigger is mandatory. CDF expects about 20000 selected events in the first two years of operation with a signal-to-background ratio between 1/2 and 2¹⁰). The significance of the measurement of Δm_s (in number of standard deviations) or of the related, dimensionless parameter x_s introduced above, is given by

$$Sig(x_s) = \sqrt{\frac{N \epsilon_{tag} D^2}{2}} \exp\left(-\frac{(x_s \sigma_t / \tau)^2}{2}\right) \sqrt{\frac{S}{S+B}} , \quad (7)$$

where N is the number of selected events, ϵ_{tag} is the tagging efficiency, D is the dilution factor, σ_t is the proper time resolution, τ is the B_s lifetime and S and B are the number of signal and background events selected, respectively.

Looking at the formula, one sees that the “quality factor” $\epsilon_{tag}D^2$ gives the effective tagging efficiency and that good proper time resolution is, clearly, crucial. No matter how many events one can collect, the reach in Δm_s is going to be limited by the time resolution to something of order $\mathcal{O}((1-3)/\sigma_t)$. CDF expects a time resolution around 50 fs and a quality factor $\epsilon_{tag}D^2 = 0.113$, which translate into a sensitivity to $x_s < 63$ at the five standard deviation level¹⁰⁾. This goes well beyond the current LEP limit of 21.8 and the expected range in the Standard Model, from 20 to 30. In summary, CDF should be able to determine x_s quite precisely unless it is much larger than expected.

2.3 Measurement of $\sin 2\beta$

The standard procedure to determine the angle β uses the time integrated asymmetry in the B^0/\bar{B}^0 decays to $J/\Psi K_s$:

$$\begin{aligned} A_{CP} &= \frac{N(B^0 \rightarrow J/\Psi K_s) - N(\bar{B}^0 \rightarrow J/\Psi K_s)}{N(B^0 \rightarrow J/\Psi K_s) + N(\bar{B}^0 \rightarrow J/\Psi K_s)} \\ &= -D_{mix} \sin 2\beta, \quad \text{with} \\ D_{mix} &= x_d / (1 + x_d^2) \simeq 0.47. \end{aligned} \quad (8)$$

Here D_{mix} is a dilution factor due to $B_d^0 - \bar{B}_d^0$ mixing. Since x_s is much larger than x_d this dilution factor is very small in the B_s^0 asymmetries, so that time-dependent measurements are needed.

The experimentally observed asymmetry is further diluted by mistagging and background:

$$\begin{aligned} A_{obs} &= D_{tag} \cdot D_{bgd} \cdot A_{CP} \\ D_{tag} &= 1 - 2p_{mistag}, \quad D_{bgd} = \sqrt{S/(S+B)}, \end{aligned} \quad (9)$$

so that the final uncertainty on $\sin 2\beta$ can be written as

$$\delta(\sin 2\beta) = \frac{1}{D_{mix}D_{tag}} \frac{1}{\sqrt{\epsilon_{tag}N}} \sqrt{\frac{S+B}{S}}. \quad (10)$$

CDF believes they can obtain a total $\epsilon_{tag}D_{tag}^2$ around 9.1 %, including the kaon tagging using the proposed time-of-flight system. With the statistics available in the first two years of data-taking, that would imply $\delta(\sin 2\beta) \simeq 0.07$ ¹⁰⁾. On the other hand, total $\epsilon_{tag}D_{tag}^2$ for D0 is expected to be around

5.0 %, implying $\delta(\sin 2\beta) \simeq 0.15$, using only the muon decay of the J/Ψ (11). Analyses are underway to quantify the precision attainable in the electron channel.

2.4 Other CP Angles

Determination of CP angles other than β can also be attempted by CDF. It will be more difficult for D0 because of their lack of a fully hadron trigger. A quick summary of CDF capabilities follows:

- $\sin 2\alpha$ could, in principle, be obtained from the $B^0 - \bar{B}^0$ asymmetry in the $\pi^+\pi^-$ decay. However, the large penguin contribution, with different phase, may preclude the effective extraction of α from this channel. Some other methods will be described in section 3. In any case, CDF can have a quality factor around 9.1% for this channel, leading to a precision in the determination of the asymmetry of $\delta A(\pi^+\pi^-) \simeq 0.09$ (10).
- There are several ways of studying the angle γ . CDF has explored, for instance, the use of the asymmetries in the decays $B_s^0/\bar{B}_s^0 \rightarrow D_s^\pm K^\mp$ and $B^\pm \rightarrow K^\pm D_{CP}^0$, where D_{CP}^0 is the $CP = 1$ eigenstate of the D^0 system. For the moment, however, there are no quantitative estimates of the possible $\sin 2\gamma$ reach.
- Finally, the asymmetry in the decays $B_s^0/\bar{B}_s^0 \rightarrow J/\Psi\phi$, the “golden decay” equivalent in the B_s sector, can be determined to about 10% by CDF, depending on the value of x_s (10). This asymmetry provides a direct determination of $\delta\gamma$. They expect about 6000 events with $\epsilon_{tag}D_{tag} \simeq 9.7\%$. While only an asymmetry of order a few percent is expected in the Standard Model, a larger value, if found, would be a sign of new physics. It should be noted that since in this channel the triggering is based on the leptonic decays of the J/Ψ , D0 should be able to do a similar job.

3 The More Distant Future: ATLAS, CMS, LHCb, BTeV

3.1 The situation in 2005

In about 2005 ATLAS, CMS and LHCb will start taking data at the LHC accelerator at CERN. At about the same time, BTeV, if approved, will start at the Tevatron. At that time a lot of progress will have been made by the earlier

experiments, both at hadron machines and at the electron-positron factories. In particular, one could expect $\sin 2\beta$ to be measured with a precision around 0.04 by a combination of BaBar, Belle, HERA-B, CDF and D0. The length of the side opposite γ will be known thanks to the B_s oscillations measurements at HERA-B, CDF and D0 but it is rather unclear the amount of information that will be gathered about α and γ . The outcome of the combination of all the different measurements should be one of the following:

- either a clear inconsistency with the Standard Model predictions will be seen in the precise measurements (β and B_s mixing);
- or a hint of inconsistency with the less precise measurements (α , kaon results) will appear;
- or all measurements will look consistent with the Standard Model.

In any case, the next generation of experiments will be needed for a full understanding of the CP violation mechanism. That will involve more precise measurements of the same parameters in the same channels, measuring the same parameters in different channels and determining for the first time some parameters, notably the angle γ .

3.2 The detectors

Around year 2005, four new hadron-machine experiments with interesting capabilities in b physics will start taking data. Two of them are specifically designed for b physics, LHCb¹²⁾ and BTeV¹³⁾. Both of them cover only the forward region, since most of the $b\bar{b}$'s produced are in this region. BTeV actually covers also the backward region, thus doubling the acceptance. The larger cross section available at LHC energies ($500 \mu\text{b}$ vs. $100\mu\text{b}$) more than compensates for the smaller acceptance of LHCb. Covering only the forward/backward regions has clear advantages:

- $b\bar{b}$ production peaks forward;
- limited solid angle coverage leads to limited cost;
- the b hadrons have higher momentum which leads to easier vertex finding and improved decay time resolution;

- open geometry allows for easy installation and maintenance.

These advantages compensate for the higher minimum bias background, occupancies and radiation dose that have to be overcome at low angles.

The main advantages that LHCb and BTeV have over the all-purpose detectors, ATLAS and CMS, are in particle identification and, especially, in the triggering capabilities. LHCb and BTeV have RICH systems that allow π/K separation in a large momentum range ($1 < p < 150$ for LHCb, $3 < p < 70$ GeV for BTeV). This is mandatory to separate signal from background in the $B \rightarrow \pi\pi, KK, K\pi$ channels and adds the possibility of using kaon tagging, as mentioned in chapter 2 for CDF.

Both LHCb and BTeV can trigger efficiently in all-hadron events, thanks to their vertex triggers. In contrast, ATLAS and CMS need a high- p_T lepton to start the triggering sequence. This considerably reduces the b -physics capabilities of the two multipurpose detectors.

3.3 Physics Reach

3.3.1 $\sin 2\beta$

The angle β can be measured very precisely by the second generation b experiments using the same “golden” decay used by CDF and D0: $B^0/\bar{B}^0 \rightarrow J/\Psi K_S$. Since the J/Ψ is only reconstructed through its lepton-pair decays, the triggering and particle-id advantages of LHCb and BTeV are of no importance and the kind of precision that can be achieved by the four experiments is very similar, ranging from $\Delta \sin 2\beta = \pm 0.015$ for LHCb to ± 0.025 for CMS^[14], with ATLAS and BTeV somewhere in between.

3.3.2 x_s reach

The B_s mixing analysis is much improved by the availability of a pure hadron trigger and, therefore, the differences between the reach of the experiments are large. Whereas ATLAS and CMS could only reach x_s values around 50^[14], lower than what can be explored already at CDF with their hadron trigger, the dedicated experiments can go up to 60 (BTeV) or 75 (LHCb)^[14]. It should be said, however, that Standard Model expectations for x_s are in the range 20–30, easily accessible by the first generation experiments.

3.3.3 $\sin 2\alpha$

The asymmetry in the $B_d^0 \rightarrow \pi^+\pi^-$ channel has already been mentioned in section 2 as a possibility for measuring α , although, at present, its usefulness is not clear due to the large penguin contribution with different phase. In any event, LHCb and BTeV can measure the asymmetry in this all-hadron channel with a ± 0.025 precision¹⁴⁾.

More promising, if more involved, seems to be the $B_d^0/\overline{B}_d^0 \rightarrow \pi^+\pi^-\pi^0$ channel, which proceeds through ρ intermediate states. Here, all amplitudes can be determined and the remaining ambiguities can be resolved using the interference regions in the Dalitz plot¹⁵⁾. The analysis seems feasible, but no experiment has yet made public the precision it could achieve in α .

3.3.4 $\sin 2\gamma$

There are several ways of getting to the angle γ , all of them rather challenging. For example, it can be obtained from the simultaneous measurement of six time-integrated decay rates in the $B_d^0 \rightarrow D^0 K^{*0}$ channel: $B_d^0 \rightarrow D^0 K^{*0}$, $B_d^0 \rightarrow \overline{D}^0 K^{*0}$, $B_d^0 \rightarrow D_{CP}^0 K^{*0}$, $\overline{B}_d^0 \rightarrow \overline{D}^0 \overline{K}^{*0}$, $\overline{B}_d^0 \rightarrow D^0 \overline{K}^{*0}$, $\overline{B}_d^0 \rightarrow D_{CP}^0 \overline{K}^{*0}$, with D^0 decaying to $K^-\pi^+$, \overline{D}^0 to $K^+\pi^-$, and D_{CP}^0 to either K^+K^- or $\pi^+\pi^-$. The final state, therefore, consists in all cases in four charged kaons or pions resonating in different masses. It is clear that proper pion/kaon separation is crucial. LHCb claims a precision in γ around 10° from this channel¹²⁾.

BTeV has studied a similar channel: $B^- \rightarrow D^0/\overline{D}^0 K^-$, where D^0 and \overline{D}^0 go to the same final state, and the corresponding B^+ decays. Using now nine time-integrated decays, the precision in γ is found to be about 13° ¹⁶⁾.

3.3.5 Other CP angles

Apart from α , β and γ , other CP angles are also accessible to the second generation CP experiments:

- The small angle $\delta\gamma$ introduced in section 1 can be measured precisely using the $B_s^0/\overline{B}_s^0 \rightarrow J/\Psi\phi$ asymmetry as already mentioned above. Precisions around $0.5 - 0.9^\circ$ seem possible, even for ATLAS and CMS¹⁴⁾, because of the leptonic decays of the J/Ψ .
- The combination $\gamma - 2\delta\gamma$ can be determined with a precision around 10° ¹⁴⁾ by both BTeV and LHCb through the decay $B_s^0 \rightarrow D_s^- K^+$ and

its charge conjugated. Since $\delta\gamma$ is expected to be small in the Standard Model, this can be viewed as yet another way of getting γ , only in this case through B_s decays, and, hence, a very interesting check.

- LHCb has also studied the extraction of $2\beta + \gamma = \pi + \beta - \alpha$ from $B^0 \rightarrow D^{*+}\pi^-$. The precision that can be obtained is around 9° [14]. Again, since β will be well known, this method could be used to obtain γ or α .

The ability of measuring a single angle with different processes can be very useful in checking whether the Standard Model by itself is able to explain CP violation.

4 Summary

This talk has tried to convey the message that hadron machines have a very comprehensive program for understanding the origin of CP violation in the period 2001–2015 or so, at the Tevatron and LHC.

In a first phase, starting in 2001, CDF and, to a lesser extent, D0 will be able to measure $\sin 2\beta$ to about 0.07 and study B_s mixing for values of the mixing parameter x_s up to 63.

In a second phase, from 2005 on, LHCb, BTeV, if approved, plus ATLAS and CMS will improve on β and x_s and will be able to determine both α and γ to about 10° , thus putting strong constraints on the Standard Model ability to explain all the phenomenology of CP violation in the b sector.

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