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Prospects for CP Violation Searches at Tevatron

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In the near future CP violation measurements will be one of the most crucial test for the Standard Model. Several B factories are going to be built to study these phenomena in the B system. These goals can be achieved also at the Tevatron Collider by the two experiments: CDF and D0. Starting from data collected during Run I the sensitivity expected in Run II is shown.

1. Introduction

CP violation in the B system is described in the Standard Model [1] through the well-know unitarity triangle [2]. Experiments provide us with tools to measure the parameters of this triangle. In particular 2 angles, α and β , can be obtained measuring the asymmetry, $A_{CP} = (N_{\bar{B}^0} - N_{B^0}) / (N_{\bar{B}^0} + N_{B^0})$ of the B^0 and \bar{B}^0 decays into the CP eigenstates $\pi^+ \pi^-$ and $J/\Psi K_S^0$ respectively.

Analysis can be performed on time-dependent or time-integrated basis. In the time-dependent measurement [2] $A_{CP} = \mathcal{A} \sin(\Delta m t)$ where Δm is the mass difference between the two mass matrix eigenstates and t is the proper time. \mathcal{A} represents $\sin(2\beta)$ for $B^0 \rightarrow J/\Psi K_s$ and $\sin(2\alpha)$ for $B^0 \rightarrow \pi^+ \pi^-$ [2] if the so-called ‘‘penguin diagrams’’ contributions are neglected. The time-integrated asymmetry has an extra term in front of \mathcal{A} due to $B^0 - \bar{B}^0$ mixing making the measurement less sensitive to \mathcal{A} . Moreover, in the time-dependent measurements we can easily get rid of the background which is concentrated at short lifetime while in the time-integrated ones it contributes as an additional dilution factor.

The basic requirements to perform a time-dependent measurement are:

- a) reconstruct with enough statistics the final CP eigenstates;
- b) reconstruct the decay time;
- c) tag the flavour at the production time.

The error on \mathcal{A} can be evaluated only at the fit level, while an upper limit is given by the error on time-integrated measurement [3]:

$$(\sigma_{\mathcal{A}})^2 \approx \frac{1 + x_d^2}{x_d} \frac{1}{\epsilon D^2 N} \frac{S + B}{S} \quad (1)$$

where N is the number of signal events before flavor tagging, S and B are the numbers signal and background events after tagging, ϵ is the tagging efficiency and D the tagging dilution, $D = (N_R - N_W) / (N_R + N_W)$. Here, N_R and N_W are the numbers of right and wrong sign tags. $x_d = \Delta m / \tau$, where τ is the B^0 lifetime. ϵD^2 represents the figure-of-merit to compare different tagging algorithms.

2. Results achieved with Run I data

CDF has demonstrated the possibility of doing B physics at hadron colliders exploiting the unique aspect of hadron production. Several measurements have been done that are preliminary for future CP studies. Key elements were the excellent tracking resolution and secondary vertex reconstruction. D0 did not have such a possibility with Run I data since the detector was optimized for high momentum physics.

CDF has proven its ability to fulfill the basic requirements of time-dependent analysis. Outstanding achievements are the lifetimes and $B^0 - \bar{B}^0$ mixing measurements.

In samples of fully reconstructed B charged and neutral lifetimes are determined with a very good

precision [4] showing also that a proper time resolution of $\sim 40 \mu\text{m}$ is achievable.

Several time-dependent $B_d^0 - \bar{B}_d^0$ mixing measurements have been done with CDF data [5,6]. To accomplish this goal, CDF developed different tagging algorithms. One is referred as ‘‘Same Side Tagging’’ (SST) [7–9] and it exploits the charge correlation between the B meson and charged particles produced in the fragmentation of the b quark. While this method gave good results at LEP [8], figure 1 proofs that it can be successfully used also at hadronic colliders. With this technique the $B_d^0 - \bar{B}_d^0$ oscillation frequency has been determined: $\Delta m = 0.46 \pm 0.07$ (*stat.*) ± 0.04 (*syst.*) ps^{-1} . The figure-of-merit for SST is 1.5 ± 0.4 . The lepton (μ and e) tagging uses

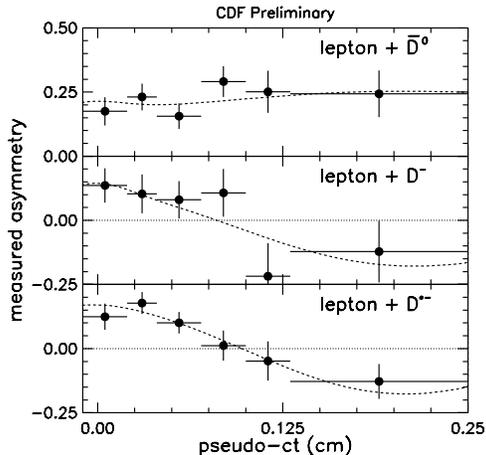


Figure 1. Asymmetry versus ct for different decay signatures obtained by applying Same Side Tagging. Dotted line is the results of the fit.

the correlation between the lepton charge and the B meson to identify the flavour at the production. For muon tagging we have $\epsilon D^2 = 0.6 \pm 0.1$ and for electron tagging 0.3 ± 0.1 . The ‘‘jet charge’’ making use of the silicon vertex infor-

mations reconstructs the charge of the second B from the hadronic decay products. In this case $\epsilon D^2 = 1.0 \pm 0.4$. To find the overall ϵD^2 , correlations have to be taken into account. A global correlation of $\sim 80\%$ is evaluated that gives $\sum \epsilon D^2 = 2.7\%$.

3. The Tevatron and its experiments in Run II

For Run II (expected to start late in 1999) the Tevatron collider will have the Main Injector and it is supposed to deliver 2 fb^{-1} in two years. Both the experiments CDF and D0 are involved in important upgrades of the detectors. The main goals are to extend the lepton coverage increasing also the transverse momentum (P_t) acceptance, redo the tracking system to work at high luminosity and redesigning the trigger for the shorter bunch crossing. D0 will also install a superconducting solenoid to have a 2 Tesla magnetic field in the central region.

3.1. Studies for $\sin(2\beta)$ at D0

Prospects for CP violation at D0 are based on Monte Carlo studies. They simulated $p\bar{p}$ interactions at $\sqrt{s} = 2.0 \text{ TeV}$ using ISAJET. The b and c hadron are let to decay using CLEO Monte Carlo with $B^0 \rightarrow \Psi K^0$ branching ratio 7.5×10^{-4} . All particles are simulated through the detector using a parameterization of detector response.

The analysis requires $\Psi \rightarrow \mu^+ \mu^-$ with minimum muon P_t of 1.5 GeV . Right now the only tagging method used is based on leptons, for this analysis in particular just the muon is taken in consideration. The minimum P_t is at 1.5 GeV and the detector acceptance is 40%. With this method $\epsilon D^2 = \epsilon \cdot 0.25$ where ϵ here represents all detector losses due to trigger and reconstruction inefficiencies. With an assumed signal to noise ratio of 2:1 the lower limit on $\sin(2\beta)$ precision evaluated with eq. 1 is

$$\sigma(\sin 2\beta) = 0.12.$$

If a realistic efficiency of 60% is assumed the precision becomes

$$\sigma(\sin 2\beta) = 0.15.$$

3.2. Measurement of $\sin(2\beta)$ at CDF

CDF has at the moment the world's largest sample of $B^0 \rightarrow J/\Psi K_S^0$ and can use it for preliminary studies of CP violation and for extrapolation in Run II. In 110 pb^{-1} of data $\sim 240 J/\Psi K_S^0$ are reconstructed (see figure 2) with a signal to noise ratio of 1.2. This number can be improved easily up to 2 by tuning the track requirements. In Run II the number of $J/\Psi K_S^0$ events is ex-

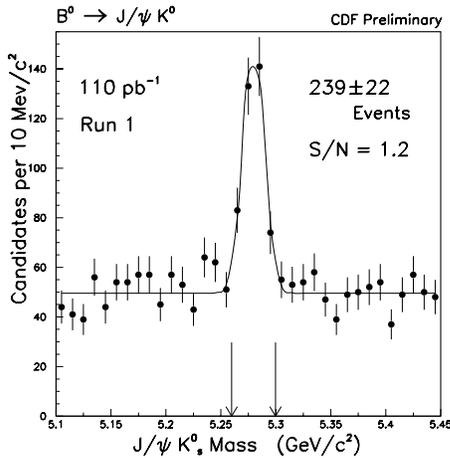


Figure 2. Run I $J/\Psi K_S^0$ invariant mass.

pected to be increased by several factors. First of all there will be a factor 20 that is the ratio of 2 fb^{-1} of data expected in 2 years of running to 100 pb^{-1} of Run I data. A factor 2 should be gained lowering the dimuon trigger threshold and widening the acceptance. Scaling the 240 events from Run I around 10,000 reconstructed events are expected. If then it will be possible to trigger also on $J/\Psi \rightarrow e^+e^-$ there will be an other factor 1.5. In this case $\sim 15,000$ events should be available.

In Run II CDF expects improvements also in the tagging efficiency and dilution. The extended lepton coverage and the upgraded tracking system is expected to give $\epsilon D^2 = 1.8\%$ for a lepton tagging. Again the new tracking system with the

extended coverage of the silicon vertex detector will result in a cleaner selection of fragmentation tracks around the B meson. This should improve the same side tagging obtaining $\epsilon D^2 = 2\%$. For the same reasons also the jet charge tagging algorithm is expected to be improved up to $\epsilon D^2 = 3\%$. The total $\epsilon D^2 = 5.4\%$ taking into account a correlation of 80%.

Now it is possible to evaluate the expected precision on $\sin 2\beta$. This is done using eq. 1, i.e. σ is overestimated and as consequence the CDF provisions are quite conservative.

Results are quoted for different numbers of expected events and varying ϵD^2 . A summary of these numbers is in table 1. As can be seen CDF can easily reach an error of 0.09 on $\sin 2\beta$.

3.3. Studies for $B \rightarrow \pi^+ \pi^-$

The study of CP asymmetry in $B \rightarrow \pi^+ \pi^-$ is much complex than in $J/\Psi K_S^0$ specially at hadron colliders. The greatest challenge is the trigger. A signal with a branching ratio $\sim 10^5$ has to be detected in a hadronic environment. CDF is planning to do this with a three level trigger:

Level 1: Requirement of 2 oppositely-charged tracks with $P_{t1} > 2 \text{ GeV}$ and $P_{t2} > 3 \text{ GeV}$ found with a fast track processor. The trigger rate extrapolated from Run I data is $\sim 16 \text{ KHz} @ 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$;

Level 2: Cut on tracks impact parameter, d , calculated at runtime by SVT processor. The trigger rate inferred from Run I data demanding $100 \mu\text{m} < d < 1 \text{ mm}$, forward decay, and B from primary vertex is $20 \text{ Hz} @ 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$;

Level 3: Since the full event information is available it will be easy to reduce the trigger rate to $\sim 1 \text{ Hz}$

With this trigger CDF expects $\sim 10,000$ events of $B \rightarrow \pi^+ \pi^-$ in 2 fb^{-1} of data.

In order to measure $\sin 2\alpha$ several other issues have to be solved. The physics background coming from $B^0 \rightarrow K\pi$, $B_S^0 \rightarrow K\pi$ and $B_S^0 \rightarrow KK$ can be eliminated with the help of the invariant mass cut and the particle identification. Based on Run I data CDF is expecting an invariant mass

Table 1
Uncertainties expected on $\sin(2\beta)$ extrapolating the actual number

Scenario	ϵD^2 (%)	$N(J/\Psi K_S^0)$	$\sigma(\sin 2\beta)$
$\mu^+\mu^-$ triggers; "measured" tags only	2.7	10,000	0.16
$\mu^+\mu^-$ triggers; improved lepton & same side π tags	3.8	10,000	0.13
$\mu^+\mu^-$ & e^+e^- triggers; improved lepton & same side π tags	3.8	15,000	0.11
$\mu^+\mu^-$ & e^+e^- triggers; impr. lepton & same side & jet charge tags	5.4	15,000	0.09

resolution of ~ 20 MeV at $P_t \sim 6$ GeV in Run II. CDF will not have a dedicated particle identification detector but can use the dE/dx information from the central chamber to separate K from π at momenta of 2 GeV. The combinatorial background can be an important issue and it is right now under study. The expectations are $S : B \approx 1 : 1$. Finally, there is the contribution of strong interactions (penguin diagrams) to the asymmetry. This is a controversial item not completely solved yet.

Assuming 10,000 $B \rightarrow \pi^+\pi^-$, $\epsilon D^2 = 5.4\%$ and $S/B \sim 1/4$ for all tagging methods it is possible to evaluate the error on \mathcal{A} with eq. 1 $\sigma_{\mathcal{A}} = 0.33$. If in the future CDF will have a time of flight system it will be possible to tag on K . That will increase ϵD^2 up to 7.8% giving $\sigma_{\mathcal{A}} = 0.10$.

4. Conclusions

Studies done by D0 on Monte Carlo and by CDF on real data from Run I show that at the Tevatron Collider it will be possible to do CP violation measurements. The precision expected on $\sin 2\beta$ will be the order $\sigma(\sin 2\beta) = 0.09$. There will be a possibility of studying the asymmetry on $B \rightarrow \pi^+\pi^-$ and to measure $\sin 2\alpha$ if the theoretical uncertainties will be solved.

Beyond the Run II, both experiments will have large samples of data to reduce the errors. The Tevatron Collider could also have at that time a dedicated heavy flavor detector at C0.

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