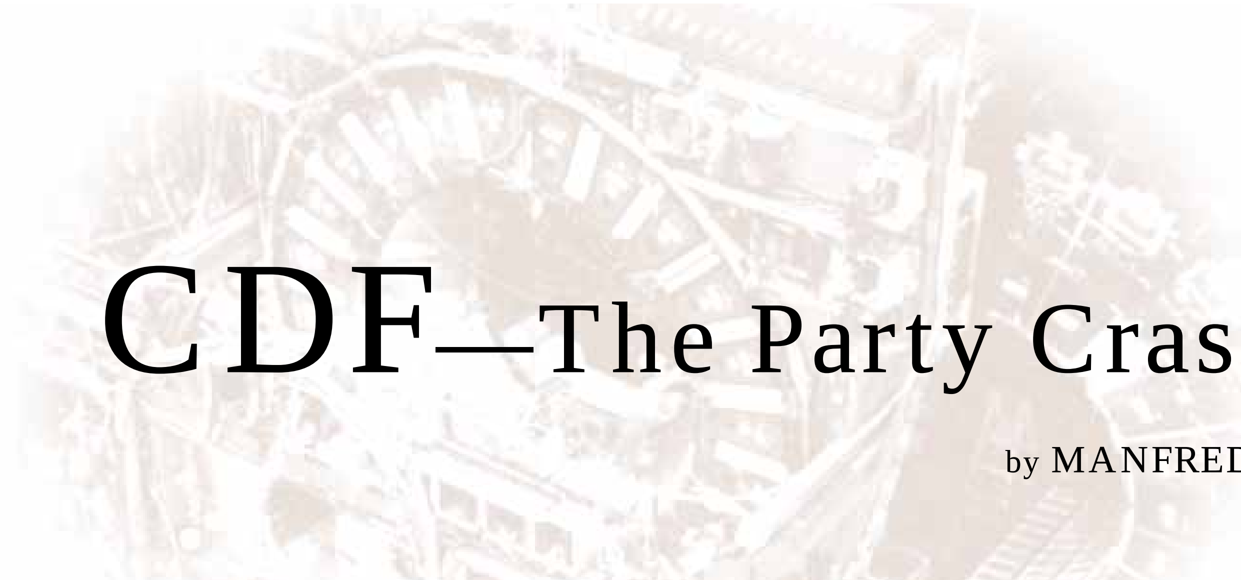


CDF—The Party Crashers

by MANFRED PAULINI

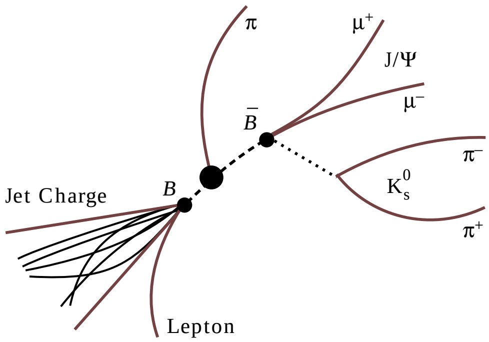
You see things as they are and ask 'Why'? I dream things as they never were and ask 'Why not'?

—*George Bernard Shaw*

IMAGINE A WELL PREPARED celebrity affair. Everything is perfectly planned. The candles match the color of the napkins. The program has been rehearsed many times. Everybody is anxiously awaiting the appearance of the two superstars. Everything is expected to go smoothly, but something unexpected happens. This is the story of some uninvited party crashers.

The Collider Detector at Fermilab (CDF) studies proton-antiproton collisions at the world's highest energy accelerator, the Tevatron Collider. The study of B mesons, subatomic particles containing a bottom quark, b, is among the most exciting goals for CDF—although this was not at all anticipated when the detector was designed. The collision of a proton with an antiproton had been considered too complex an environment, in which it seemed to be too hard to identify the B meson. CDF was built primarily to study the properties of the W boson, a particle mediating the weak force, and to find the top quark, which was indeed discovered in 1995 (see the article by Bill Carithers and Paul Grannis in the Fall 1995 *Beam Line*, Vol. 25, No. 3).

Several features in the original detector design were however advantageous for studies of B mesons. CDF has a large magnetic tracking volume, in which the flight paths of electrically charged particles are bent, a well-segmented calorimeter to detect electrons and to measure their energy, as well as muon chambers that allow the detection of muons even at low momentum. But it was the later installation of a silicon micro-vertex detector in 1992 that made the study of B particles possible in a competitive way. This device finds the point of origin (vertex) of particles, indicating how far a B meson traveled before it broke down and thus how long it lived. In 1993, CDF physicists presented their first measurements of



B particles emerging from the collision between a proton and antiproton are relatively long-lived, traveling on average about 1 mm (dashed lines) before decaying. Here a $\bar{B}$ meson decays into a J/ψ and a K^0_s particle. The J/ψ further disintegrates into two muons (μ^+, μ^-) while the K^0_s decays further into two pions. To determine whether the B particle was born as a B^0 or its antiparticle $\bar{B}^0$ certain clues are used: another pion produced in conjunction with the B decay products, a jet, or a lepton produced by the second B particle in the event.

the lifetimes of *B* mesons, demonstrating the capabilities of its silicon micro-vertex detector. Since then, the collaboration has pursued a broad program studying the decays of *B* particles. With a detector not specifically designed for *B* physics, we are now participating in the race to discover CP violation in the *B* meson system, competing with physicists whose accelerators and detectors are optimized for this single purpose. In this article, I illustrate why we feel confident in joining the celebrants setting out to reveal the nature of CP violation in *B* decays.

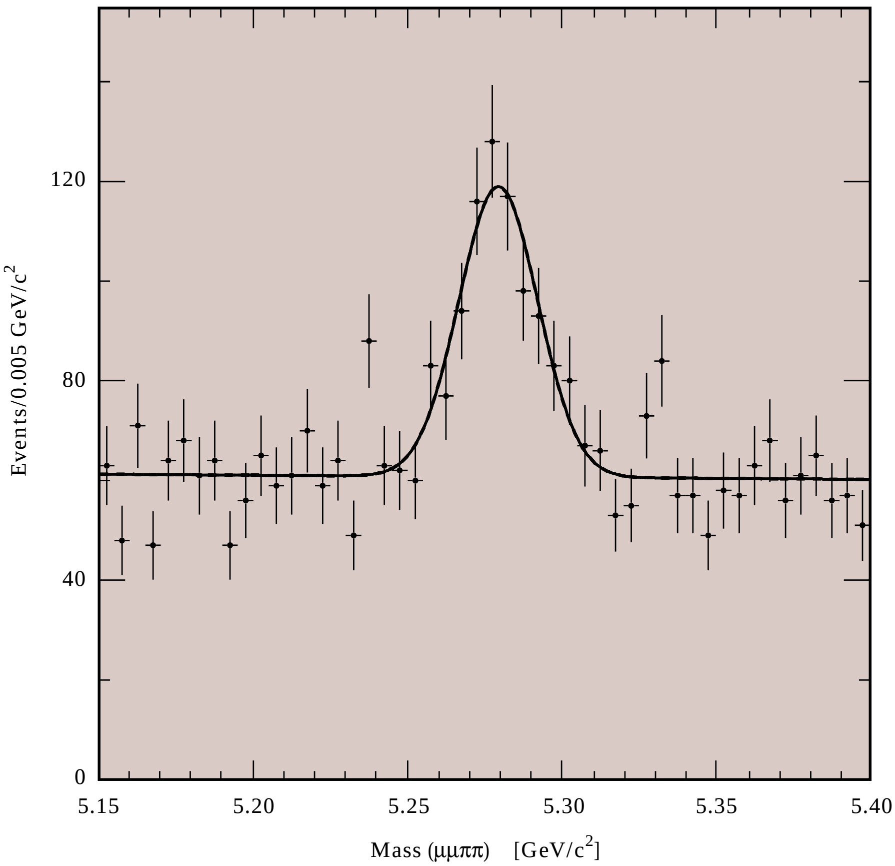
There are particular advantages to pursuing *B* physics at the Tevatron Collider. It produces all species of *B* particles, in contrast to the *B* factories, where only certain kinds of *B* mesons appear. But the primary motivation is that the *B* meson production rate is about 3000 times larger at the Tevatron than at the *B* factories. About 5 billion $b\bar{b}$ pairs were produced during the 1992–96 run of the Tevatron Collider, called Run I. Producing *B* particles at high rate is thus easy. But isolating events that contain them is a major issue, since they are produced in only one in every thousand collisions. *B* mesons appear in every fourth event at the *B* factories. The task at CDF is therefore identifying the desired events while rejecting copious backgrounds. The "trigger" decides whether an event is interesting enough to be recorded. In Run I, all triggers used to find *B* particles were based on easily identified leptons, electrons or muons.

Soon after CDF presented its first *B* lifetime results in 1993, the collaboration embarked on a program to explore whether CDF would be able to study CP violation in the *B* meson system. The best chance is with the "gold-plated" decay mode $B^0 \rightarrow J/\psi K_S$ (see the illustration on the left). In general, there are three ingredients that are essential to measure CP violation in this decay. First, one needs to reconstruct the decay by finding $\pi^+\pi^-$ pairs that come from K_S decays in events where two muons from a J/ψ set off the trigger. Approximately 400 signal events, currently the world's largest sample of $B^0 \rightarrow J/\psi K_S$, have so far been reconstructed at CDF (see the graph on the next page). Now the lifetime of the B^0 meson that decayed to $J/\psi K_S$ must be measured. Since *B* mesons are produced independently at the Tevatron, the clock starts ticking with the initial proton-antiproton collision whereas at the *B* factories the clock runs from the decay of the first *B* meson to the decay of the second one. As the third ingredient, we must determine whether the *B* meson involved was a B^0 or its antiparticle $\bar{B}^0$. This detective work—usually called *B*-flavor tagging—requires examining the remainder of the event. CDF physicists use certain clues to tag the B^0: another pion produced in conjunction with the *B* meson disintegrating to $J/\psi K_S$, or a jet or lepton produced by the other *B* particle in the event (using the fact that *B* particles always come in pairs). The charge of the pion, jet, or lepton tells us whether a B^0 or $\bar{B}^0$ decayed to the $J/\psi K_S$. All these methods are imperfect, however, and cause uncertainties in the measurement of the CP asymmetry. Since *B* flavor tagging is the crucial element of a CP violation measurement, CDF has done extensive studies of the various methods which do indeed work. However, they are not as effective as they are at the SLAC and KEK *B* factories. On the other hand, the Tevatron's much higher production rate for *B* mesons compensates for this disadvantage.

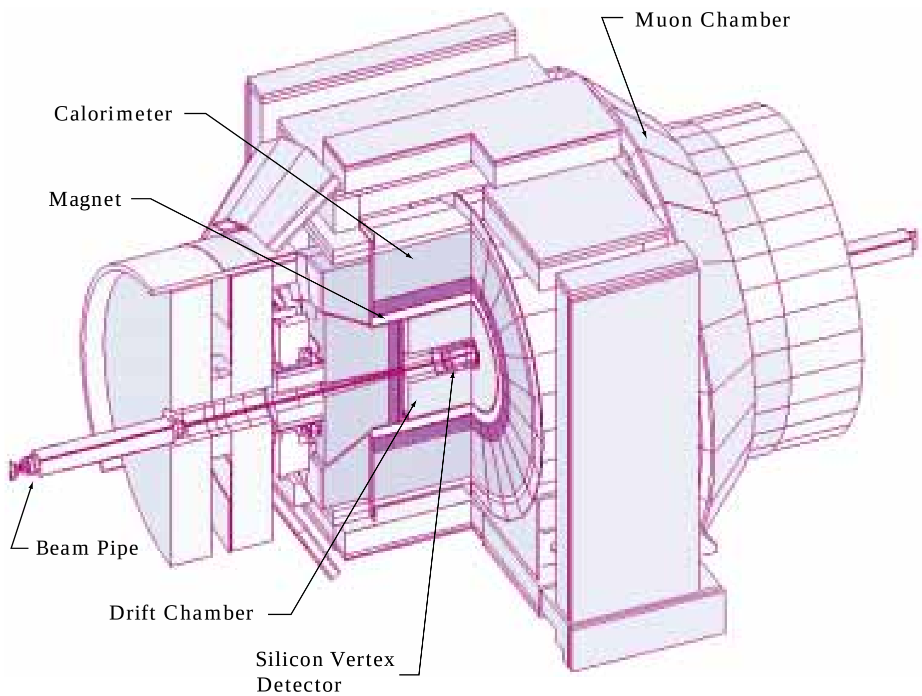
CDF recently demonstrated its ability to measure CP violation in the *B* meson system by applying these three tagging methods to its sample of 400 $J/\psi K_S$ events. If there were no asymmetry, 200 of the 400 events would come from B^0's and the other 200 from $\bar{B}^0$'s, and there would be no evidence for CP violation. The existence of an asymmetry would then indicate that CP symmetry is violated in the *B* meson system, resulting in a non-zero value for the CP violation parameter sin 2β. As it turned out the measured CDF value for sin 2β is 0.79±0.44. While this result is a tantalizing indication that sin 2β is non-zero, it is not conclusive proof for CP violation in *B* meson decays. But it clearly establishes the feasibility of measuring CP asymmetries at CDF and is the best direct measurement of the CP violation parameter sin 2β in the *B* meson system to date.

The Fermilab accelerator complex is currently being upgraded to produce an order of magnitude higher event rates in the Tevatron Collider—scheduled to run again in the summer of 2000. Within two years thereafter, the current data set is expected to be eclipsed by another that is 20 times larger. The CDF detector (see illustration on the next page) is also undergoing major upgrades, including the charged particle tracking system vital for the study of *B* particles at CDF. Among these improvements are a next-generation silicon micro-vertex detector and a new drift chamber filled with gas and wires used to reconstruct the trajectories of particles from *B* decays. A trigger upgrade allows for higher data rates and increases the sophistication of the triggering decision. For the first time, CDF plans to operate a track trigger that identifies *B* decay modes with no leptons, such as $B^0 \rightarrow \pi^+\pi^-$. This trigger will use information from the new silicon micro-vertex detector. In addition, two projects that will significantly enhance the *B* physics capabilities of CDF have recently been approved: an additional layer of silicon detectors just outside the beam pipe and a time-of-flight system to determine the velocity of particles and give clues about their identities.

With the improved detector, CDF physicists expect to identify 10,000 $B^0 \rightarrow J/\psi K_S$ events in two years of running. Together with enhanced tagging capabilities, this data set will allow the observation of CP violation and a measurement of sin 2β with a precision of ±0.08, comparable to the



Invariant mass distribution of $J/\psi K_S$ events at CDF comprising about 400 signal events in the peak.



Schematic cut-away view of the upgraded CDF detector.

uncertainties projected for the *B* factories. Another goal of future *B* physics is the observation of an asymmetry in $B^0 \rightarrow \pi^+\pi^-$ decays, thus measuring the CP violation parameter sin 2α and further checking the consistency of the unitarity triangle. The key to this measurement is the ability to trigger on the $\pi^+\pi^-$ decay mode. The CDF collaboration plans to do this using the new track trigger and expects to record about 10,000 $B^0\rightarrow \pi^+\pi^-$ events in two years. This would result in an estimated precision on the measurement of sin 2α similar to that of the *B* factories (although theoretical uncertainties in the extraction of this parameter from just the $B^0\rightarrow \pi^+\pi^-$ mode still need to be addressed). Better instrumentation will also allow the collection of large samples of other *B* decay modes, especially decays of B^0_S mesons which offer further ways of probing CP violation. In particular, CDF is equipped to observe oscillations between a B^0_S meson and its antiparticle $\bar{B}^0_S$. The physics of B^0_S mesons represents a unique capability for CDF until at least the year 2005.

Thus the CDF collaboration is well prepared to search for the nature of CP violation in the *B* meson system. With data taking just beginning at the *B* factories and the next run of CDF following in the summer of 2000, there will be a heated race for the answer. Armed with the knowledge from Run I, the party crashers are ready to knock on the door!