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Beauty Physics at CDF

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Abstract

The CDF experiment has performed several measurements in the area of beauty and charm physics with the data collected during the Run I of the Tevatron. The experiment is now ready to collect new data at higher luminosity with a substantially improved detector. We discuss these improvements and the future measurements in this area of physics accessible after the first few years of data taking. These include the measurement of the mixing frequency of B_s mesons and that of CP violation effects in the B_0 sector.

1 Introduction

CDF is the only experiment that has been able to do extensive b-quark physics measurements in hadronic interactions. This was not expected; indeed such a program was absent from the 1981 CDF Design Report [1], which described the planned detector and its physics goals. With the data of the first physics run taken in 1988 and 1989 (Run 0) the first observation of exclusive decays of B_d and B_u mesons in channels containing a J/ψ was made [2]. This proved to be a strong encouragement to improve all the single and di-lepton triggers, and to install a new silicon vertex detector, which had never before been used in a hadronic collider. The data taken with this new detector configuration during Run I (1992 - 1996) proved to be extremely rich of information about particles with beauty and more than 50 papers on related subjects have been published so far by the CDF collaboration. In section 2 we briefly review the major results from Run I.

During and after Run I the CDF collaboration has started a significant detector upgrade program to make it ready to cope with a substantial increase in the luminosity of the Tevatron. In addition the detector has been improved in many ways. In section 3 we describe the expected Tevatron performance and the status of the upgraded CDF detector with special emphasis on the new components that most affect our future b-quark physics program.

We have high expectations for our physics reach after the new data-taking period, Run II, which has started in March 2001. Indeed we have a unique opportunity to observe for the first time, and measure, the mixing frequency of B_s mesons, and we are competitive with the B factories in the measurement of the CP violating parameters such as $sin(2\beta)$. The measurement of the angle γ of the unitarity triangle is also feasible with good resolution. We will give a quantitative assessment of the expected quality of all those measurements in section 4.

2 Overview of some Run I results

The cross section for b production at the Tevatron is very large, $\sim 100\ \mu b$. Most of this cross section is at low transverse momentum; therefore the difficult part is finding a trigger that enhances the b-hadron content. In Run I this was achieved using single and di-lepton triggers with the lowest possible momentum thresholds. In the first case data sets with several thousand semileptonic decays of the type $B \rightarrow l\nu D$, with the D meson fully or partially reconstructed, were obtained; in the second about half a million J/ψ's were selected (see fig. 1-left), 20% of which

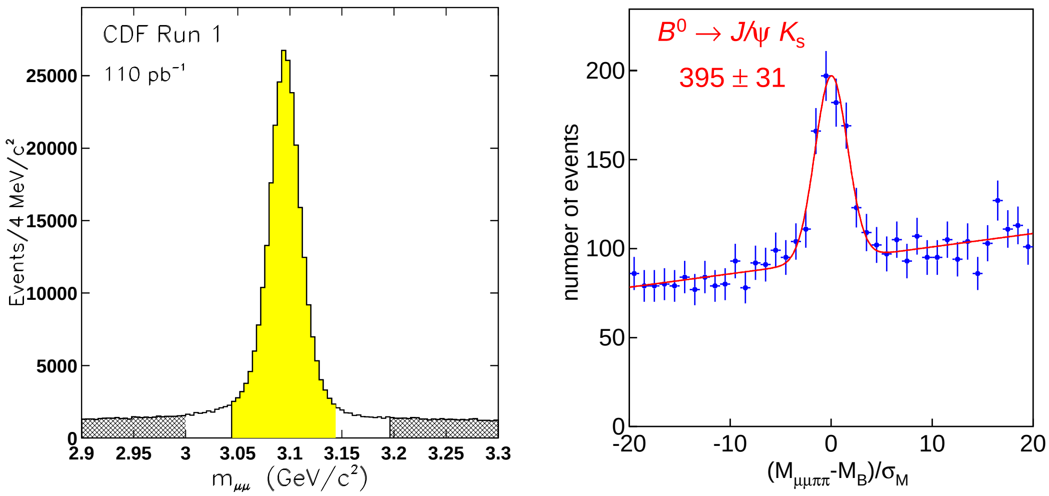

Figure 1: *Left: CDF J/ψ signal in Run I. Shaded areas indicate signal and sideband regions. Right: CDF's $B_0 \rightarrow J/\psi K^0_S$ signal.*

originating from b-hadron decays. This significant sample of J/ψ's gave us access to many exclusive B meson decays, for instance the $B_0 \rightarrow J/\psi K^0_S$ channel (fig. 1-right), that has been the fundamental ingredient for our measurement of $sin(2\beta)$. Key to the implementation of these triggers has been the capability to include tracking information and match it with other specific electron and muon signatures at an early trigger stage.

Accurate decay vertex resolution has been possible at CDF thanks to its 4-layer silicon vertex detector followed by a large volume drift chamber. This information, coupled with the large b-enriched data sets, has allowed a detailed measurement of the lifetimes of all b-hadrons with accuracy comparable to that of the individual LEP experiments. In particular CDF has made the only existing measurement of the B_c lifetime [3] and the most accurate single experiment measurement of the B_s lifetime [4]. In fig. 2-left we show for instance a comparison of the several measurements of the B_s meson lifetime [5].

After having the basic lifetime analyses under control, the CDF collaboration has invested a significant effort into B_0 mixing measurements. A comparison of our results to those of other e^+e^- experiments is shown in fig. 2-right. This work on B mixing has been important to develop and characterize flavor tagging techniques, and setup all the necessary tools to deal with CP violating asymmetries. Indeed CDF has made in Run I a rather remarkable measurement of $sin(2\beta)$ [6], which has

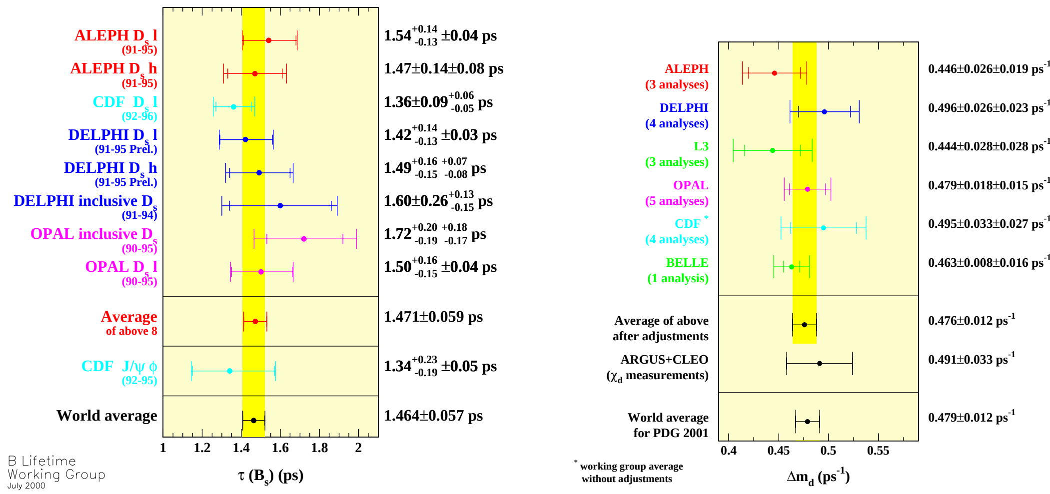

Figure 2: *Left: A comparison of measurements of the B_s lifetimes (Summer 2000). Right: A comparison of B_d mixing oscillation frequency measurements (March 2001).*

been improved only after the onset of experiments at dedicated B factories.

3 Accelerator and detector upgrades

The Fermilab accelerator complex has been significantly upgraded and additional improvement are still foreseen. The expectation is that of a major increase in the delivered luminosity relative to Run I as shown in Table 1. In order to limit the average number of interactions per beam crossing to a value similar to Run I a reduction of the time between bunches from 3.5 μsec to 132 nsec (396 nsec in an intermediate phase) has been necessary. This has had a major impact on the CDF and D0 detectors; in particular the front end electronics, the trigger and Data Acquisition systems had to be replaced. At CDF other "slow" detectors like the Central Tracking Chamber, the Silicon Vertex Detector and the Endplug and Forward gas calorimeters had to be replaced.

Besides replacing existing sub-systems to deal with the increased luminosity and shorter bunch spacing, new features have also been added to improve the performance of the detector. In the following is a list of the most important additions, which affect b-quark physics:

- A scintillator-based time of flight system has been added. The expected time

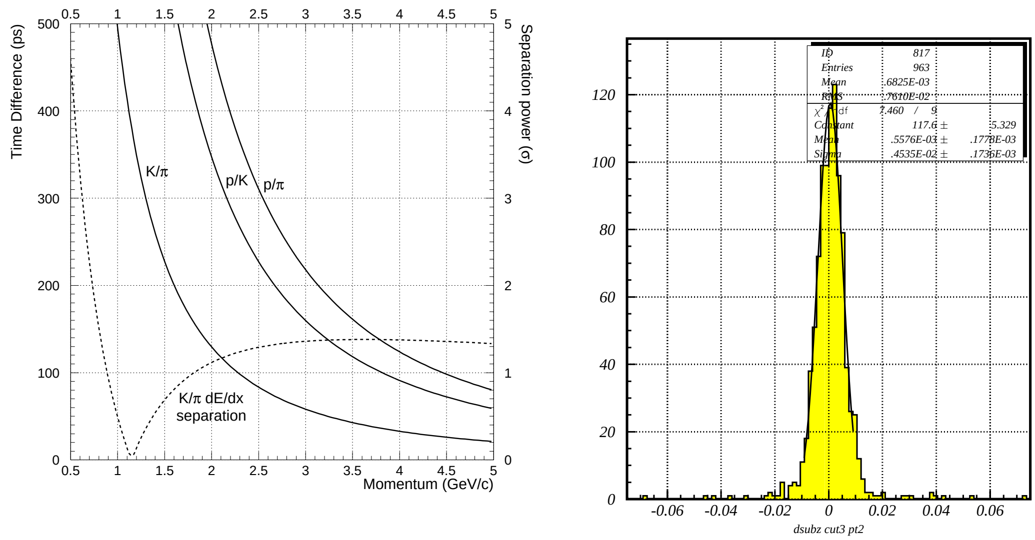

Figure 3: *Left: predicted Kaon/Pion separation using the new TOF detector (100 ps resolution) and dE/dx in the central tracking chamber. Right: impact parameter distribution from prompt tracks as measured with the SVT hardware trigger tracker. See text for more details.*

resolution is about 100 psec. As shown in fig. 3-left this allows a $\pi - K$ separation at the 2 σ level up to a transverse momentum of 1.6 GeV/c. This complements nicely our dE/dx measurements using the central tracking chamber. An improvement of approximately 50% in our flavor tagging effective efficiency is expected by the addition of this information.

- An inner layer of silicon mounted directly on the beam pipe has been added. This improves significantly our track impact parameter resolution and therefore our sensitivity to B_s oscillations. An average proper lifetime resolution of 45 fsec is expected using the decay $B_s \to D_s \pi$.

- A new tracking trigger system is implemented at an earlier trigger stage (level 1) relative to Run I. This allows to lower the p_t threshold on our leptonic triggers. Moreover it makes it possible to trigger on displaced vertices at level 2.

- A secondary vertex trigger system (SVT) has been added. This consists of a set of hardware processors that reconstruct tracks with impact parameter resolution comparable to offline processing. Tracks with significant impact parameter signal the presence of displaced vertices and therefore short lived particles like b and c-hadrons. This new trigger gives access for the first time to large samples of fully hadronic b-hadron decays. Much of our B_s mixing and CP violation measurement programs depends on this trigger. In fig. 3-right we show the impact parameter distribution of tracks from real $p\bar{p}$ interactions as reconstructed online by the hardware processors, after correcting offline for the beam slope and the central tracking information. A resolution of $\sim 45\mu$m, consistent with the beam transverse size is observed. Such corrections will be performed online in the near future.

Table 1: *Expected Tevatron luminosity profile.*

Year	2001	2002	2003	2004	2005	2006	2007
Luminosity ($\times 10^{31}$ cm$^{-2} \cdot sec^{-1}$)	1	8	12	20	40	50	50
Integrated luminosity (fb^{-1})	0.1	1.0	2.0	3.0	6.3	10.5	15.0

4 Run II physics prospects

CDF can address a large number of b-physics topics during Run II. The full extent of our physics reach after 15 fb^{-1} of integrated luminosity has not been yet assessed. We will concentrate here on a few "flagship" analyses and we shall assume an integrated luminosity of 2 fb^{-1}, which corresponds to the end of the Tevatron Run IIa. More details can be found in reference [7].

The expected resolution on the CP violating parameter $sin(2\beta)$ is rather straightforward to estimate by extrapolating our previous measurement [6]. Several trigger improvements are implemented in Run II: mostly the lowering of the di-muon p_t threshold, the increased muon coverage in the intermediate rapidity region and some tuning of the trigger cuts. Better triggering and increased luminosity give approximately a factor 50 in the total number of $J/\psi K^0_S$ collected, that is 20,000 scaling from the 400 observed in Run I. CDF also plans for an additional $J/\psi \rightarrow e^+e^-$ trigger, which would increase this sample by 50%. The yield of 20,000 events represents therefore a conservative estimate. The effective flavor tagging efficiency, ϵD^2, will be improved by our better coverage for leptons, a bigger vertex detector and the possibility of kaon tagging using the new TOF system. We expect all of these factors to improve the effective flavor tagging efficiency from the 6.2% observed in Run I to 9.1%. Scaling the Run I measurement resolution for the factors

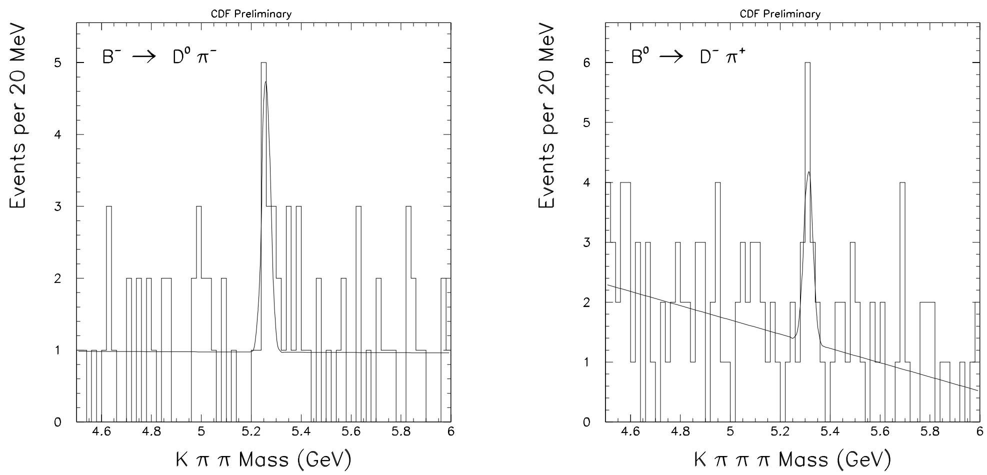

Figure 4: *Left:* $B^- \rightarrow D^0\pi^-$ *signal in run I data (8.1±3.5 events). Right:* $B^0 \rightarrow D^-\pi^+$ *signal in run I data (6.5±3.6 events).*

described above we estimate $\Delta(sin(2\beta)) \sim 0.05$. The resolution as a function of the integrated luminosity is shown in fig. 5.

CDF has two strategies for the measurement of the B_s oscillation frequency: one uses fully hadronic decays of the type $B_s \rightarrow D_s\ n\pi^\pm$, where n is a small odd number; the other uses the semileptonic decay of the type $B_s \rightarrow D_s l\nu$. The D_s are always assumed to decay to all charged tracks. In both cases, due to the special role played by kaons in the same side tagging of B_s relative to B_d mesons, we expect an effective flavor tagging efficiency of 11.3%, slightly higher than the one used for the $sin(2\beta)$ measurement. The event yield expected is ~75,000 events for the fully adronic channel. This estimate is based on emulating the secondary vertex trigger on Run I data and then scaling for acceptance corrections. The signal to noise ratio is evaluated using again run I data. We look for hadronic B decays in events triggered with inclusive leptons. We find a small signal of $B^- \rightarrow D^0\pi^-$ and $B^0 \rightarrow D^-\pi^+$, as shown in fig. 4. Scaling the S/N ratio observed for the B_s relative production fraction and the specific branching ratios used in the mixing analysis, we predict a S/N in the range of 0.5 to 2. After taking into account the expected proper lifetime resolution of 0.045 ps, we predict to be sensitive to x_s up to 60 with 2 fb^{-1}. The maximum x_s detectable at the 5σ level as a function of the integrated luminosity is shown in fig. 5. The semileptonic channel gives a lower sensitivity since the loss of the neutrino makes the proper time resolution worse. Still, in 2 fb^{-1} we expect to

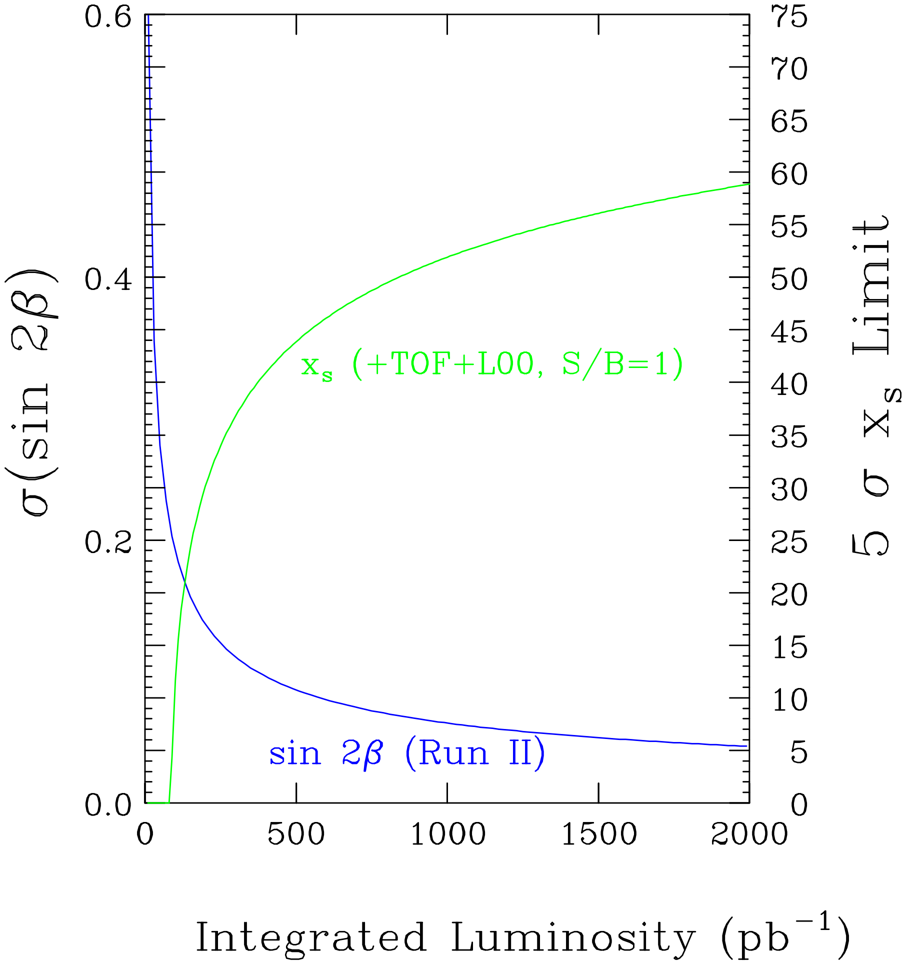

Figure 5: *CDF's resolution on* $sin(2\beta)$ *and maximum* x_s *measurable with* 5σ *sensitivity as a function of integrated luminosity.*

be able to detect x_s up to about 30.

We notice from fig. 5 that CDF starts having an interesting measurement of $sin(2\beta)$ and x_S well before the full 2 fb^{-1} have been accumulated.

The measurement of the unitarity triangle angle γ is certainly more demanding, still we believe it to be within the reach of the CDF experiment with 2 fb^{-1} of data. CDF can accumulate more than 5,000 (20,000) $B_d \to \pi^+\pi^-$ $(K^+\pi^-)$ and more than 10,000 (2,500) $B_s \to K^+K^-$ $(K^-\pi^+)$ events, thanks to the new track impact parameter trigger. These events need however to be disentangled from each other as well as from a continuum background of approximately 50,000 events. The relative fractions of $\pi^+\pi^-$, $K^+\pi^-$ and K^+K^- events can be obtained using dE/dx

information from the Central Outer Tracker, which provides $\sim 1.5\ \sigma$ separation between π and K at p_t above 2 GeV/c. Additional separation can be obtained using the invariant mass distribution, based on an estimated mass resolution of 25 MeV/c^2. Finally the different oscillation frequencies of the CP asymmetries for B_d and B_s is taken into account. In practice a simultaneous unbinned fit of the mass and lifetime distributions is made, where the time dependent CP asymmetries of $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are parametrized as:

$$\mathcal{A}_{CP} = \mathcal{A}_{dir} cos(\Delta m t) + \mathcal{A}_{mix} sin(\Delta m t)$$

From a Monte Carlo study we estimate typical resolutions at the 10% level for all four measured asymmetries. The extraction of γ from this measurement requires that we express the four CP asymmetries as a function of γ, β and the complex ratio of the amplitudes of the penguin contributions over the amplitude of the tree contributions. This ratio is in general different for $B_d \to \pi^+\pi^-$ relative to $B_s \to K^+K^-$, however, according to a suggestion by Fleischer [8], we can assume that the two ratios are the same within 20%. With this assumption and a pessimistic choice of the phase of the Penguin to Tree ratio, we estimate a statistical resolution of 6° on γ and a systematic error associated to the model dependence of 3°.

5 Conclusions

In summary with the startup of the Tevatron Run II in March 2001 we expect significant measurements in the area of mixing and CP violation already during the next year. By the end of Run IIa (2 fb^{-1}) accurate measurements of $sin(2\beta)$, x_s and quite possibly γ will be available. This program of physics complements nicely that of the B-factories. The combination of the results of CDF, D0 , BaBar and Belle will be able to test at a very deep level the standard model in the b sector during the next few years.

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