B PHYSICS IN RUN II WITH UPGRADED CDF II

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At the beginning of next millennium B-factories at KEK or PEP colliders will be operating and will provide precise measurements of CP violation parameters in the B^0 systems. In order to test the Standard Model predictions, measurements of parameters which involve B_s, B_u and Λ_b decays will be necessary. We present here how the upgraded CDF detector will be suited for these studies.

1. DETECTOR UPGRADES

CDF Run II is expected to begin in year 2000. This Run will use an upgraded detector in order to take advantage of the higher luminosity of the upgraded collider.

The Tevatron with the Main Injector will reach an instantaneous luminosity of 2×10^{32} cm^{-2}s^{-1} with an energy in the center of mass of 2 TeV. The goal is to integrate 2 fb^{-1} of data in 2 years. At the beginning of operations the crossing time will be 396 ns with 36 bunches and at regime 132 ns with 108 bunches.

The detector issues are driven by luminosity, number of bunches and interaction time. The number of bunches and the luminosity determine the average number of overlapping interactions in one beam crossing. The short time between crossings requires the use of fast front-end electronics, pipelined readout and trigger.

The tracking system is the most relevant upgrade for B physics. The new drift chamber, (Central Outer Tracker) has been designed with small drift cells and faster gas in order to cope with the the short interbunch time. The silicon vertex detector (SVXII) will cover $\sim 2.5\sigma$ of the luminous region and will increase b-tagging efficiency. The insertion of additional silicon layers between the COT and the SVXII will extend track finding capabilities to the region $1 < |\eta| < 2$. This new tracker will allow:

1. three dimensional tracking;
2. excellent pattern recognition;
3. good momentum resolution.

The muon detector coverage will be extended up to the forward region ($\eta = 2$) which will be equipped also with a new electromagnetic calorimeter. The increased coverage of lepton detectors and the improved tracking system will allow the design of new lepton triggers. The information from tracking in the COT will be available for the trigger at level 1. This provides a much better lepton definition than in the previous run and allows us to lower the lepton P_t thresholds. A completely new impact parameter trigger at level 2 will allow for the first time access to a large number of hadronic B decays.

2. PROSPECTS FOR b HADRON LIFETIME MEASUREMENTS

In the Spectator Model all B lifetimes are due to $b \to cW^-$ and are expected to be equal. Non Spectator effects, like quark interference, W exchange and weak annihilation, produce lifetime differences among B hadrons. Theories based on $1/m_b$ expansion predict the hierarchy $\tau_{\Lambda_B} < \tau_{B^0} \sim \tau_{B_S} < \tau_{B^-}$. The ratios $\tau_{\Lambda_B}/\tau_{B^0}$ and τ_{B^-}/τ_{B^0} have been analyzed to third order in m_b expansion [1]. These predictions depend on some unknown "bag parameters"; figure 1 shows the ranges of the lifetime ratios covered using sensible values for these parameters. Although the theoretical predictions for τ_{B^-}/τ_{B^0} match well with the average of the experimental results, these predictions have such large spread that no constraint can be put on theory. For the ratio $\tau_{\Lambda_B}/\tau_{B^0}$ the theoretical expectations are centered at 0.95 and their spread is very narrow. But in this case only a small tail of theoretical prediction extends into the experimental region. The partial agreement between data and prediction prevents to further constrain the theory and new experimental results are needed.

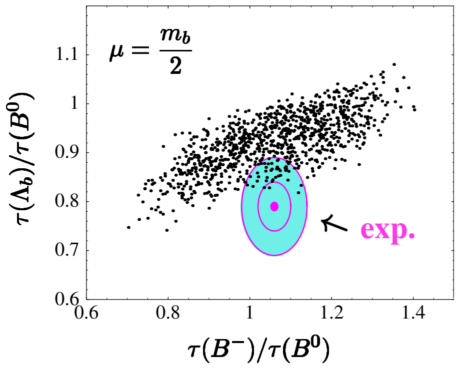

Figure 1. Distribution of lifetimes ratios (theory predictions: small dots) with the 1σ and 2σ contours around the experimental values.

2.1. B^0, $B^\pm$ AND Λ_b LIFETIMES

Measurement of decay length (l) and transverse momentum (P_t) are the basic ingredients for the B lifetime measurements. This requires a detector with good resolution on vertex position and on transverse momentum. CDF has done several measurements during Run I achieving $\Delta P_t/P_t \approx$ few % and $\Delta l \sim 50$ μm on fully reconstructed B decays (figure 2). The accuracy obtained by CDF on lifetime measurements is comparable with world average results (see table 1). In Run II CDF will improve lifetime ratio measurements by a factor of ~ 4 thanks to 20 times increased statistics (in 2 years of data taking). This assumes that the detector will have the same performance as in Run I and that the systematic errors scale somewhat with statistics.

2.2. B_s LIFETIME

The theory predicts that $|\tau_{B_S}/\tau_{B^0} - 1| < 1\%$ and the world average is $\tau_{B_S}/\tau_{B^0} = 0.98 \pm 0.05$. In future it will be very difficult to push the experimental accuracy to a level of sub-1% [1].

CDF has performed this measurement exploiting two different decay channels. The first channel is $B_S^0 \rightarrow J/\psi\phi$, which is expected to be dominated by the CP even state. The second channel is $B_S^0 \rightarrow D_S l X$, which is an equal mixture of CP even and odd states. The $J/\psi\phi$ sample consists of 58 events and the result is dominated by the statistical error ($\tau = 1.34^{+0.23}_{-0.19} \pm 0.05$ (ps) [2]). The second one has higher statistics, the error is smaller but not as expected since the decay is not fully reconstructed. ($\tau = 1.36 \pm 0.09^{+0.06}_{-0.05}$ (ps) [3]).

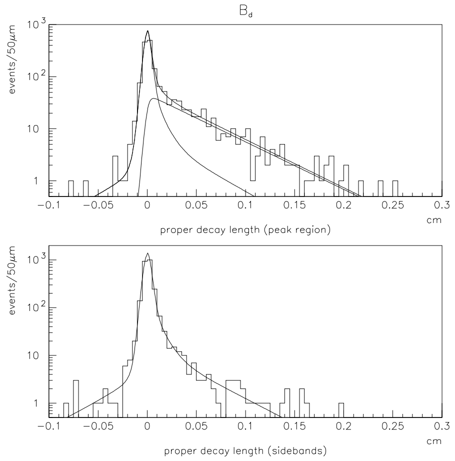

Figure 2. Decay length distribution for exclusive B decays.Top: signal bottom: Background. The width of the background distribution gives the resolution reached in Run I.

For high value of B_S mixing frequency the width difference, $\Delta\Gamma$, between the light and heavy quark, is sizeable. This suggests a new method to measure the mixing frequency (see mixing section). From lifetime measurement in the partially reconstructed sample, CDF has been able to set the limit $\frac{\Delta\Gamma}{\Gamma} < 0.83$ @ 95% C.L. [3].

3. $B^0 - \bar{B}^0$ MIXING AND CP VIOLATION EXPECTATIONS

$B\bar{B}$ mixing theory is well established within the Standard Model. The oscillation frequency of the B_d system has been precisely measured by several experiments, including CDF[4]. For B_S the expected mixing frequency is high and so far only

Table 1
Comparison of b-hadrons lifetime measurements.

b-hadron	CDF τ (ps)	World av. τ (ps)
B^0	1.51 ± 0.05	1.57 ± 0.04
B^+	1.66 ± 0.05	1.67 ± 0.04
ratio B^+/B^0	1.09 ± 0.05	1.07 ± 0.04
Λ_b	1.32 ± 0.17	1.23 ± 0.08

lower bounds on X_s have been measured. The ratio $X_d/X_S \approx |V_{td}|^2 / |V_{ts}|^2$ ($X_{d,s} = \Delta m_{d,s}\tau_{d,s}$ and V_{td} and V_{td} are elements of the CKM matrix). CDF goal for Run II is to measure X_d and X_S oscillation frequencies and to evaluate these two matrix elements.

Within the Standard Model CP violation in the B system is closely related to mixing. Although the statistical significance is poor, CDF has recently published a measurement of one parameter, $\sin 2\beta$, which describes this phenomenon [5].

Mixing and CP measurements require to reconstruct the decay time and to identify the B at production and decay time. In mixing measurements this is done tagging the B flavour. For CP analysis the final CP eigenstate has to be reconstructed and the B flavour at production tagged.

Some tagging algorithms have been developed and optimized in Run I. The figure of merit to compare different methods is the effective tagging efficiency $\epsilon\mathcal{D}^2$ ($\epsilon = \frac{(N_R+N_W)}{N}$, $\mathcal{D} = \frac{(N_R-N_W)}{(N_R+N_W)}$ and $N_{R(W)}$ is the number of events with right(wrong) tag). Run I results and projections for Run II are summarized in table 2.

3.1. B_s REACH

The theoretical expectation for X_S is $12.2 < X_S < 24.2$ [6] and the present experimental limit is $\Delta m_S > 12.4$ (ps^{-1}) @ 95% C.L. This corresponds $X_S > 18.4$ for $\tau_{B_S} = 1.48$ (ps)

CDF has only one experimental result for X_S from Run I data [7]. In Run II new powerful tools like the silicon vertex tracker will be available and a tracking of the silicon vertex will be possible at trigger level. New trigger solutions to select secondary vertices will be implemented. A possible trigger will require two tracks with an impact parameter. The idea is that the two highest P_t tracks in the decay chain $B_S \to D_S^+\pi^-$ or $B_S \to D_S^+\pi^-\pi^+\pi^-$ (with $D_S \to KK\pi$) have impact parameter and pass the trigger. Monte Carlo studies show that about 1600 fully reconstructed and tagged B_S will be collected in 2 fb^{-1} of data. With this sample CDF can measure X_S up to 20. Dilepton or the single lepton triggers could be also exploited, but with lower expectation to reach $X_S \approx 15$.

CDF will be able to measure X_S via lifetime difference if $X_S > 20$. In the Standard Model $\frac{\Delta\Gamma_{B_S}}{\Delta m_{B_S}} \sim \frac{m_b^2}{m_t^2} \frac{\eta_{QCD}^{\Delta\Gamma_{B_S}}}{\eta_{QCD}^{\Delta m_{B_S}}}$ [8], and a measurement of $\Delta\Gamma$ is a measurement of Δm. There is a Model dependence expected around 20%. The present limit for CDF on $\Delta\Gamma$ quoted before corresponds to $\Delta m_s < 96\, ps^{-1} \times 5.6 \cdot 10^{-3}/(\Delta\Gamma/\Delta m) \times (1.55\, ps/\tau_B)$. The expected sensitivity on $(\Delta\Gamma) \sim 3\%$.

3.2. STUDY FOR CP VIOLATION MEASUREMENTS

CP violation in the B system can be described by three measurable parameters, ($\sin 2\beta$, $\sin 2\alpha$ and $\sin 2\gamma$). $\sin 2\beta$ can be determined from the measurements of the asymmetry in the $B \to J/\psi K_S^0$ decay. $\sin 2\alpha$ is correlated to the asymmetry in the $B \to \pi^+\pi^-$ decay, but in this case there are theoretical uncertainties in the evaluation of the contribution of strong and weak penguin diagram to the decay amplitude. This does not allow a straightforward determination of $\sin 2\alpha$ from the asymmetry. $\sin 2\gamma$ can be probed via the decay $B_S \to D_S K$.

Up to now only two preliminary evaluations of $\sin 2\beta$ are available[9,10] and more data are needed to have a precise measurement. CDF in Run II has good prospects to measure $\sin 2\beta$ with good accuracy and will try to evaluate the asymmetry in the $B \to \pi^+\pi^-$. On the other hand it

Table 2
ϵD^2 for all tagging methods measured in Run I and extrapolated to Run II. The relevant upgrade responsible for the improvement is also quoted.

Tagger	$\epsilon\mathcal{D}^2$ (Run I)	$\epsilon\mathcal{D}^2$ (Run II)	Relevant Upgrade
Soft leptons (SLT)	0.9 ± 0.1	1.7	Extended coverage
Same side $\pi(SST)$	1.7 ± 0.2	2.0	New tracking
Jet Charge (JetQ)	1.0 ± 0.4	3.0	New tracking
All combined	3.6	6.7	

will be very difficult to say something on $\sin 2\gamma$ because of the B_S mixing involvement.

3.2.1. $\sin 2\beta$ IN $J/\psi K^0_S$ DECAY MODE

The accuracy expected in Run II is evaluated using preliminary results from Run I [7,9]. The number of $J/\psi K^0_S$ events reconstructed in Run I was 198. The number expected in Run II in 2 years of data taking is $\sim 10,000$. This takes into account the increased luminosity the extended silicon vertex detector and the upgraded muon detector. This expectation is conservative because it does not take into account the possibility to have J/ψ reconstructed in e^+e^- channel. A certain amount of these events has been reconstructed as exercise (see fig. 3) from Run I data. The sample is small since CDF did not have a $J/\psi \rightarrow e^+e^-$ trigger but it will be possible in Run II and the expectation is to have 5,000 events in 2 fb^{-1}. Adding also these events CDF expects to have around 15,000 events of $B \rightarrow J/\psi K^0_S$ in Run II.

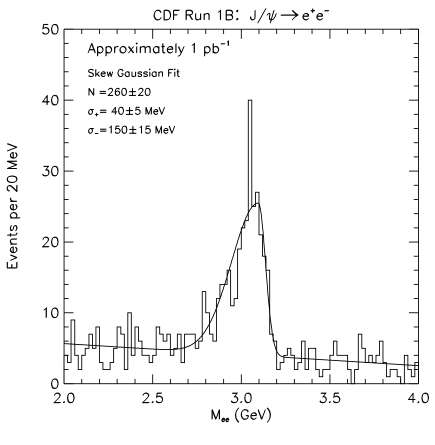

Figure 3. $J/\psi \rightarrow e^+e^-$ invariant mass.

The asymmetry is defined as $\mathcal{A} = \mathcal{D}\sin 2\beta$ and its error is:

$$\sigma(\sin 2\beta) = \frac{\sigma(\mathcal{A})}{\mathcal{D}} \oplus (\sin 2\beta)\frac{\sigma(\mathcal{D})}{\mathcal{D}}$$

where $\sin 2\beta$ replaces $\mathcal{A}/\mathcal{D}$ and $\oplus$ means addition in quadrature. The first term in this formula is the statistical error and the second one is systematic error. The statistical contribution can be written as $\sigma_{stat.}(\sin 2\beta) = K_{stat.}/\sqrt{N \cdot \epsilon\mathcal{D}^2}$. The factor $K_{stat.}$ depends on on Run I measurements and is constant with respect to Run II projections. Its value is 2.034. The systematic error is due to the dilution and to the efficiency. $\sigma(\mathcal{D})/\mathcal{D} = \left(1/\sqrt{N\epsilon\mathcal{D}^2}\right)\sqrt{1+B/S}$, ($S/B$ is the signal-to-noise ratio). As in the previous formula, $\sigma(\mathcal{D})/\mathcal{D}$ can be rewritten $K_{sys.}/\sqrt{N\epsilon\mathcal{D}^2}$. $K_{sys.}$ depends on which tagger is used. In Run I $K_{sys.}$ has been evaluated for all taggers: 1.24 for SST, 0.68 for SLT and 0.68 for JetQ. The assumption $K_{syst.} = 1.24$ for all tagger is believed conservative. The final formula is $\sigma(\sin 2\beta) = 1/\sqrt{N\epsilon\mathcal{D}^2} \times [K_{stat.} \oplus \sin 2\beta \times K_{sys.}]$ where $\epsilon\mathcal{D}^2$ is the sum on all taggers (see table 2) and $\sin 2\beta$ is assumed 1. The final error quoted by CDF is $\sigma(\sin 2\beta) = 0.078 \oplus 0.031 = 0.084$. If the number of events becomes 15,000 $\sigma(\sin 2\beta) = 0.064 \oplus 0.025 = 0.069$

3.2.2. STUDY OF $B \rightarrow \pi^+\pi^-$

The identification and the reconstruction of $B \rightarrow \pi^+\pi^-$ decays is very challenging at hadronic collider because of the low decay branching ratio ($\sim 10^{-5}$) and of the enormous combinatorial background due to the many low P_t charged tracks produced in $p\bar{p}$ collisions. The main problems are: the trigger, the background contribution and the theoretical uncertainties. CDF is making a lot of effort to study the trigger and the background rejection. A trigger fully dedicated to $B \to \pi^+\pi^-$ is under study. This trigger will be based on 3 levels. At Level 1 two oppositely charged tracks with a minimum transverse momentum of 2 GeV/c and some azimuthal separation are required. Level 2 is based on impact parameters cuts. The idea is to selects tracks with impact parameter $> 100\ \mu m$. Level 3 will use the full event information to apply a mass cuts.

Signal to background separation is one of the main issues. The major contribution arises from $B_{d,s} \to K^+\pi^-$ and $B_s \to K^+K^-$ decays (figure 4).

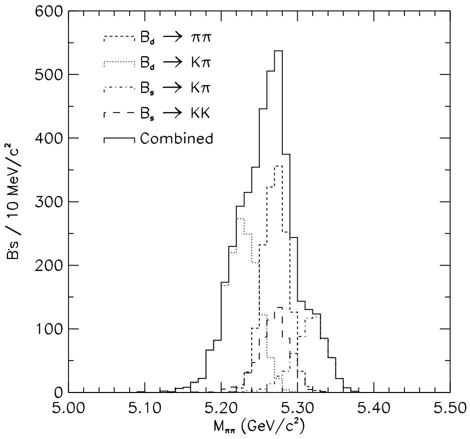

Figure 4. Invariant mass of B decays in $\pi^+\pi^-$, $K^+\pi^-$ and K^+K^-.

CDF is not planning to do an event by event π/K separation. The plan is to find a mass peak over combinatorial background and use the partial K/π separation given by dE/dx. The idea is to measure the fraction of decays in $\pi^+\pi^-$, $K^+\pi^-$ and K^+K^- before tagging. From the fraction $\pi^+\pi^-$/all, and exploiting the fact that there is no CP violating asymmetry in the other decays, the observed time-dependent asymmetry will be corrected and divided by the $\pi^+\pi^-$ fraction.

For the moment CDF quotes an error on the asymmetry using the time-integrated formula:

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

The ratio $x_d/\left(1+x_d^2\right)$ is evaluated ~ 0.82 due to the impact parameter cut. Assuming 10,000 events in 2 fb^{-1}, $S/B = 1/4$ [11], $\epsilon\mathcal{D}^2 = 6.7\%$, $\sigma_{\mathcal{A}} = 0.11$.

4. CONCLUSIONS

Based on results obtained from the analysis of Run I data, CDF has shown a good capability of doing B physics. CDF goal for Run II is to measure the CP violating parameter $\sin 2\beta$ and to observe the CP asymmetry in $B \to \pi^+\pi^-$. These measurements put CDF in strong competition with B factories. In the next few years the precise measurements of lifetime ratios and B_S mixing will be possible only at hadronic colliders. The upgraded CDF detector appears an extremely favorable environment for the physics of the 2000.

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