B, $Λ_b$ and Charm Results from the Tevatron

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**ABSTRACT**

Recent results on $B_d$, $B_u^\pm$, $B_s$, $Λ_b$ and Charm hadrons are reported from $\approx 75\text{pb}^{-1}$ and $\approx 40\text{pb}^{-1}$ of data accumulated at the upgraded CDF and D0 experiments at the Fermilab Tevatron $\bar{p}-p$ collider, during Run-II. These include lifetime and mass measurements of $B$ and Charm hadrons, searches for rare decays in charm and $B$ hadrons and CP-violation in Charm decays. Results relevant to CP-violation in $B$-decays are also reported.
1 Tevatron $p - \bar{p}$ collider and performance during Run-II

The Tevatron $p - \bar{p}$ collider is being used for extended data-taking for the second time in 10 years. During the period between 1992 and 1996 (Run-I) an integrated luminosity of 110pb$^{-1}$ was delivered; the goals for the current period starting May 2001 (Run-II) are 2 fb$^{-1}$, which is a $\times$ 20 increase over Run-I. The upgrades for Run-II consist of a new injection stage delivering more protons, an increased $\bar{p}$ transfer efficiency and a $\bar{p}$ recycler (undergoing commissioning) that uses remaining $\bar{p}$ from the previous store. A table of Run-I and Run-II operating parameters is given in table 1. The peak luminosity, though improving, is still $\times$ 4 below target.

| Collision Rate | Bunches | Center of Mass Energy | Peak Luminosity |
|----------------|---------|-----------------------|-----------------|
| Run-I: 3.5$\mu$s (Run-I) | 6x6 | 1.8 TeV/$c^2$ | 2.4x10$^{31}$ |
| Run-II: 396 ns | 36x36 | 1.96 TeV/$c^2$ | 4.4x10$^{31}$ |

2 B Physics at Hadron Colliders: The CDF and D0 Detectors

The $b\bar{b}$ production cross section $\sigma(b\bar{b})$ is $\approx 150\mu$b at $p - \bar{p}$ at the Tevatron, 1 nb at the $\Upsilon(4s)$ and 7 nb at the $Z_0$. All $B$-hadrons are produced at the Tevatron (unlike the $B$ factories), the drawback being the inelastic cross section which is 1000$\times\sigma(b\bar{b})$ making online data selection crucial.

The CDF [1] and D0 detectors [2] have been described elsewhere. In order to utilize the high $b\bar{b}$ production cross section clean signatures of $B$ hadron decays must be used when selecting data online. During Run-I CDF used the clean signatures of $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$ and the decays of $B$ hadrons to high transverse momentum ($P_T$) leptons. Now the long lifetime of $B$ hadrons is being utilized at CDF, events containing $\geq 2$ tracks with high impact parameters ($d_0$) consistent with being daughters of $B$ hadrons are selected using the Silicon Vertex Trigger, events selected in this way are categorized as “hadronic $B$ trigger” or “displaced track trigger” events. Another trigger used for $B$ selection selects events requires the presence of a single high $P_T$ lepton and a high $d_0$ track, this is called the “lepton+SVT trigger” or “lepton+displaced track trigger”. The high $d_0$ triggers have allowed CDF to significantly advance its $B$ and charm physics capability, now CDF can reconstruct $B$ decays to fully hadronic final states as well as use the conventional $J/\psi$ and high $P_T$ lepton triggers.
The D0 experiment utilizes the $\mu^+\mu^-$ signature to select $J/\psi$s (which may be prompt or long-lived—coming from $B$ hadrons). D0 triggers also use $B$ decays to high $P_T$ leptons. With the advent of a magnetic field and a completely new tracking system D0 has acquired a whole new capability in $B$ physics and several $B \to J/\psi X$ decay modes have been observed during Run-II. The D0 experiment is on its way to introducing a hadronic $B$ trigger that uses online silicon pattern recognition to select tracks with high $d_0$, this will be a welcome addition to D0’s already enhanced capability in $B$ physics.

3 Physics Results: Testing Heavy Quark Expansion: Lifetimes of $B$ Hadrons at CDF and D0

Precise measurements of lifetimes of $B$ hadrons allow tests of the Heavy Quark Expansion (HQE) which predicts the following hierarchy for $B$ hadron lifetimes: $\tau_{B_s^\pm} < \tau_{B_d} \approx \tau_{B_s} < \tau_{B_b^\pm}$. Both CDF and D0 are working toward precision tests of this theory.

3.1 Charged to Neutral Lifetime Ratio of $B$ Hadrons, and $B_s$ Lifetime from fully reconstructed decays

The ratio of the lifetimes of $B_u^\pm$ to $B_d$ has been measured at CDF, and the $B_u^\pm$ lifetime has been measured at D0 using fully reconstructed $B_d \to J/\psi K^*$ and $B_u^\pm \to J/\psi K^\pm$ decays. The decays are fully reconstructed, the invariant mass and proper decay length ($c\tau$) distributions of the $B$s are calculated from an un-binned log-likelihood function determining both mass and lifetime in a single fit. The result is $1.11 \pm 0.09$ at CDF using 70 pb$^{-1}$ of data, whereas the $B_u^\pm$ lifetime has been measured to be $1.76 \pm 0.24$ ps at D0. Both these measurements test HQE and are consistent with the more accurate measurements at BaBar and Belle.

3.2 $B_s$ Lifetime from the fully reconstructed decay $B_s \to J/\psi \phi$, $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$

The world’s largest number of fully reconstructed $B_s$ decays has been at the Tevatron since Run-I. CDF and D0 has successfully reconstructed this decay using data from their $J/\psi \to \mu^+\mu^-$ trigger during Run-II, the reconstructed signals are shown in Fig. A measurement of the lifetime is underway at D0, CDF has measured a ratio of $\frac{\tau_{B_s}}{\tau_{B_d}} = 0.89 \pm 0.15$ based on 70 pb$^{-1}$ collected during Run-II.

Strictly speaking this ratio isn’t what should be tested, since the CP composition of the final state is not known. The final state is a mixture of CP eigenstates,
and the $B_s$ CP even and odd eigenstates can have a difference in lifetime of up to 10% as predicted by theory, by fitting a single lifetime in this mode an “average” lifetime has been determined. The relationship between splitting in width (lifetime) of the $B_s$ CP eigenstates and the $B_s$ mixing parameter is known in the Standard Model, therefore a measurement of the width (lifetime) difference and mixing parameter provides a test of new Physics. It is planned to measure the lifetime difference of the $B_s$ CP eigenstates by utilizing angular variables to disentangle the two CP eigenstates and fitting two lifetimes, this approach will become viable with higher statistics. An accuracy of 5% in determining the lifetime splitting is expected at CDF using 4000 $B_s \to J/\psi \phi$ decays.

A clean measurement of the width difference ($\Delta \Gamma$)$_{B_s}$, can be made by measuring a single lifetime in a decay of the $B_s$ to a CP eigenstate e.g. $B_s \to D_s^+D_s^-$ and $B_s \to K^+K^-$. This approach is planned as well.

### 3.3 Measurement of the $\Lambda_b$ Lifetime

The $\Lambda_b$ has been reconstructed at both CDF and D0 in various modes, Fig. 2 shows the reconstruction in the fully hadronic mode at CDF and in $\Lambda_b \to J/\psi \Lambda$ at D0.

CDF has also reconstructed $\Lambda_b$ in the decays $\Lambda_b \to J/\psi \Lambda$ (53 events) and $\Lambda_b \to \Lambda \nu \ell$ (640 events) and in the purely hadronic decay mode $\Lambda_b \to \Lambda_c^\mp \pi^\pm$ with $\Lambda_c \to pK\pi$. A lifetime measurement has just been completed at CDF using the fully reconstructed decay $\Lambda_b \to J/\psi \Lambda$ with a result $\tau_{\Lambda_b} = 1.25 \pm 0.26(stat) \pm 0.1(syst)$ ps shown in Fig. 3. Work on D0’s $\Lambda_b$ lifetime currently underway.

The decays $\Lambda_b \to \Lambda_c^{\mp} \ell \nu_{\ell}$ and $\Lambda_b \to \Lambda_c^{\pm} \pi^\mp$ are selected using a trigger with $d_0$ cut, the resulting biases in the $ct$ distribution have to be understood before a
4 Charm Physics: $D_s^\pm - D^\pm$ mass difference

The first CDF Run-II publication [3] was a measurement of the mass difference $\Delta M = M_{D_s^\pm} - M_{D^\pm}$. Both the $D_s^\pm$ and $D^\pm$ decay to $\phi\pi^\pm$ with $\phi \rightarrow K^+K^-$ with almost identical kinematics. Using data selected by the displaced-track hadronic trigger 2400 $D_s^\pm$ and 1600 $D^\pm$ were reconstructed using only 11.6 pb$^{-1}$ of data. The measurement of $\Delta M = 99.28 \pm 0.43(stat) \pm 0.27(syst)$ MeV/c$^2$ is consistent with the current world average [10] of $99.2 \pm 0.5$ MeV/c$^2$.
Rare Decays: The Search for the Flavour Changing Neutral Current Decay $D \rightarrow \mu^+\mu^-$ and $B_s^0 \rightarrow \mu^+\mu^-$

The standard model predicts a branching ratio of $O(10^{-13})$ for the decay $D^0 \rightarrow \mu^+\mu^-$ via second order weak interactions. Some R-parity violating SUSY models predict branching ratios $\leq O(10^{-6})$ \cite{10}. CDF has searched for $D^0 \rightarrow \mu^+\mu^-$ decays using hadronic trigger data and $D^0 \rightarrow \pi^+\pi^-$ decays which have almost identical acceptance and kinematics to $D^0 \rightarrow \mu^+\mu^-$. The probability of a $\pi^\pm$ faking a $\mu^\pm$ must be calculated, unambiguously identified pions are obtained using the decay chain $D^{*\pm} \rightarrow D^0\pi^\pm$, $D^0 \rightarrow K^\mp\pi^\pm$, the charge of the $\pi^\pm$ from the $D^{*\pm}$ determines the flavour of the $D^0$ and distinguishes the $K^\pm$ from the $\pi^\pm$. The number of times a $\pi^\pm$ is reconstructed as a $\mu^\pm$ is determined after which $D^0 \rightarrow \mu^+\mu^-$ are reconstructed and expected number of $D^0 \rightarrow \pi^+\pi^-$ decays faking $D^0 \rightarrow \mu^+\mu^-$ is subtracted, 0 events are found in a $2\sigma$ search window. A limit for this branching ratio $\leq 2.4 \times 10^{-6}$ is calculated at 90 % confidence level, better than the best published limit of $4.1 \times 10^{-6}$ \cite{11} \cite{16}.

CDF has done a similar analysis of the decay $B_s \rightarrow \mu^+\mu^-$ using 113 pb$^{-1}$ of Run-II data. Standard Model prediction for the branching ratio is $3.8 \pm 1 \times 10^{-9}$. Various SUSY models \cite{13} allow for an enhancement by a factor of upto $\times 10^3$, areas of m-SUGRA space that overlap those predicting deviations of the $g_\mu$ from 2 are roughly consistent \cite{14} with recent experimental measurements \cite{15}. CDF’s measurement yields limits $BR(B_s \rightarrow \mu^+\mu^-) < 9.5 \times 10^{-7}$ and $1.2 \times 10^{-6}$ at the 90 % and 95 % confidence intervals respectively—a factor of 2 better than the best.
6 CP Violation in Charm Decays

The Standard model prediction for CP violation in charm decays is of order 0.1-1 \%. Since $c$ and $u$ quarks do not couple to $t$ quarks, box diagram contributions to mixing in charm are tiny, and so CP violation in Charm decays is almost entirely due to interference in decay (direct CP violation). A search for CP violation in charm decays has been done at CDF. Rates of decays of $D^0$ and $\bar{D}^0$ decaying to the CP eigenstates $f = K^+K^-$ and $f = \pi^+\pi^-$ are measured. The flavour of the $D^0$ is tagged as described in section 5, and $D^0 \to \pi^+\pi^-$ and $\to K^+K^-$ decays are reconstructed and counted and the asymmetry

$$A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

for each mode is calculated. The results are $A_{CP}(D^0 \to \pi^+\pi^-) = 2.0 \pm 1.7(stat) \pm 0.6(syst) \%$ and $A_{CP}(D^0 \to K^+K^-) = 3.0 \pm 1.9(stat) \pm 0.6(syst) \%$, consistent with both the world averages of 0.5 \pm 1.6 \% and 2.1 \pm 2.6 \% and better than the most recent (2001) CLEO results of 0.0 \pm 2.2 \pm 0.8 \% and 1.9 \pm 3.2(stat) \pm 0.8(syst)\% respectively.

As a check of possible biases in counting, the ratios of branching ratios: \frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^\pm\pi^\mp)} and \frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^\pm\pi^\mp)} were also calculated and found to be 9.38 \pm 0.18(stat) \pm 0.10(syst)\% and 3.686 \pm 0.076(stat) \pm 0.036(syst)\% respectively. These compare well with the measurements at FOCUS 9.93 \pm 0.14(stat) \pm 0.14(syst)\% and 3.53 \pm 0.12(stat) \pm 0.06(syst)\%.

7 Towards CP violation in $B$-hadron decays and $B_s$ mixing

In Run-I the CDF was able to competetively measure the $B_d$ mixing parameter \((\Delta M)_{B_d} = x_d\) and also perform a 2\sigma measurement of the CP asymmetry in the decay $B_d \to J/\psi K_S$ (sin 2$\beta$) \[6]. The Run-I measurement was sin 2$\beta = 0.79 \pm 0.39(stat) \pm 0.16(syst)$. BaBar and Belle already have measurements of 0.76 \pm 0.067(stat) \pm 0.034(syst) and 0.733 \pm 0.057(stat) \pm 0.028(syst) respectively \[7] \[8]. With \times 40-50 more decays expected when 2 fb$^{-1}$ have been accumulated, CDF’s precision should be $\delta$(sin 2$\beta$) \approx 0.05, D0 should have similar statistics. Clearly D0 and CDF cannot compete with the $B$-factories sin 2$\beta$ measurement, but sin 2$\beta$ will be measured as a benchmark, and a test of various flavour tagging schemes.
Various tagging schemes are under examination at CDF; including jet-charge, opposite and same-side tagging and using time of flight to identify $K$s. A final number for the statistical power i.e. $\epsilon D^2$ has not yet been calculated using data.

7.1 Measurement of $\sin 2\gamma$ using $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$

Both tree and penguin graphs contribute to $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ with the tree dominating in the former and the penguin in the latter. Without the penguin contributions the CP asymmetry ($A_{CP}$) in $B_d \rightarrow \pi^+\pi^-$ is proportional to the CKM quantity $\sin(2(\gamma + \beta))$ and $A_{CP}$ in $B_s \rightarrow K^+K^-$ is proportional to $\sin 2\gamma$. Assuming SU(3) symmetry and interchanging $s$ and $d$, the hadronic matrix element penguin to tree ratios are the same, the mixing and decay induced $A_{CP}(t)$ are functions of $\sin 2\gamma$, $\sin 2\alpha$, $\sin 2\beta$, the ratio of the hadronic matrix element amplitudes and the phase of this ratio. A measurement of the $A_{CP}$ thus determines $\sin 2\gamma$ and $\sin 2\alpha$.

Before measuring this asymmetry the various $B_d \rightarrow h^+h^-$ and $B_s \rightarrow h^+h^-$ decays must be separated. Reconstructing $B_d \rightarrow \pi^+\pi^-$ without clear hadron identification leads to a very broad peak in which the individual modes $B_d \rightarrow K^\pm\pi^\mp$, $B_s \rightarrow K^\pm\pi^\mp$, $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ are indistinguishable. These can be separated at CDF utilizing $dE/dx$ using drift chamber charge deposition and kinematical variable separation. CDF has reconstructed $39 \pm 14 B_d \rightarrow \pi^+\pi^-$ and $90 \pm 17 B_s \rightarrow K^+K^-$ decays, the latter is a first observation. The invariant mass distribution of all $B$ hadrons decaying to $h^+h^-$ is shown in figure 5.

![CDF Run 2 Preliminary Invariant Mass distribution of all $B \rightarrow h^+h^-$, decays at CDF. Both tracks are assigned the mass of a $\pi$.](image)

As a check the ratio of branching ratios $\frac{\Gamma(B_d \rightarrow \pi^+\pi^-)}{\Gamma(B_d \rightarrow K^\pm\pi^\mp)}$ has been measured,
the result $0.26 \pm 0.11$ (stat) $\pm 0.055$ (syst) is consistent with the world-average $0.253 \pm 0.064$ [16]. The CDF experiment expects to be able to measure $\gamma$ to an accuracy of $\sigma(\gamma) \approx 10$ degrees.

7.2 Measurement of the $B_s$ Mixing parameter $x_s = \frac{\Delta M_{B_s}}{\Gamma_{B_s}}$

The measurement of the $B_s$ mixing parameter $x_s = \frac{\Delta M_{B_s}}{\Gamma_{B_s}}$ is one of the major goals of the Tevatron during Run-II. An observation of the flagship mode for measuring $x_s$, $B_s \to D^\pm_s \pi^\mp$ has been made at CDF. In addition to this mode $B_s$ mixing can also be measured using modes such as $B_s \to \mu^\pm \nu_\mu D^\mp_s$ and $B_s \to e^\pm \nu_e D^\mp_s$, however the vertex resolution in these decays is worse due to the missed neutrino. If a single $B_s$ lifetime is fit in any of these or any flavour specific mode the relation between the fit lifetime $\tau_{\text{fit}}$ and the CP odd and even lifetimes $\tau_{CP^+}, \tau_{CP^-}$ is $\tau_{\text{fit}} = \frac{\tau_{CP^+}^2 + \tau_{CP^-}^2}{\tau_{CP^+} + \tau_{CP^-}}$, which can be used for a measurement of $\Delta \Gamma_{B_s}$ and to provide a useful constraint for the two-lifetime fit with $B_s \to J/\psi \phi$ described earlier. The first observation of 40 $B_s \to D^\pm_s \pi^\mp$ decays has been made using hadronic trigger data at CDF, shown in Fig. 6. Also 309 $B_s \to \mu^\pm \nu_\mu D^\mp_s$ and 245 $B_s \to e^\pm \nu_e D^\mp_s$ have been observed using lepton+displaced track trigger data.

![Figure 6: First observation of $B_s \to D^\pm_s \pi^\mp$, made at CDF.](image)

8 Conclusions

Both CDF and D0 are in the first phase of data taking ($f L dt < 200 \text{pb}^{-1}$) which will test HQE with $\Lambda_B$ and $B_s$ lifetimes, and yield limits for CP violation and rare decays in $B$ and charm decays. Tagging and lifetime measurement techniques (for hadronic trigger data) will also be tested. In the next phase ($200 < f L dt < 500 \text{pb}^{-1}$) limits
on $B_s$ mixing will be set and CP violation searches in the $B$ system will be done. In the final phase ($500 < \int L dt < 2000 \text{pb}^{-1}$) $\Delta \Gamma_{B_s}$, $\alpha_s$, and the CKM angle $\gamma$ will be measured and finally a search for unexpectedly large CP violation in $B_s \to J/\psi \phi$ will be pursued.

References

1. R. Blair et al, FERMILAB-PUB-96-390-E (1996).
2. D0 Collaboration, FERMILAB-PUB-96-357 (1996).
3. CDF II Collaboration, FERMILAB-PUB-03-048-E, Aug 2003. 24pp. Accepted for Publication in Phys. Rev D.
4. Cleo Collaboration, [hep-ex/0111024]
5. S.E.Csorna et al., CLEO Collaboration, Phys. Rev. D 65 (2002) 092001
6. FOCUS Collaboration (J. M. Link et al.), Phys. Lett. B 555: 167-173, (2003), [hep-ex/0212058]
7. Belle Collaboration, Aug 2003. 9pp, [hep-ex/0308037]
8. BABAR Collaboration, SLAC-PUB-9816, DAPNIA-03-111, May 2003. 8pp. [hep-ex/0305055]
9. CDF Collaboration, Phys. Rev. D 61, 072005 (2000)
10. G. Burdman, E. Golowich, J. Hewett, S. Pakvasa, [hep-ph/0112235] v2 (March 2002)
11. BEATRICE Collaboration, Phys. Lett. B408469 1997.
12. G. Buchalla and A. J. Buras, Nucl. Physics B 412 (1994) 106.
13. A. Dedes, H. K. Dreiner, U. Nierste and P. Richardson, [hep-ph0207026] (2002).
14. A. Dedes, H. K. Dreiner and U. Nierste Phys. Rev. Lett. 87 (2001) 251804.
15. Muon (g-2) Collaboration, Phys. Rev. Lett. 89(2002) 101804; Erratum-ibid 89 (2002).
16. K.Hagiwara et al. Phy. Rev. D 66 010001 (2002)