Proceedings of the DIS'2004, Štrbské Pleso, Slovakia

BEAUTY AND CHARM DECAY PHYSICS AT CDF-II

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In this paper we report on the most recent results achieved by the CDF-II Collaboration in the field of beauty and charm phyiscs. CDF-II can provide unique contributions in the sector of B_s and of the b baryons, with mixing as well as CP violation measurements.

1 Introduction

The $b\overline{b}$ production cross section at the Tevatron, where protons and anti-protons are collided with a center of mass energy of 1.96 TeV, is very large ($\approx$100 μb) when compared to the typical e^+e^- cross sections at the $\Upsilon(4S)$ ($\approx$1 nb) and Z^0 ($\approx$7 nb). At the current record instantaneous luminosity of $\approx 10^{32}$ cm^{-2} sec^{-1} reached by the Tevatron, the $b\overline{b}$ production rate is 10 KHz. All the B species, from the familiar B_u^+ and B_d^0 light mesons, to the heavier B_s^0 and B_c^+ mesons and the Λ_b^0 baryon, are created. The problem of the hadronic environment is the large level of background ($\sigma_{inel}(p\overline{p}) \approx$50 mb) and track multiplicity ($\approx$50 track/event) due to the fragmentation of the hard interaction products and to the underlying event or pile up of multiple events.
The crucial CDF-II detector componenents for reconstructing beauty as well as charm events in such a complicated environment are the tracking system, which must provide an excellent momentum resolution extended to low transverse momenta and vertexing capability to exploit the relatively long b hadrons lifetime, as well as the trigger, which must provide a large bandwidth and a strong background reduction capability. In addition, particle identification is crucial in the analyses of rare hadronic decays and in the field of b flavor tagging when kaons are involved.

2 CDF-II triggers for Beauty and Charm

The CDF-II trigger reconstructs the information provided by the muon chambers and by the calorimeter and thus allows to select semileptonic b decays ($B \to Dl\nu_l$ and $B \to J/\psi X$) to muons and electrons. This is the conventional way of triggering on b events, successfully used already in Run I analyses. CDF-II has the innovative online silicon vertex tracker which reconstructs offline quality track impact parameters at trigger level. This helps significantly in triggering on beauty and charm events, characterized by the presence of displaced secondary vertices.
The *dimuon trigger* selects muon pairs with the transverse momentum of the muons larger than 1.5 GeV/c. This provides mostly fully reconstructed $B \to J/\psi X$ modes down to very low $p_t(J/\psi)$ ($\approx$0 GeV/c), which are used for measurements of the

B decay	mass (MeV/c)	lifetime (ps)
$B_u^+ \to J/\psi K^\pm$	$5279.10 \pm 0.41_{(stat)} \pm 0.36_{(sys)}$	$1.662 \pm 0.033_{stat} \pm 0.008_{sys}$
$B_d^0 \to J/\psi K^{*0}$	$5279.63 \pm 0.53_{(stat)} \pm 0.33_{(sys)}$	$1.539 \pm 0.051_{stat} \pm 0.008_{sys}$
$B_s^0 \to J/\psi \phi$	$5366.01 \pm 0.73_{(stat)} \pm 0.33_{(sys)}$	$1.369 \pm 0.100_{stat} \pm 0.010_{sys}$
$\Lambda_b \to J/\psi \Lambda$	$5619.7 \pm 1.2_{(stat)} \pm 1.2_{(sys)}$	$1.25 \pm 0.26_{stat} \pm 0.10_{sys}$

Table 1. b hadron masses and lifetimes measured by CDF-II using the decay modes listed in the first column. The measurements use $\approx$2264 $B^\pm$, $\approx$1278 B_d^0, $\approx$184 B_s^0 and $\approx$89 Λ_b events reconstructed in the modes listed in the first column. The measurement of the Λ_b lifetime uses a subsample of $\approx$65 pb^{-1} ($\approx$46 signal events) of the dataset used for the mass measurement.

masses and lifetimes. In addition the dimuon samples are used for studies of the quarkonia states and for the search of rare decays, like $B_{d,s}^0 \to \mu^+\mu^-$.
The *lepton + track trigger* selects one lepton (muon or electron) of transverse momentum larger than 4 GeV/c and one displaced track with transverse momentum larger than 2 GeV/c and impact parameter larger than 120 μm. This provides large and clean samples of semileptonic modes which are very useful for tagging studies and possibly for B_s mixing if x_s is moderate.
The *hadronic trigger* selects track pairs with transverse momentum larger than 2 GeV/c and impact parameter larger than 100 μm. This provides samples of fully hadronic B decays, like $B \to D\pi$ and $B \to h^+h^{'-}$. This trigger provides also large samples of charm events.

3 Measurements performed with the dimuon sample

3.1 Masses, lifetimes and the B_s^0 lifetime difference

CDF-II achieves mass measurements at the 1 MeV level for all the B species, except the B_c^+ meson, by using the J/ψ modes. These measurements have been performed using 220 pb^{-1} of data, except for the Λ_b lifetime measurements which uses only 65 pb^{-1}. The most up to date CDF-II results are reported in Tab. 1.
While the mixing phenomenon is expected to produce eigenstates with very small lifetime difference in the B_d^0 system, recent calculations predict $\Delta\Gamma_s/\Gamma_s = 0.074 \pm 0.024$ [1]. One possible way to measure $\Delta\Gamma_s/\Gamma_s$ at CDF-II is by decomposing the B_s decays to two spin-1 particles, for example $B_s^0 \to J/\psi\phi$, into CP-odd and CP-even states through an angular analysis. The pseudoscalar to vector-vector decays are determined by three decay amplitudes which correspond to linear polarizations of the vector mesons which are either longitudinal (A_0) or transverse to their flight direction and parallel or perpendicular to one another ($A_\parallel$ and $A_\perp$, respectively). The amplitude $A_\perp$ is associated with decays in which the two vector mesons are emitted with relative orbital angular momentum $l = 1$ and therefore with the CP odd decays in the B_s. The amplitudes A_0 and $A_\parallel$ are associated with mixtures of the $l = 0$ and 2 decays which are CP even. By analyzing the angular distributions of the final state particles, it is possible to statistically separate the CP even and odd decays and do so as a function of the time between production and decay of the B meson. From the analysis of 240 pb^{-1} CDF-II has measured in the $B_s^0 \to J/\psi\phi$

Tagging algorithm	B_d decay	ϵD^2 (%)
SLT (muon)	incl. semilep.	$0.735 \pm 0.122_{stat}$
SLT (electron)	incl. semilep.	$0.583 \pm 0.134_{stat}$
JCT	incl. semilep.	$0.419 \pm 0.024_{stat}$
SST	$J/\psi K^{*0}$, $D^- \pi^+$	$1.0 \pm 0.5_{stat} \pm 0.1_{syst}$

Table 2. b flavour tagging efficiencies. SLT and JCT performance has been measured using samples of semileptonic decays, SST has been tuned using fully reconstructed signals.

mode:

$$A_0 = 0.784 \pm 0.039 \pm 0.007,\ A_{\parallel} = (0.51 \pm 0.082 \pm 0.013)e^{(1.94 \pm 0.36 \pm 0.03)i}$$
$$\mid A_{\perp} \mid = 0.354 \pm 0.098 \pm 0.003$$
$$\tau_L = 1.05^{+0.16}_{-0.13} \pm 0.02 \text{ ps and } \tau_H = 2.07^{+0.58}_{-0.46} \pm 0.03 \text{ ps}$$
$$\Delta\Gamma/\Gamma = 0.65^{+0.25}_{-0.33} \pm 0.01 \text{ and } \Delta\Gamma = 0.47^{+0.19}_{-0.24} \pm 0.01 \text{ ps}^{-1}$$

3.2 Search for $B_{d,s} \to \mu^+\mu^-$

The branching ratio for the flavor-changing neutral current decay $B_s^0 \to \mu^+\mu^-$ is one of the most sensitive probes to the physics beyond the Standard Model. The expected branching ratio is BR($B_s^0 \to \mu^+\mu^-$) = $(3.8 \pm 1.0) \times 10^{-9}$ and the most stringent limit has been set by CDF in run I at BR($B_s^0 \to \mu^+\mu^-$) $< 2.0 \times 10^{-6}$ at 90 % CL. In a similar way, the most stringent limit on BR($B_d^0 \to \mu^+\mu^-$) is about three orders of magnitude larger than the Standard Model expectations. Both branching ratios can be enhanced by one to three orders of magnitude in various supersymmetric extensions of the Standard Model. From the analysis of 171 pb^{-1} of dimuon data, CDF-II has found 1 (1) event in the B_s (B_d) search region, defined as $\pm$ 80 MeV/c^2 centered on the world average B_s (B_d) mass, which is compatible with the background expectation. From this analysis CDF-II sets the upper limits BR($B_s^0 \to \mu^+\mu^-$) $< 5.8 \times 10^{-7}$ and BR($B_d^0 \to \mu^+\mu^-$) $< 1.5 \times 10^{-7}$.

4 Measurements performed with the lepton + track sample

The impact parameter trigger combined with the lepton trigger allows to collect significant samples (from a few thousands to tens of thousands) of semileptonic decays of all the B species. These samples are good candidates in particular to optimise the soft lepton (SLT) and jet charge (JCT) b flavor taggers (Tab. 2).
Using 180 pb^{-1} of data CDF-II has measured the first two moments of the hadronic invariant mass squared $M^2_{X_c}$ distribution in the semileptonic B decays. These measurements are useful to improve the overall precision on the matrix element $\mid V_{cb} \mid$ which is generally extracted from semileptonic B decays through the measurement of Γ_{sl}. The theory allows to predict any weighted integral of $d\Gamma_{sl}/ds_H$, with $s_H = M^2_{X_c}$, like the first two moments (mean and variance) of the hadronic mass distibution $M^2_{X_c}$. Although the moments are not directly sensitive to $\mid V_{cb} \mid$, they are more sensitive to the non perturbative parameters of HQET than Γ_{sl}. The measurement of the moments provides thus useful constraints on the theory parameters which improve the overall precision on $\mid V_{cb} \mid$. In Fig. 1 we have reported the

comparison between CDF-II and previous measurements.

5 Measurements performed with the hadronic sample

5.1 Charmed hadronic decays

From the analysis of 245 pb^{-1} of data CDF-II has reconstructed clean signals of $B^+ \to \overline{D}^0\pi^+$ (4K events) and of $B^0 \to \overline{D}^-\pi^+$ (5K events). These hadronic samples combined with the $B^+ \to J/\psi K^+$ (3K events) and $B^0 \to J/\psi K^{*0}$ (1K events) have been used to study the performance of the same side tagging algorithm in association to a $B_d^0 - \overline{B}_d^0$ mixing measurement. This measurements finds $\Delta m_d = 0.55 \pm 0.10_{stat} \pm 0.01_{sys}$ ps^{-1} and the values of ϵD^2 reported in Tab. 2.
The accurate study of the B_d system allows tuning the tools to attack the much more ambitious mixing measurement in the B_s^0-$\overline{B}_s^0$ system. The first ingredient of this measurement is a large B_s^0 yield of fully reconstructed decays, like $B_s^0 \to D_s^-\pi^+$, in order achieve the maximum proper time resolution. It has been shown that a proper time resolution worse than 67 fs^{-1} will significantly reduce the prospects for a mixing measurement if Δm_s is larger than 15 ps^{-1}. In Fig. 2 we have reported the $B_s^0 \to D_s^-\pi^+$ signal (84$\pm$11 events) reconstructed using a subsample of 119 pb^{-1} of the presently available statistics.

5.2 Charmless hadronic decays

From the analysis of $\approx$180 pb^{-1} of hadronic data CDF-II has reconstructed a signal of 47$\pm$8 $B^\pm \to \phi K^\pm$ events, with the $\phi \to K^+K^-$. For comparison the more abundant and topologically very similar $B^\pm \to J/\psi K^\pm$ decay has been also reconstructed in the same data without applying any explicit request on the muon identification in the muon chambers in order to have similar systematics. The measurements of the relative branching ratio and of the A_{CP} asymmetry in the $B^\pm \to \phi K^\pm$ decay have been performed:

$$\mathrm{BR}(B^\pm \to \phi K^\pm)/\ \mathrm{BR}(B^\pm \to J/\psi K^\pm) = 0.0072 \pm 0.0013_{stat} \pm 0.0007_{syst}$$

$$\mathrm{A}_{CP}(B^\pm \to \phi K^\pm) = \text{-}0.07 \pm 0.17_{stat} \pm 0.06_{syst}$$

CDF-II has also reconstructed the first signal of the QCD penguin dominated decay $B_s \to \phi\phi$. The branching ratio has been measured relatively to the topologically similar $B_s \to J/\psi\phi$ and turned into an absolute branching ratio. The measured value is $\mathrm{BR}(B_s \to \phi\phi) = (1.4 \pm 0.6_{stat} \pm 0.2_{syst} \pm 0.5_{BR}) \cdot 10^{-5}$ where the last uncertainty is due to the uncertainty on the $B_s \to J/\psi\phi$ branching ratio. This measurement is consistent with the theoretical predictions, which cover the range $(0.4 - 37) \times 10^{-6}$ [2].
In Fig. 2 (*right plot*) we have reported the invariant mass distribution of the $B^0 \to h^+h^{'-}$ candidates when the pion mass is assigned to both tracks in the final state reconstructed from the analysis of $\approx$180 pb^{-1} of data. Four main contributions overlap to generate this signal: $B_d \to \pi^+\pi^-$, $B_d \to K^+\pi^-$, $B_s \to K^+K^-$ and $B_s \to K^-\pi^+$. The first step towards the more ambitious time dependent measurement of the CP asymmetry has been the measurement of the relative fractions of the several contributions to the $B^0 \to h^+h^{'-}$ signal and of the direct CP asymmetry in

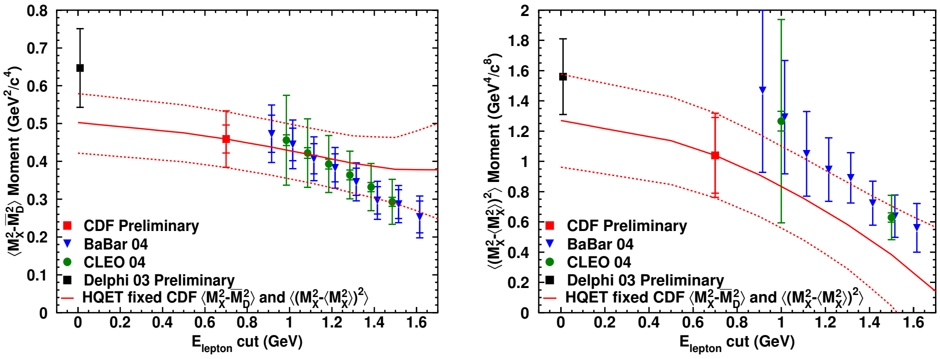

Figure 1. Comparison between the CDF-II measurement of $< M^2_{X_c} > -m^2_{\overline{D}}$ (*left plot*) and of $< (M^2_{X_c} - < M^2_{X_c} >)^2 >$ (*right plot*) and previous determinations. $m_{\overline{D}} = 0.25 m_D + 0.75 m_{D^*}$ is the spin averaged D mass.

the $B_d \to K\pi$ decay. To perform this measurement CDF-II has used the statistical separation power provided by the combination of the specific ionization in the drift chamber (1.4 σ π/K separation at 2 GeV/c) and the slight but non null differences in the kinematics of the various signals. These differences are contained in the correlation between the invariant mass $M_{\pi\pi}$ computed assigning the pion mass to both tracks and the variable $(1 - p_{min}/p_{max}) \cdot q_{min}$ where p_{min} and q_{min} are the scalar momentum and the charge of the softer particle [3]. The results of this analysis are the measurement $\mathrm{BR}(B_s \to K^+K^-) = (34.3 \pm 5.5_{stat} \pm 5.9_{syst}) \cdot 10^{-6}$ and $\mathrm{A}_{CP}(B_d \to K^+\pi^-) = -0.04 \pm 0.08_{stat} \pm 0.01_{syst}$ [5].
In a similar way CDF-II has searched for a $\Lambda_b \to h^+h^{'-}$ signal. The predicted branching ratios are $(1.4 - 1.9) \cdot 10^{-6}$ for $\Lambda_b^0 \to pK^-$ and $(0.8 - 1.2) \cdot 10^{-6}$ for $\Lambda_b^0 \to p\pi^-$. No evidence for a signal has been found and the presently best upper limit has been set at $\mathrm{BR}(\Lambda_b^0 \to p\pi^-, pK^-) \leq 22 \times 10^{-6}$ at 90 % CL [6].

5.3 CP violation in Cabibbo suppressed D^0 decays and search for $D^0 \to \mu^+\mu^-$

The hadronic trigger collects very large samples of all the species of charmed mesons and baryons. A CP asymmetry measurement has been performed in the Cabibbo suppressed $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. The D^0 flavor has been determined from the sign of the soft pion produced in the D^* decay. The measurement finds $\mathrm{A}_{CP}(D^0 \to K^+K^-) = 2.0 \pm 1.2_{stat} \pm 0.6_{syst}$ and $\mathrm{A}_{CP}(D^0 \to \pi^+\pi^-) = 1.0 \pm 1.3_{stat} \pm 0.6_{syst}$.
A search for the FCNC $D^0 \to \mu^+\mu^-$ decay has been performed. An anomalously

large branching ratio could imply R-violating SUSY models. The limit BR($D^0 \to \mu^+\mu^-$) $< 2.5 \times 10^{-6}$ @ 90'% CL has been set [4].

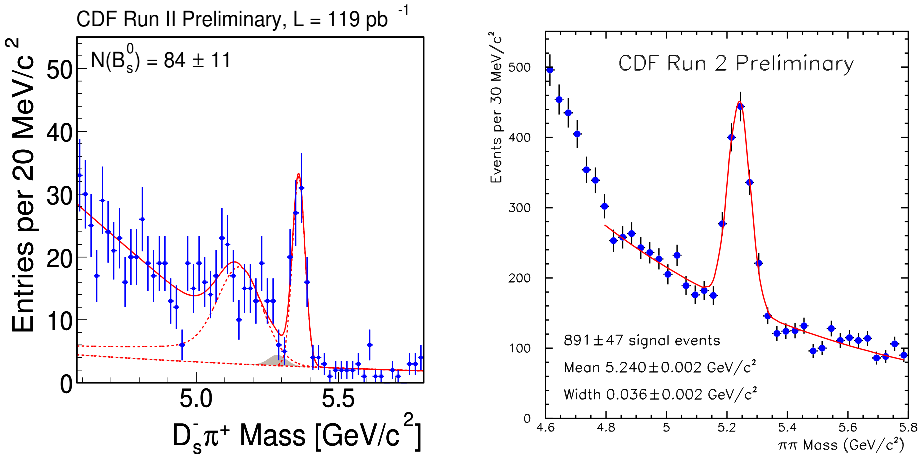

Figure 2. (*Left plot*) $B_s^0 \to D_s^- \pi^+$ signal wih the D_s^- reconstructed in the $\phi\pi^+$ channel using ≈119 pb^{-1} of hadronic data. (*Right plot*) $B^0 \to h^+h^{'-}$ signal reconstructed in ≈180 pb^{-1} of hadronic data.

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