UNIVERSITY
of
GLASGOW

Department of Physics & Astronomy
Experimental Particle Physics Group
Kelvin Building, University of Glasgow,
Glasgow, G12 8QQ, Scotland
Telephone: +44 (0)141 339 8855 Fax: +44 (0)141 330 5881

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b-Physics measurements at the Tevatron: m and Δm

Saverio D'Auria[1]
on behalf of the CDF and D0 collaborations

[1] Department of Physics and Astronomy, University of Glasgow,
Glasgow, G12 8QQ Scotland, U.K.

Abstract

We present experimental results on b-hadron mass measurements and b-meson oscillations based on integrated luminosity of 250 to 450 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.98$ TeV by the CDF and D0 collaborations at the TeVatron. The masses of b-hadrons have been measured precisely by the CDF collaboration in decays containing a J/ψ. A blind search of the decay mode $B_c \to J/\psi\pi^+$ resulted in a peak of 18.9 ± 5.4 candidates at a mass value of $6287.0 \pm 4.5 \pm 1.1$ MeV$/c^2$. A new limit has been set to the decay $B_{d,s} \to \mu^+\mu^-$. Both CDF and D0 collaborations are in the position to put a limit on the frequency of the B_s oscillations. D0 reports $\Delta m_s > 5.0$ ps^{-1}.

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1 Introduction

This article reviews the recent results on b-physics from the experiments D0 and CDF, which are presently collecting data from the $p\bar{p}$ collisions produced at the TeVatron collider with a centre of mass energy of 1.96 TeV. The description of the two experiments and an update on the Tevatron performance are given elsewhere in these proceedings [1]. Here we review the mass measurements of b-hadrons, the search for their rare decays and the search for the B_s oscillations.

A precise measurement of the mass of b-hadrons allows testing of methods used in Lattice QCD and in potential models. At present all but one of the ground states of b-mesons foreseen by the quark theory have been detected and for all but two the mass has been experimentally measured with uncertainties below the theoretical uncertainty. The mass of the B_c meson has been calculated using non-relativistic potential models [2, 3], Lattice QCD [4] and perturbative QCD calculations [5] with an error that up to now has been about two orders of magnitude below the experimental uncertainty [6]. The CDF collaboration reports here their recent and more precise measurements of the the masses of B^0,B^+, B_s and Λ_b. Also reported here is the first evidence of the B_c meson decay in a fully reconstructed mode, thus allowing the measurement of the B_c mass with a precision comparable to the mass of other b-mesons.

Both collaborations have updated their upper limit on the branching fractions of B_s and B^0 to muon pairs, which would indicate the presence of new Physics [8, 9] if detected at a level above $\approx 5 \times 10^{-9}$. The D0 collaboration reports the first evidence of the decay $B_s \to D_{s1}(2536)\mu+$ *anything*. The mass and production yield of excited b-mesons have also been observed by both experiments.

The measurement of the $B_s - \bar{B}_s$ oscillation parameters is one of the main physics goals of both experiments at the Tevatron. This paper will review the methods used and report on the recent limits achieved.

2 b production cross section and trigger

The production cross section of b quarks at the Tevatron is approximatively a factor 1000 times larger than at the B-factories. However, the signal due to b physics has to be extracted from a background due to other QCD processes that is 1000 times larger than the signal. This is accomplished using three types of triggers: a trigger based on muon pairs from the decay of a J/ψ, a trigger based on the detection of a “soft lepton” and a trigger based on tracks that are originating from a secondary decay vertex [10] that is presently implemented only in the CDF experiment. The data from the J/ψ trigger have been used for mass and lifetime measurements, the data from the semileptonic and the secondary vertex triggers have been used for lifetime[11] and mixing measurement. Using the data collected with the J/ψ trigger the CDF collaboration has measured [12] the single b-quark production cross section integrated over one unit of rapidity:

$$\sigma(pp \to \bar{b}X, |y| < 1) = (29.4 \pm 0.6(stat.) \pm 6.2(syst.))\ \mu b \tag{1}$$

3 b-hadron masses

The b-hadron masses have been measured by reconstructing decays containing a muon pair from a J/ψ. The two experiments have complementary design features: CDF has a better mass resolution, while D0 has a larger angular acceptance for muons. The spectrometer of the CDF detector has been calibrated using the J/ψ mass as a reference by correcting for passive material effect, to eliminate the p_T dependence of the mass. The actual value of the magnetic field has been tuned to obtain the world average J/ψ mass value [13]. The calibration has been checked against the Υ mass. The high statistics of $J/\psi \to \mu^+\mu^-$ decays available has allowed the CDF experiment to reduce the systematic uncertainties to sub-MeV values. Using the following decay modes and a luminosity of 220 pb^{-1} CDF has measured the following preliminary values for hadron masses, all in MeV/c^2:

$B^\pm \to J/\psi K^\pm$	$m(B^+) = (5279.10 \pm 0.41 \pm 0.36)$
$B^0 \to J/\psi K^{*0}$	$m(B^0) = (5279.63 \pm 0.53 \pm 0.33)$
$B_s \to J/\psi \phi$	$m(B_s) = (5366.01 \pm 0.73 \pm 0.33)$
$\Lambda_b \to J/\psi \Lambda^0$	$m(\Lambda_b) = (5619.7 \pm 1.2 \pm 1.2)$

4 Evidence of the decay $B_c^\pm \to J/\psi\pi^\pm$ and B_c mass measurement

The B_c meson has been observed [6] at the Tevatron Run I by the CDF collaboration in decays containing a neutrino, and therefore its mass has a large experimental uncertainty. The D0 collaboration has recently observed the semileptonic decays of the B_c meson in the Run 2 data [7]. The LEP experiments searched for the fully reconstructed decays of the B_c meson [15, 14, 16], but the B_c production cross section from Z decays was too low for detecting these decays. The CDF collaboration has now evidence for the fully reconstructed decay mode $B_c^\pm \to J/\psi\pi^\pm$, with $J/\psi \to \mu\mu$. This simple decay mode has a relatively large expected branching ratio [17] when the daughter decays are also included. It is detected with a trigger that is relatively efficient and is not based on the decay vertex. The CDF collaboration has used an analysis technique that blinded a wide range of the mass distribution during cut optimization. The statistical test that was used to assess the significance of the signal was completely set before unblinding the mass distribution. The test was based on the score function $\Sigma = N_s/(1.5 + \sqrt{N_b})$ where N_s and N_b are the number of signal and backgorund candidates as obtained from a fit in a sliding mass window that was 300 MeV/c^2 wide. As the mass value was known with an uncertainty of $\pm$400 MeV/c^2 the mass peak corresponding to this decay was searched for in the range $5700 \leq M(B_c) \leq 7000$ MeV/c^2. The analysis required a good fit to a displaced vertex using well defined tracks with silicon hits, making use of the innermost silicon layer (L00). Upon unblinding the mass distribution, it was found that one region contained a peak that satisfied the predefined statistical test. The probability that the background generates a fluctuation equal or larger than the observed signal, anywhere in the search region, was estimated using Monte Carlo generated distributions that simulated only the background. This probability was found a posteriori to be about 0.27%. The experimental evidence of this decay mode allowed measuring the B_c mass. The $J/\psi\pi$ mass distribution is shown in fig. 1. The unbinned likelihood fit returns 18.9 ± 5.4 B_c candidates on a background of 10.1 ± 1.4 events. The main contribution to the systematic uncertainties comes from fitting with different background shapes. Other systematic uncertainties are derived from the mass measurements reported above. The experimental value of the B_c mass is

$$m(B_c) = 6287.4 \pm 4.5(stat.) \pm 1.1(syst.)\ \mathrm{MeV/c}^2 \qquad (2)$$

The details of this analysis will be published in a forthcoming paper [18]. This result is in very good agreement with the theoretical expectations mentioned above [2, 3, 4, 5]. Checks

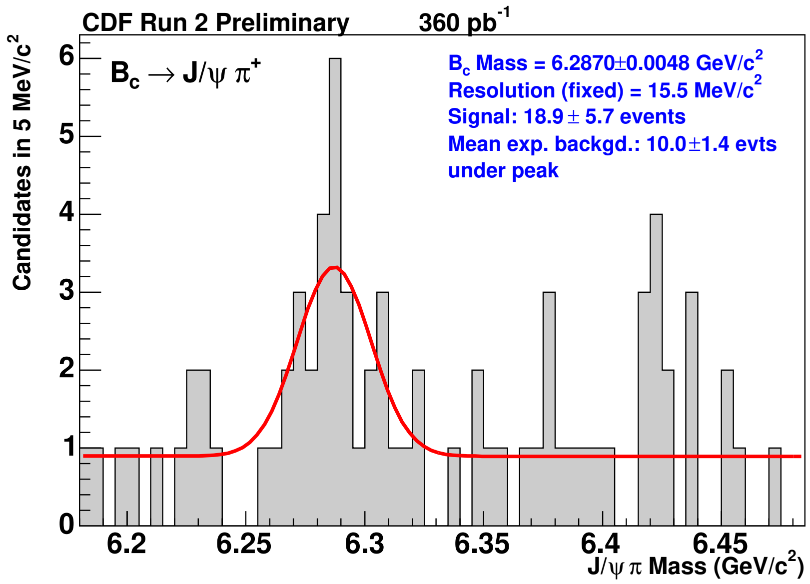

Figure 1: Mass distribution of the B_c candidates. The fit is a gaussian function with a linear background.

on the detection of the partially reconstructed decays $B_c \to J/\psi+$ *track* + *anything* in the same sample also gave a positive result, with a significant excess only for $m(J/\psi\pi) < m(B_c)$, in agreement with the expectations.

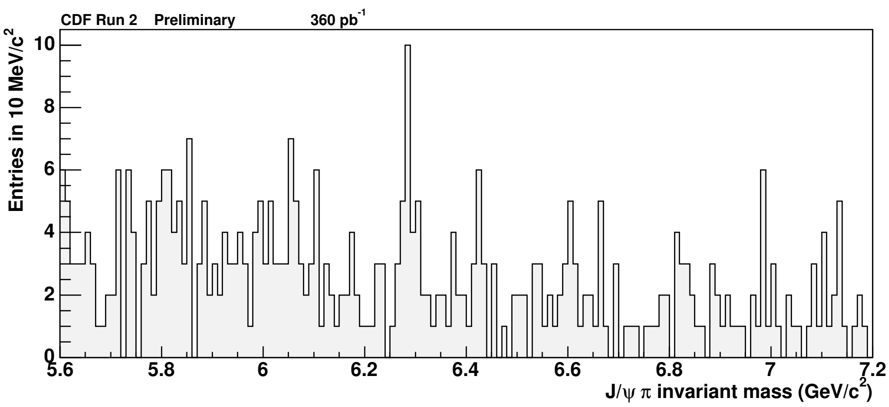

Figure 2: Mass spectrum for the $J/\psi\ \pi^{\pm}$ candidates in the whole search region for the $B_c \to J/\psi\pi^+$.

5 Excited B mesons

The excited states of the b-mesons are of great interest to measure their mass, branching ratios and width, that are predicted with a good precision by various theoretical models. In addition, at the hadron collider the excited states of the b mesons must be taken into account in mixing measurements, when using a flavour tagging method that is based on the information from tracks that are near to the candidate b meson. The excited B states had been studied at LEP by the Aleph collaboration [19]. The D0 collaboration has measured the mass of the two narrow states corresponding to the orbital angular momentum L=1 B_1 and B_2^* in their decay to $B^{(*)}\pi$. Also the CDF collaboration confirms evidence of two separate peaks. In both experiments fully reconstructed decays of the B^+ and B^0 mesons are detected and are associated with a track from the primary vertex. The three contributions are from the decays $B_1 \to B^*\pi$, $B_2^* \to B^*\pi$ and $B_2^* \to B\pi$, with $B^* \to B\gamma$. The undetected photon of about 46 MeV causes the larger shift in the mass peak. The D0 preliminary results are [7]:

$$m(B_1) = 5274 \pm 4(stat.) \pm 7(syst.)MeV/c^2 \tag{3}$$

$$m(B_2^*) - m(B_1) = 23.6 \pm 7.7(stat) \pm 3.9(syst)MeV/c^2 \tag{4}$$

$$\Gamma_1 = \Gamma_2 = 23 \pm 12(stat) \pm 9(syst)MeV \tag{5}$$

6 Search for rare decays

The decay of a neutral b-meson into two opposite charged muons is mediated in the standard model by flavour changing neutral currents due to ladder diagrams and the corresponding branching ratio is calculated to be [20, 21] $BR(B_{d,s} \to \mu^+\mu^-) = (3.4\pm0.54)\times10^{-9}$. A branching ratio that is larger than this value would indicate the presence of new Physics processes, that can considerably enhance this decay channel. The D0 collaboration has searched for the decay of b-mesons to two muons using data from an integrated luminosity of 300 pb^{-1}. Four candidates were found in the mass window, giving a limit on this branching ratio $BR(B_{d,s} \to \mu^+\mu^-) \leq 3.7 \times 10^{-7}$ at 95% conficence level. The CDF collaboration uses its better detector resolution

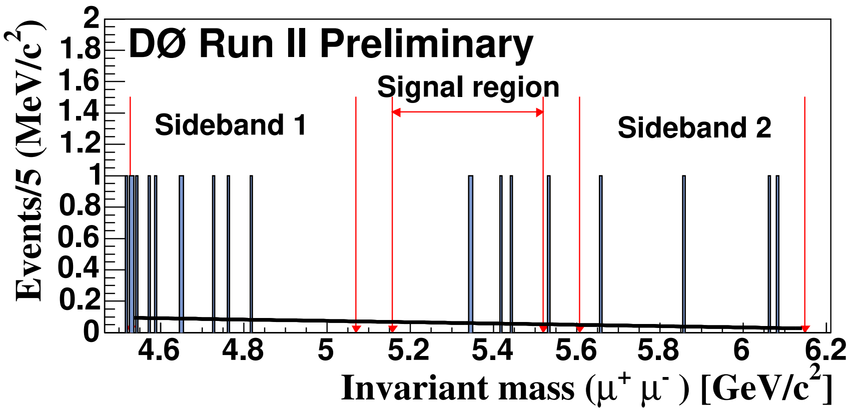

Figure 3: Invariant mass distribution of the muon pairs. Four candidates are found in the signal region.

to put separate limits on the decay rate of the two mesons [22]: $BR(B_s \to \mu^+\mu^-) \leq 5.8 \times 10^{-7}$ and $BR(B_d \to \mu^+\mu^-) \leq 1.5 \times 10^{-7}$ at 90% confidence level using a collected luminosity of 171 pb^{-1}. This result has been updated shortly after this conference. The D0 collaboration has also measured the sensitivity to detect a signal from the decay $B_s \to \mu\mu\phi$. Using data from 300 pb^{-1} they can put a limit on the branching fraction $BR \leq 1.2 \times 10^{-5}$ at 95% CL.

7 Flavour oscillation measurements

To perform time-dependent mixing measurements at the hadron collider it is necessary to select a flavour–specific decay signal (e.g. $B_s \to D_s\pi^-$), establish the flavour of the b-meson at production and measure precisely the proper decay time, which involves measuring the decay length and the momentum of the reconstructed meson. The relevant parameters are the purity of the sample ($f_{sig} = N_{signal}/N_{background}$), which indicates the fraction of decay signal in the sample, the tagging efficiency ϵ, which indicates the fraction of the signal sample that has a flavour tag, $\epsilon = \frac{N_{tag}}{N_{cand}}$, and the dilution D, which indicates the probability that the tag is correct: $D = \frac{N_R - N_W}{N_R + N_W}$ The statistical power of the sample is diluted by a factor ϵD^2: the significance of oscillation signal is given by [13]:

$$S \propto f_{sig} \sqrt{1/2\ \epsilon D^2 N_{cand}}\ \ e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2} \tag{6}$$

where Δ_m is the mixing parameter that determines the frequency of the oscillations and σ_t is the proper time resolution. The latter is the sum in quadrature of two terms: one related to the spatial resolution of the secondary vertex and the second related to the momentum resolution of the reconstructed meson.

For B_s mixing we have a lower statistics compared to the B^0 channel and a larger oscillation parameter, which implies faster oscillations. Therefore, to have a large significance for large Δm_s we need a very good proper time resolution, which can be better achieved with fully reconstructed decays, at the price of smaller statistics.

Both collaborations have used until now only the "opposite side" tagging methods, which rely on tagging the flavour of a b-meson by looking at the characteristics of particles that are produced "away" from the reconstructed meson and that presumably contain hadrons from the b-quark that was produced in association with the one that originated the reconstructed b-meson. This tagging method is independent on the nature of the meson under study, so it has been tested on the B^0 mixing and applied to the search for B_s mixing.

8 B^0 Mixing

The D0 collaboration has used only the semileptonic decays $B^0 \to D^{*\pm}\mu^{\mp}X$, (Here X denotes any set of particles produced in the decay). The CDF collaboration has analysed some fully reconstructed decays from the vertex trigger, for which the lifetime bias is now well understood [11]. Both collaborations have results that are in very good agreement with the precise measurements, which have been performed at the B-factories, as shown in Table 1. The purpose of these measurement was mainly to test the fit algorithms and to obtain the dilution factors, to be used in the search for B_s oscillations.

9 B_s Mixing

The D0 collaboration has applied an updated version of the opposite side muon tagging algorithm to the signal sample enriched in B_s semileptonic decays $B_s \to D_s \mu X$, with $D_s^{\pm} \to \phi\pi^{\pm}$. Using 376$\pm$31 reconstructed and tagged decays (on a total of 7037), and with a tagging dilution of $D = 0.552 \pm 0.016$ a very preliminary fit gives a null result on oscillations, with a limit to the parameter $\Delta m_s \geq 5.0$ ps^{-1} at 95% confidence level and a sensitivity of 4.6 ps^{-1}, using both the statistic and the systematic uncertainties. This result is not as good as the world average, that indicates $\Delta m_s \geq 14.5$ ps^{-1} but it is only the first attempt to fit the data. A considerable improvement is expected, both on statistics and on tagging efficiency. In particular, using the same-side-tagging techniques the tagged sample can be increased using the same data collected to date.

Table 1: Values of Δm_d obtained by CDF and D0 using only the opposite-side flavour tag, for semi-leptonic decays (S.L.) and hadronic decays (Had).

	Δm_d (ps^{-1})	ϵD^2 (%)
D0 (S.L.)	0.558 ± 0.048 (stat.)	1.6 ± 0.05 (stat.)
CDF (S.L.)	0.497 ± 0.028 (stat.)± 0.015 (syst.)	1.43 ± 0.09 (stat.+syst.)
CDF (*Had.*)	0.503 ± 0.063(stat.)± 0.015(syst.)	1.12 ± 0.18(stat.) ± 0.04(syst.)

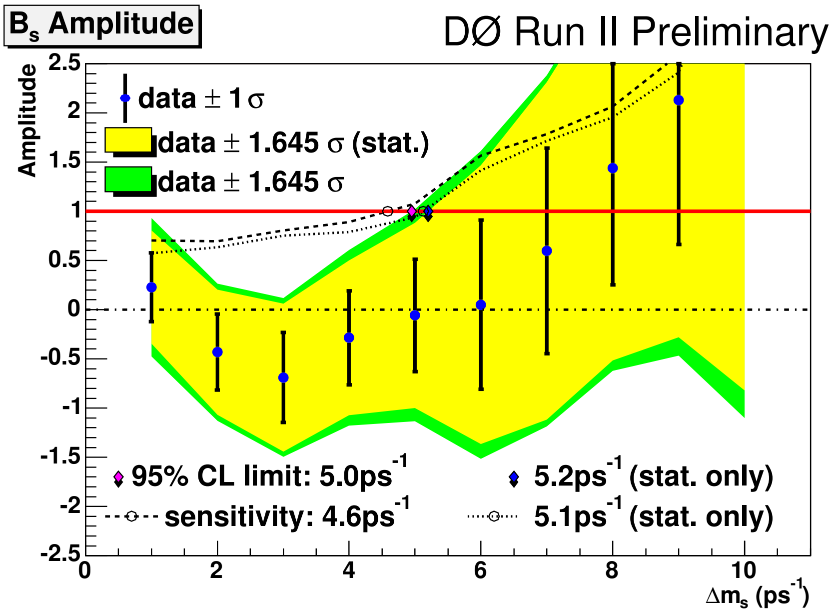

Figure 4: Amplitude scan analysis and Δm_s limit from the D0 collaboration.

By comparison, the CDF collaboration has obtained similar results in terms of ϵD^2. The CDF sample has about 7500 candidates to B_s semileptonic decays, in three reconstructed decay modes of the D_s: $\phi\pi^+$, $K^{*0}K^+$ and $\pi^+\pi^-\pi^+$. For fully–reconstructed hadronic decay candidates $B_s \to D_s\pi^-$, with the D_s decaying to the same modes as above, the statistics is ≈ 900 candidates; the expected tagging power ϵD^2 factors are reported in Table 1.

10 Other results

The D0 collaboration has found evidence for the decay $B_s \to D_{s1}(2536)\mu + X$, heading to a measurement of this branching ratio and of the mass of the $D_{s1}(2536)$.

11 Conclusions and prospectives

The experiment at the Tevatron have considerably improved the precision on b-mesons mass measurements. In particular, the B_c mass has been measured with good precision thanks to the detection of a signal in a fully reconstructed mode, which is reported here for the first time. Also the masses of several B-mesons excited states has been measured. The mixing parameter Δm_d is in good agreement with the world average, but an initial look at the B_s oscillations has given a null result on the measurement of Δm_s, with a limit that is still more than a factor of two lower than the world average. Large improvements are expected not only with more statistics, but also with improved techniques in tagging, improving vertex resolution and adding other decay channels.

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