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B Physics at the Tevatron

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The CDF and D0 experiments have collected large samples of b hadrons during the 1992-1996 $p\bar{p}$ collider run at the Fermilab Tevatron. We report the discovery of the B_c meson in the semileptonic decay $B_c \to J/\psi \ell \nu X$ and give updates on $B^0 - \bar{B}^0$ mixing and B_s lifetime results. Improved limits on the branching fractions of rare B decays are also shown.

1 Introduction

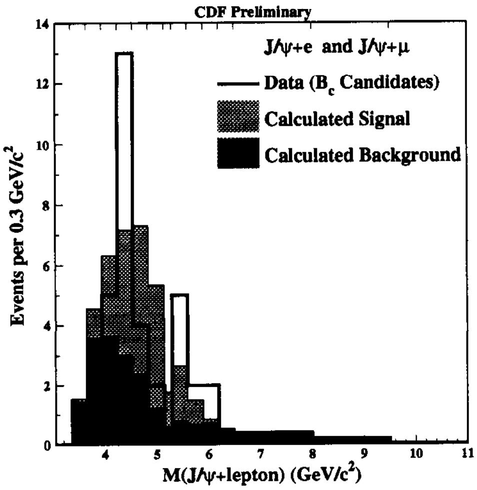
During Run I the Tevatron delivered an integrated luminosity of 110 pb^{-1} of $p\bar{p}$ collisions at a center of mass energy of $\sqrt{s} = 1.8$ TeV. The production cross section for b quarks is large and results in a huge number of b hadrons. For this luminosity, the number of B^0 and $\bar{B}^0$ mesons produced in the central rapidity region $|y| < 1$ with transverse momenta of 6 GeV/c or more is 5×10^8. The spectrum of produced b hadrons is not limited to the B_u and B_d as in B factories running on the $\Upsilon(4S)$ energy but also includes the B_s, B_c and b baryons. Offline, the secondary vertex of b hadrons provides an important signature detectable with the CDF silicon detector (SVX). At the trigger level, however, due to the three orders of magnitude larger total inelastic cross section, B physics samples are restricted to final states involving leptons.

2 Observation of the B_c

The B_c is the lowest bound state of a b and a c quark. Nonrelativistic potential models are expected to describe the B_c very well and predict its mass [1] between 6.2 GeV/c^2 and 6.3 GeV/c^2. The production is expected to be suppressed with respect to B_u by three orders of magnitude. Due to the spectator decay of the c quark, the lifetime of the B_c is predicted to be 0.45 ps, much shorter than other B mesons, but still detectable with the SVX. However, binding effects can lead to a longer lifetime.[2] A large fraction of the B_c mesons, approximately 20 %, is expected to decay into final states involving J/ψ, providing a useful experimental signature.

CDF has searched for the decay [a] $B_c^+ \to J/\psi \ell^+ \nu$, where ℓ is either a muon or an electron. The J/ψ is reconstructed through its decay to $\mu^+\mu^-$ which also provides the trigger. A third track, required to be identified as an electron ($p_t > 2$ GeV/c) or a muon ($p_t > 3$ GeV/c), must be compatible with forming a common vertex with the J/ψ. The true proper decay time is not known because of the unreconstructed neutrino. Instead the quantity $ct^* = \frac{L_{xy} \times M(\psi\ell)}{p_t(\psi\ell)}$ is

[a] Throughout this article, unless we quote a branching fraction, the charge conjugate mode is always included.



source	candidates in $(4\ldots6)\mathrm{GeV}/c^2$	method
false ψ	negligible	sidebands
false 3^{rd} lepton		(ψ+track) data $\times$ fake probability
hadron $\rightarrow$ "μ"	6.4 ± 1.4	detector simulation
hadron $\rightarrow$ "e"	2.6 ± 0.3	jet data + dE/dx
conversion	1.2 ± 0.9	rec. conversions
$B\bar{B}$ (e)	1.2 ± 0.5	MC
$B\bar{B}$ (μ)	0.7 ± 0.3	MC
Total	background	observed
e	5.0 ± 1.1	19
μ	7.1 ± 1.5	12

Figure 1: Combined $J/\psi + e$ and $J/\psi + \mu$ mass distribution of B_c candidates. Superimposed is the fit result for the sum of a B_c signal and the measured backgrounds. Note that the bin width varies. If the invariant mass of the three tracks is compatible with a B^+ when the kaon mass is assigned to the third track, the candidate is assumed to be a $B^+ \rightarrow J/\psi K^+$ decay and rejected. A narrow $J/\psi + \ell$ bin has been chosen that contains these decays. Wide bins are used above 6.5 GeV/c^2. The table on the right summarizes the backgrounds between 4 GeV/c^2 and 6 GeV/c^2.

defined, where L_{xy} is the distance between the reconstructed decay vertex and the beam position measured in the plane perpendicular to the beam. For this analysis a ct^* of 60 μm or more was required in order to remove prompt background sources. The SVX typically provides a vertex position resolution of 50 μm, and the beam spot has a size of 25 μm. $p_t(\psi\ell)$ is the vector sum of the transverse momenta of the three tracks. The three track mass $M(\ell\psi)$ is expected to lie between 4 GeV/c^2 and 6 GeV/c^2 for most B_c decays. Candidates compatible with $B^+ \rightarrow J/\psi K^+$ decays are removed, and electrons identified as coming from photon conversions are rejected.

After all selection cuts, 31 J/ψ–lepton candidates (19 $J/\psi e$ and 12 $J/\psi\mu$) are found with three track masses between 4 GeV/c^2 and 6 GeV/c^2 (fig. 1). Because of the missing neutrino, the mass distribution from the B_c signal is expected to be broad, and in order to establish that these candidates are due to B_c decays it is crucial to precisely determine the backgrounds. Background can be due to hadrons misidentified as the third lepton, random leptons or misidentified hadrons forming a J/ψ candidate, or true J/ψ-lepton combinations from other sources than B_c decays.

Hadrons misidentified as the third lepton are found to be the dominant source of background. In the case of muons this can be due to punch-through where a hadron is not stopped in the steel of the hadron calorimeter and reaches the muon chambers, or decay-in-flight where a hadron decays semileptonically on its way through the detector, and the decay muon reaches the muon chambers and is linked to the track of the hadron. A hadron can be misidentified as an electron if the shower shape in the electromagnetic calorimeter accidentally resembles that of an electron.

These backgrounds are estimated by dropping the lepton identification requirement on the third track and then weighting the candidates found this way with the probability that the third track, assumed to be a hadron, is misidentified as a lepton.

The false lepton probabilities were determined from data and detector simulations and cross checked in a sample dominated by sequential double semileptonic B decays, where essentially only opposite sign lepton pairs can be real leptons. The predicted number of like sign "lepton" pairs is in good agreement with the data.

Another source of electrons are photon conversions to electron pairs. Two such conversion candidates are found and removed. Using the probability for finding the conversion partner

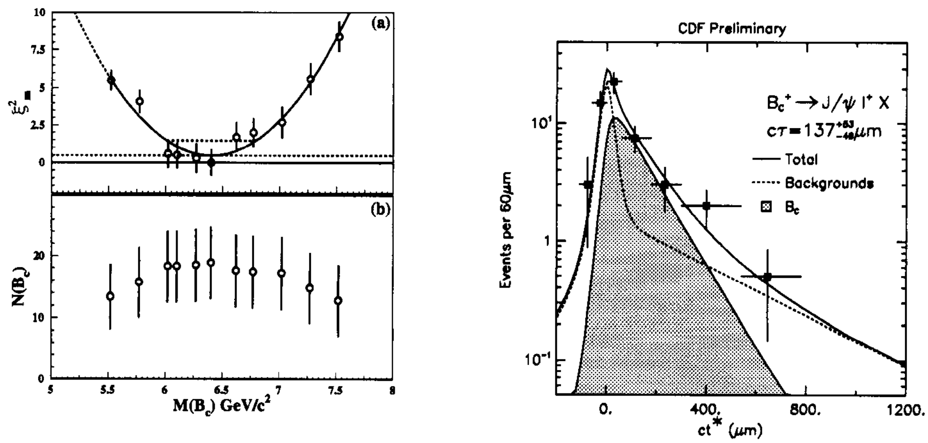


Figure 2: Shown on the left are the fitted number of B_c mesons and the normalized log-likelihood ξ^2_m of the fit for assumed B_c masses between 5.5 GeV/c^2 and 7.5 GeV/c^2. The lifetime fit is shown on the right. The shaded histogram represents the fitted B_c contribution while the dashed line shows the background with a long lifetime component due to B decays.

as determined from a simulation, the number of residual B_c candidates due to electrons from conversion is estimated to be 1.2 ± 0.9.

Background due to false J/ψ candidates is negligible. The only process that was found to result in a non-negligible real $J/\psi\ell$ background is $b\bar{b}$ production, where one of the b hadrons decays semileptonically and the J/ψ is a decay product of the second b hadron. The requirement of a common vertex for the J/ψ and lepton suppresses these combinations and a background of 1.2 ± 0.5 and 0.7 ± 0.3 events is estimated from a Monte Carlo simulation for $J/\psi + e$ and $J/\psi + \mu$ respectively.

As summarized in figure 1, the number of observed events in the 4 GeV/c^2 to 6 GeV/c^2 region exceeds the background estimates. The number of B_c mesons and the significance of this excess is obtained from a likelihood fit in the mass region between 3.35 GeV/c^2 and 11 GeV/c^2; this fit uses knowledge of the expected three track mass distribution for signal and background and the relative acceptance for electron and muon final states. The only free parameter of the fit is the number of B_c mesons, and the result of the fit is

$$N(B_c) = 20.4^{+6.2}_{-5.5}. \tag{1}$$

In 350,000 simulated experiments with the same background level but no signal, the returned value for $N(B_c)$ was always smaller than the observed 20.4. We conclude that the null hypothesis can be rejected at the 4.8σ level.

A B_c mass of 6.27 GeV/c^2 was assumed for calculating the expected J/ψ-lepton mass distribution for the signal. We determine the B_c mass by doing a series of fits with assumed masses between 5.5 GeV/c^2 and 7.5 GeV/c^2. From the parabolic shape of the log-likelihood (fig. 2) we determine

$$M(B_c) = (6.40 \pm 0.39(stat.) \pm 0.13(syst))\ \mathrm{GeV}/c^2. \tag{2}$$

The dependence of the fitted number of B_c on the assumed mass is small (fig. 2).

For the lifetime determination the $ct^* > 60\ \mu$m requirement was dropped and the background calculation repeated to obtain the background as a function of reconstructed ct^*. The background was fitted by a parametrization containing a prompt contribution together with one positive and one negative lifetime exponential, all folded with the experimental decay length resolution. The signal is described by a single exponential folded with the decay length resolution and the expected t*/t distribution (taking into account the unreconstructed neutrino). The result of a fit of signal and background to the data is shown in fig. 2. Only the lifetime and the number of B_c are free parameters of the fit, and we obtain

$$\tau(B_c) = (0.46^{+0.18}_{-0.16}(stat.) \pm 0.03(syst)) \text{ ps}. \tag{3}$$

The product of production cross section and branching fraction is measured relative to the B^+ meson and its decay to $J/\psi K^+$. Many efficiencies cancel in this ratio and we find

$$\frac{\sigma(B_c^+) \cdot \mathcal{B}(B_c^+ \to J/\psi \ell^+ \nu)}{\sigma(B^+) \cdot \mathcal{B}(B^+ \to J/\psi K^+)} = 0.132^{+0.041}_{-0.037}(stat.) \pm 0.031(syst.)^{+0.032}_{-0.020}(\text{lifetime}) \tag{4}$$

where a $(12 \pm 12)\%$ correction for decays through higher $c\bar{c}$ states has been applied.

3 Time dependent $B^0\bar{B}^0$ mixing

Precise measurements of the oscillation frequency of the neutral B_d mesons constrain the CKM matrix element V_{td}. The observation of time dependent $B^0\bar{B}^0$ mixing requires event by event measurements of the proper decay time as well as the flavors at decay and production. The decay flavor is determined by the (partially) reconstructed decay, either by a lepton charge or a combination of a lepton and a charm meson. Although b quarks are produced in pairs, most of the time the second b hadron cannot be reconstructed. The production flavor can be inferred from the charge of a pion close to the reconstructed B^0 (same side tagging) or from tracks on the opposite side, e.g. the "jet charge" or a high p_t lepton. CDF has used five different combinations of these techniques. We will briefly describe a recent result using high p_t muon pairs and give the updated results of all measurements.

3.1 $B^0\bar{B}^0$ mixing in dimuon events

The charges of the muons in events recorded with a muon pair trigger reflect the flavors of the decaying b hadrons, if direct semileptonic decays on both sides are selected. Sequential decays or muon pairs from double semileptonic decays result in a wrong flavor assignment and must be rejected by the selection. This is done by requiring that the invariant mass of the muon pair be greater than 5 GeV/c^2 and the transverse momentum of each muon be greater than 3 GeV/c. If one of the muons has a significant impact parameter and can be associated with a cluster of tracks that form a displaced vertex and have an invariant mass between 1 GeV/c^2 and 5 GeV/c^2, it is used for tagging the decay flavor and measuring the proper decay time. After all selection cuts a sample of 5968 muon pairs is left, which potentially includes $b\bar{b}$, $c\bar{c}$ and false muon events. Distributions of kinematic variables that are sensitive to the event type are fit to the data in order to find the relative fractions of each type. We use the muon impact parameter, the relative transverse momentum of the muon with respect to the track cluster, and the invariant mass of the B candidate and find a negligible $c\bar{c}$ fraction ($0^{+2}_{-0}\%$) and a false muon fraction of $(17.6 \pm 3.6)\%$.

The $b\bar{b}$ component of the sample has contributions from b hadrons other than B^0 and also from sequential decays; these are taken into account by the fit-function and are the dominant source of systematic uncertainty. The oscillation frequency is extracted from a binned χ^2 fit to the fraction of like sign muon pairs as a function of proper decay time. The fit together with the data is shown in figure 3. From the dimuon events we find $\Delta m_d = (0.503 \pm 0.064 \pm 0.071)$ ps^{-1}. The average of all CDF $B^0 - \bar{B}^0$ mixing results, taking overlap and correlations into account, is $\Delta m_d = (0.481 \pm 0.028 \pm 0.027)$ ps^{-1}.

4 Measurement of the B_s lifetime

Lifetime measurements of b hadrons probe the dynamics of their decays. The lifetime of the B_s is predicted to be very close to the lifetime of the B^0 which is known with much better

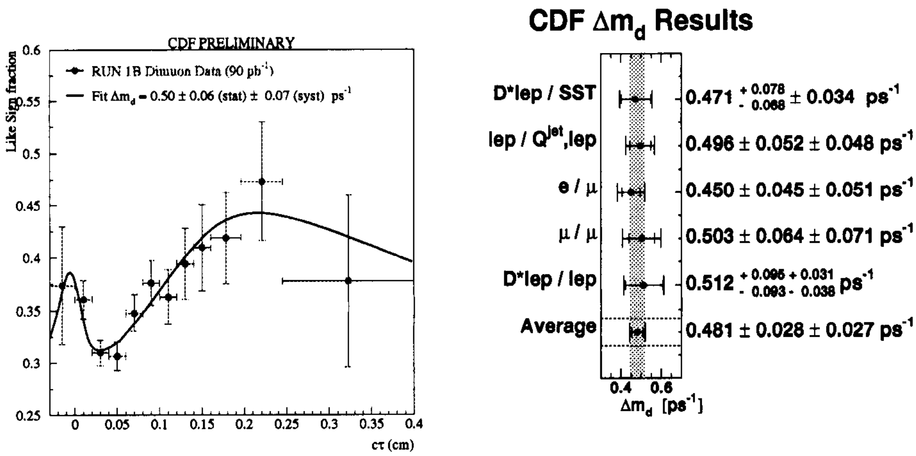


Figure 3: left: Like sign fraction in dimuon events vs. proper decay time. The data points are shown with the fit result superimposed. A summary of all CDF $B^0 - \bar{B}^0$ is shown on the right.

precision.[3] CDF has previously measured $\tau(B_s) = (1.34^{+0.23}_{-0.19} \pm 0.05)$ ps using a sample of 58 fully reconstructed $B_s \to J/\psi\Phi$ decays. [4]

We present a new result using the decays $B_s \to D_s^- \ell^+ \nu X$. The D_s is reconstructed in one of the four modes (1)$D_s^- \to \Phi\pi^-$, $\Phi \to K^+K^-$, (2)$D_s^- \to K^{*0}K^-$, $K^{*0} \to K^-\pi^+$, (3)$D_s^- \to K_S^0 K^-$, $K_S^0 \to \pi^+\pi^-$, (4)$D_s^- \to \Phi\mu^-\nu$, $\Phi \to K^+K^-$. The lepton is either an electron or a muon except for the $\Phi\mu\nu$ channel, where data from a muon pair trigger is used.

Using the reconstructed momentum of the D_s and requiring that it point from the $D_s\ell$ vertex to the D_s decay vertex, the decay length of the B_s is reconstructed with a resolution of ≈ 100 μm in the plane transverse to the beam. To obtain the proper time, a correction is applied event by event for the missing transverse momentum of the unobserved decay products.

The D_s mass distributions for candidates with $D_s\ell$ masses between 3 GeV/c^2 and 5 GeV/c^2 are shown in fig. 4. The samples contain about 600 B_s decays. Combinatorial background samples are obtained from the D_s mass sidebands and wrong sign lepton D_s charge combinations. In the case of the $D_s^- \to \Phi\mu^-\nu$ channel, Φ mass sideband events and also like sign kaon pairs are used in the background sample. Other things that the lifetime fit takes into account are D^- decays to $K^{*0}\pi^-, K_S^0\pi^-$ that can be reconstructed as D_s decays to $K^{*0}K^-$ and $K_S^0K^-$, and D_s from hadronic B decays with two charmed mesons. The combined result of the lifetime fit for modes (1)-(4) is

$$\tau(B_s) = (1.36 \ \pm 0.09(stat.) \ ^{+0.06}_{-0.05}(syst.)) \text{ ps} \tag{5}$$

where the systematic error is dominated by background uncertainties. This is the most precise measurement of the B_s lifetime from a single experiment and the result is somewhat lower than the current world averages for B_s $(1.57 \pm 0.08$ ps) and B^0 $(1.55 \pm 0.06$ ps) lifetimes.[8]

In the large sample of B_s decays we also looked for evidence of a lifetime difference between the two CP eigenstates of the $B_s - \bar{B}_s$ system. This difference could be observable if B_s mixing is very large.[5] Assuming that our sample is an equal mixture of both CP eigenstates we repeated the fit with two lifetime components, fixing the average lifetime to the world average and introducing the width difference $\Delta\Gamma$. We find no significant lifetime difference and conclude that $\Delta\Gamma/\Gamma < 0.81$ at 95% confidence level. This corresponds to $\Delta m_s < 94$ ps$^{-1} \times \left(\frac{5.6\times10^{-3}}{\Delta\Gamma/\Delta m}\right) \times \left(\frac{1.57\text{ps}}{\tau(\text{B}_s)}\right)$.

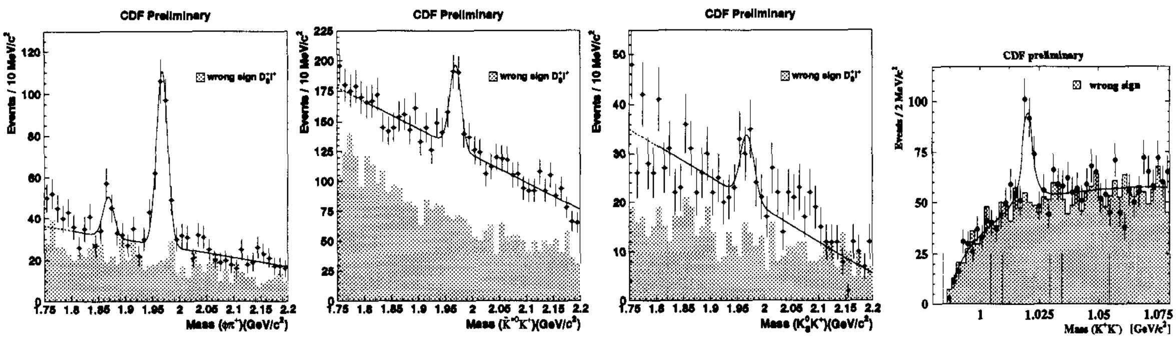


Figure 4: Invariant D_s masses of $B \to D_s \ell \nu X$ candidates. Shown shaded are the wrong sign lepton D_s combinations which are used together with D_s mass sidebands to fix the background shape for the lifetime fit. In the case of $D_s \to \Phi \mu X$ we show the invariant mass of $\Phi \to K^+K^-$ candidates. The wrong sign background in this case is $\mu^\pm\mu^\pm$ as well as $K^\pm K^\pm$ and is shown rescaled to match the right sign background.

5 Rare B decays

Decays that are suppressed or forbidden in the Standard Model are in general a good place to look for nonstandard physics. Final states with muon pairs have moderate theoretical uncertainties. An observation of branching fractions much higher than expected would be an unmistakeable signal for physics outside the Standard Model. They also provide a triggerable signature for a hadron collider experiment and thus allow us to take advantage of the large B production rate for high sensitivity searches.

5.1 $B^0, B_s \to \mu^+\mu^-$

CDF has searched for the decays $B^0, B_s \to \mu^+\mu^-$, which are highly suppressed in the Standard Model with predicted branching fractions [6] as low as 10^{-10} and 10^{-9}. Candidates are required to have a transverse momentum greater than 6 GeV/c and a proper decay length greater than 100 μm. The transverse momentum is required to point from the decay vertex back to the beam spot within 0.1 radians. The hard fragmentation of the b quarks is exploited by requiring an isolation $I > 0.75$. Isolation is defined as the fraction $I = pt(B)/[pt(B) + pt(\text{other tracks})]$, where other tracks are taken from a cone [b] around the B momentum. After all cuts we find one candidate which happens to fall into the overlap of the B^0 and B_s signal regions. From this we set the upper limits $\mathcal{B}(B^0_d \to \mu^+\mu^-) < 6.8 \times 10^{-7}$ and $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 2.0 \times 10^{-6}$ at the 90% confidence level.

5.2 $b \to s\mu^+\mu^-$

The Standard Model predictions for the flavor changing neutral current (FCNC) processes $B \to \ell^+\ell^- X_s$ are at the level of 10^{-6}, still an order of magnitude lower than current experimental limits. Resonant $b \to (c\bar{c})s$ decays followed by $J/\psi, \psi(2S) \to \mu^+\mu^-$ lead to exactly the same signature and have much higher branching fractions. Regions where the invariant mass of the muon pair is close to the $c\bar{c}$ resonances therefore must be excluded. On the other hand, the resonant decays with their well known branching fractions provide a convenient way of measuring acceptance and efficiency for this final state.

The D0 collaboration has searched for the inclusive decay $B \to \ell^+\ell^- X_s$ in a sample of oppositely charged muon pairs corresponding to 50 pb^{-1} of integrated luminosity.[7] Each muon is required to have a transverse momentum greater than 3.5 GeV/c and pseudorapidity $\eta < 1$. The

[b] The cone is defined by $\Delta\eta^2 + \Delta\phi^2 < 1$, where $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuth angle differences between a track and the B momentum.

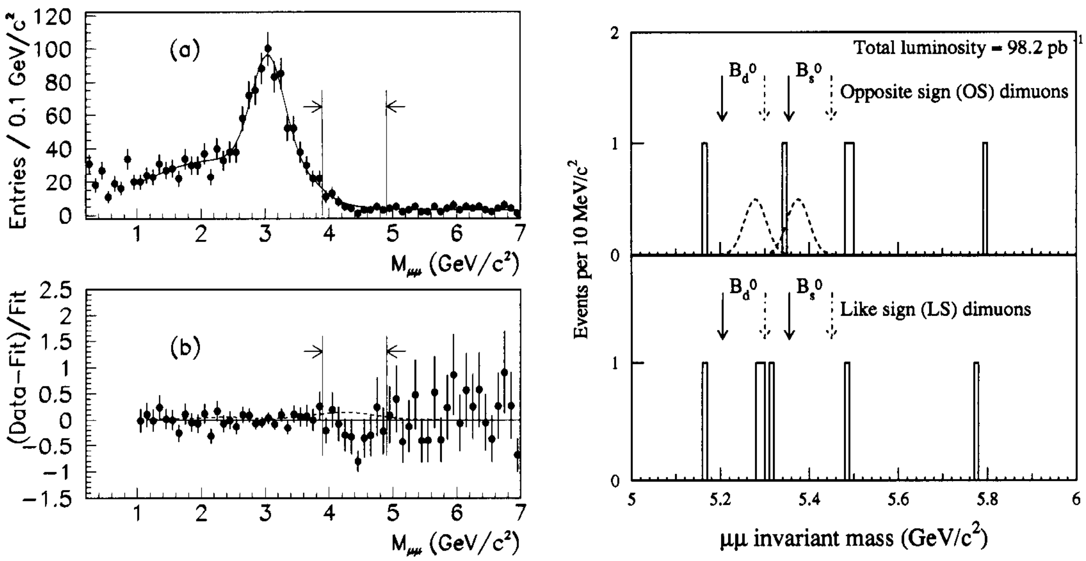


Figure 5: Invariant mass of muon pairs from FCNC searches. Left: $b \to \mu^+\mu^- s$ (D0), the dashed curve in (b) shows a signal corresponding to the 90% confidence level upper limit. Right: $B, B_s \to \mu^+\mu^-$ (CDF), the arrows indicate the signal regions.

invariant mass spectrum of selected muon pairs with total transverse momentum greater than 5 GeV/c is shown in fig. 5. A fit function including $J/\psi, \psi'$ decays as well as other known sources of muon pairs describes the data well. The sources considered are (1) $b\bar{b}$ and $c\bar{c}$ production followed by semileptonic decays of both heavy quarks or double semileptonic sequential decays of a b-quark, (2) semileptonic b or c decays together with a decay in flight muon, and (3) the Drell Yan process. In the search region, 3.9 GeV/c^2 < $M_{\mu\mu}$ < 4.9 GeV/c^2, the fit predicts $68 \pm 2(stat.) \pm 4(syst.)$ candidates while 56 are observed. No attempt is made to identify strangeness in the final state, and the contribution from the CKM suppressed mode $B \to \ell^+\ell^- X_d$ is assumed to be negligible. Using the normalization obtained from the fitted J/ψ signal, a 90% confidence level limit of $\mathcal{B}(b \to X_s\mu^+\mu^-) < 3.2 \times 10^{-4}$ is obtained.

CDF has searched for FCNC decays in the fully reconstructed exclusive modes $B^0 \to \mu^+\mu^- K^{*0}$ and $B^+ \to \mu^+\mu^- K^+$. The trigger selected muon pairs with muon transverse momenta above 2 GeV/c. B candidates with transverse momentum greater than 6 GeV/c are reconstructed in the pseudorapidity range $|\eta| < 1$ by adding a K^+ or a $K^{*0} \to K^+\pi^-$ candidate and requiring a good secondary vertex more than 400 μm away from the beam spot. Combinations with an invariant mass within 50 MeV/c^2 of 5.278 GeV/c^2 are accepted as B candidates.

Combinatorial background is rejected by requiring isolation $I > 0.6$ for the B candidate and a significant impact parameter ($> 2\sigma$) for each individual track forming the decay vertex. The results are very clean signals of 122 $B^+ \to J/\psi K^+$ candidates and 78 $B^0 \to J/\psi K^{*0}$ candidates with a dimuon mass within 100 MeV/c^2 of the world average J/ψ mass. To search for the rare decays, the dimuon mass regions of 200(100) MeV/c^2 around the $J/\psi(\psi')$ are excluded and we find 4 $B^+ \to \mu^+\mu^- K^+$ candidates and no $B^0 \to \mu^+\mu^- K^{*0}$ candidate. The efficiencies relative to the resonant decays, including the restricted dimuon mass region, are determined in a Monte Carlo calculation to be 0.79 and 0.71. Using the measured values for the resonant branching fractions [8,9] we set upper limits $\mathcal{B}(B^+ \to \mu^+\mu^- K^+) < 5.4 \times 10^{-6}$ and $\mathcal{B}(B^0 \to \mu^+\mu^- K^{*0}) < 4.1 \times 10^{-6}$ at the 90% confidence level. For both modes about 0.6 candidates are expected from rare B decays assuming branching fractions of 0.4×10^{-6} and 1.0×10^{-6}.

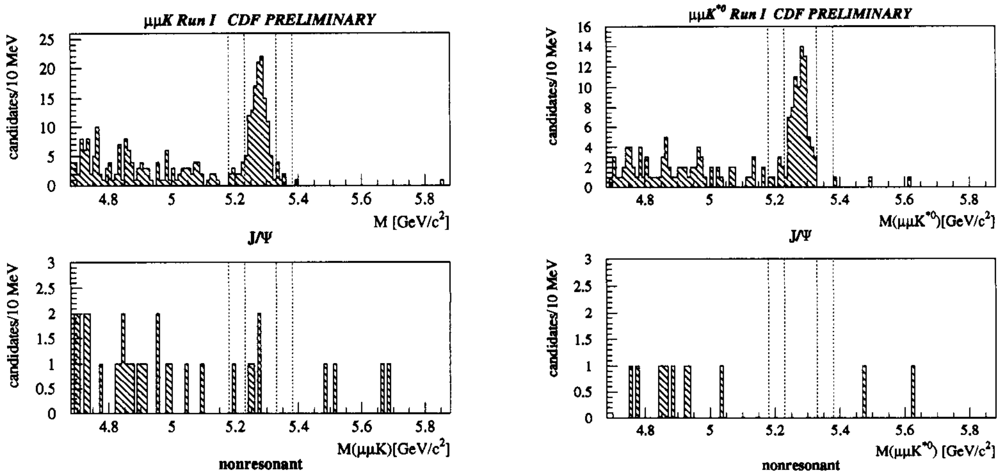


Figure 6: Invariant masses of $B \to \mu^+\mu^-K^+$ (top) and $B^0 \to \mu^+\mu^-K^{*0}$ (bottom). Very clean signals of 122 $B^+ \to J/\psi K^+$ and 78 $B^0 \to J/\psi K^{*0}$ candidates are seen when dimuon masses within 100 MeV/c^2 of the J/ψ mass are selected (left). The J/ψ and ψ' regions are excluded in the plots on the right and we find 4 $B \to \mu^+\mu^-K^+$ candidates and no $B^0 \to \mu^+\mu^-K^{*0}$. The Standard Model expectation is $\sim$ 0.6 events for both modes.

6 Summary

CDF reports the first observation of the B_c meson and measures the mass, lifetime and the product of production cross section × branching fraction. The measurements of Δm_d and the B_s lifetime at the Tevatron have been updated, and a limit is set on the width difference of the two CP eigenstates of the B_s. D0 and CDF have searched for FCNC B decays and have obtained improved limits on the branching fractions.

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