A Limit on $\sigma \cdot BR(B^+_c \rightarrow J/\psi + \pi^+)/\sigma \cdot BR(B^+_u \rightarrow J/\psi + K^+)$ in $\sqrt{s} = 1.8$ TeV Proton-Antiproton Collisions

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A Limit on
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in \[ \sqrt{s} = 1.8 \text{ TeV Proton-Antiproton Collisions} \]

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Abstract

We report on the results of a search for the \( B_c \) \((bc)\) meson in the
decay \( B_c^\pm \rightarrow J/\psi + \pi^\pm \). This search is guided by a control sample of
decays of \( B_u \) mesons to \( J/\psi + K \) and uses \( \simeq 75pb^{-1} \) of data collected
at the Collider Detector Facility (CDF) at Fermilab. The lifetime of the
\( B_c \) meson is unknown, so the 95% confidence level limit on \( \sigma \cdot \text{BR}(B_c \rightarrow J/\psi + \pi)/\sigma \cdot \text{BR}(B_u \rightarrow J/\psi + K) \)
is obtained as a function of the \( B_c \) lifetime.
Introduction

The $B_c$ is the bound state of the bottom and charm quarks and is predicted by the standard model. This particle can be found by using the fact that a large fraction of its decays ($\simeq 20\%$) are to $J/\psi$ final states. The mass of the $B_c$ is predicted to be $6.256 \pm 0.020$ GeV/c$^2$ with a lifetime of $\tau = 1.35 \pm 0.15$ ps.[1] Other theorists report smaller values for the lifetime, in the range of 0.5-0.7 ps.[2] Production estimates using perturbative QCD for the $b$ quark fragmentation to $B_c$ exist and predict production of $B_c$ relative to other $b$ mesons at $\approx 10^{-3}$ for $P_T > 10$ GeV/c.[3]

Search Method

The data sample used is 75pb$^{-1}$ collected in two separate runs of the Fermilab Tevatron. The data sample is based on a dimuon trigger with muon pair invariant mass consistent with the $J/\psi$ mass. The CDF detector is described elsewhere [5] and is defined on a coordinate system with the $z$-$y$ plane perpendicular to the beam where the proton beam direction is the positive $z$ axis.

The CDF dimuon trigger is staged. Level 1 requires two muon stubs in the muon chambers with $|\eta| < 0.6$ for the first 19pb$^{-1}$. The trigger coverage is extended to $|\eta| < 1.0$ for the remaining 54pb$^{-1}$. At level 2 at least one muon segment is required to match a central track found by the track processor. Levels 1 and 2 are hardware triggers. Within this data sample are the exclusive decays of $B_c$ to $J/\psi + \pi$ and $B_u$ to $J/\psi + K$.

The data is further processed to look for $J/\psi + K^{\pm}$, $(\pi^{\pm})$ events. The three tracks are constrained to come from the same vertex and the invariant mass of the two muons is constrained to the world average $J/\psi$ mass. Since this is a fully reconstructed event, the momentum sum of the tracks is constrained to be parallel to the vector from the run-averaged beam position in the $x$-$y$ plane to the 3-track vertex. At least one of the muon tracks and the third track are required to have hits in the silicon vertex detector (SVX) [6] and a fit with $\chi^2$ probability greater than 5% is required of the resulting 3-track vertex. Transverse momentum cuts of 2 GeV/c are placed on the muons to get above the trigger thresholds and on the third track to reduce background from combinatorics. The $P_T$ of the 3-track combination is required to be greater than 6.0 GeV/c. Since there is no particle identification, processing is done twice on the third track, once assuming a pion mass and then a kaon mass.

For the $J/\psi + K^{\pm}$ sample, a cut of $ct > 85\mu m$ is imposed to remove the prompt background. Figure 1 shows the resulting three track invariant mass distribution with a clear signal from the $B^{\pm}$ mesons. This distribution is fit to a gaussian signal and a linear background in the range from 5.15 to 5.8 GeV/c$^2$. $N_{B^u} = 289 \pm 19$ $B^{\pm}$ events are obtained.

For the $B_c$ search, the same cuts are used as for the $J/\psi + K$ sample. Shown in
Table 1: This is a table showing the $c\tau$ cut used, the chosen $B_c$ lifetime, the relative efficiency of the cuts ($R_e$), the largest number of data events in 4 consecutive bins from 6.1 to 6.4 GeV/c² ($N_{tot}$), and the fit to the data for the expected number of background events in those 4 bins ($\overline{N_{Bkg}}$).

<table>
<thead>
<tr>
<th>$c\tau$ cut</th>
<th>$B_c$ lifetime</th>
<th>$R_e \equiv \frac{d(B_c)}{d(B_u)}$ (stat+sys)</th>
<th>$N_{tot}$</th>
<th>$\overline{N_{Bkg}}$ (stat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 µm</td>
<td>0.17 ps</td>
<td>2.02 ± 0.13</td>
<td>43</td>
<td>40.6 ± 2.2</td>
</tr>
<tr>
<td>85 µm</td>
<td>0.33 ps</td>
<td>1.71 ± 0.09</td>
<td>31</td>
<td>21.6 ± 1.7</td>
</tr>
<tr>
<td>100 µm</td>
<td>0.5 ps</td>
<td>1.49 ± 0.07</td>
<td>25</td>
<td>15.8 ± 1.4</td>
</tr>
<tr>
<td>100 µm</td>
<td>0.8 ps</td>
<td>1.21 ± 0.06</td>
<td>25</td>
<td>15.8 ± 1.4</td>
</tr>
<tr>
<td>100 µm</td>
<td>1.0 ps</td>
<td>1.12 ± 0.05</td>
<td>25</td>
<td>15.8 ± 1.4</td>
</tr>
<tr>
<td>100 µm</td>
<td>1.3 ps</td>
<td>1.03 ± 0.05</td>
<td>25</td>
<td>15.8 ± 1.4</td>
</tr>
<tr>
<td>100 µm</td>
<td>1.6 ps</td>
<td>0.99 ± 0.045</td>
<td>25</td>
<td>15.8 ± 1.4</td>
</tr>
</tbody>
</table>

Figure 2 is the invariant mass distribution with the same cuts as Figure 1. Since the $B_c$ is made of two heavy quarks, there is some confidence that the predictions of the mass are correct, consequently we restrict our search region to ±150 MeV/c² around the nominal mass of 6.256 GeV/c².

Because the $B_c$ lifetime is chosen to be variable, the cut on proper decay length is varied to optimize its effectiveness based on different lifetimes. Three different cuts on $c\tau$ are used depending on the assumed $B_c$ lifetime. The $c\tau$ cuts used are shown in Table 1.

To determine the bin size in Figure 2, a Monte Carlo of $B_u$ and $B_c$ decays was run through a detector simulation. The ratio of the widths of the mass peaks obtained was used to scale the observed width of the $B_u$ mass to the estimated $B_c$ mass. The bin size of 16 MeV/c² in Figure 2 is equal to that estimate. The four largest consecutive bins in Figure 2 are defined as containing the $B_c$ signal candidates ($N_{tot}$) for the purpose of calculating the limit. The remaining events are used to fix the level of background and are fit to a straight line with the four ‘signal’ bins excluded. From the fit the average background under the signal ($\overline{N_{Bkg}}$) is obtained. These quantities are also shown in Table 1 for the different $c\tau$ cuts.

**Determination of the relative efficiency $R_e$**

If one were to see a $B_c$ signal, determination of the relative rate to $B_u$ would proceed by the following equation:

$$\frac{\sigma \cdot BR(B_c)}{\sigma \cdot BR(B_u)} = \frac{N_{\Psi+\pi}}{N_{\Psi+K}} \cdot R_e$$
where \( R_e = \epsilon_{Bu}/\epsilon_{Bc} \). The experimental advantage of comparing the \( J/\psi + \pi \) decay to the \( J/\psi + K \) is clear. The tracking efficiencies for muons and for tracks will cancel in the ratio as will the integrated luminosity. Efficiencies of the muon chambers given a track in the fiducial volume, will also cancel because both samples come from the same trigger.

To determine the relative efficiency the \( B_c \) lifetime is first set equal to the \( B_u \) lifetime. A Monte Carlo and detector simulation is run for both types of mesons where the input spectrum, the \( b \) fragmentation to \( B_u \), and the trigger simulation are varied in shape. This causes a systematic error of 4\% on the relative efficiency. The value of \( R_e \) obtained is shown in Table 1. The fragmentation of \( b \rightarrow B_c \) uses the perturbative QCD calculation in [4] and is not included in the systematic uncertainties associated with \( R_e \).

\( R_e \) must be corrected for the assumed lifetimes of the \( B_c \). The data from 5.5 to 6.0 GeV/c\(^2\) is used to characterize the \( \sigma \tau \) distribution of zero lifetime background and is fit to a parameterization. The parameterization is then used to smear an ideal \( \sigma \tau \) distribution for an arbitrary \( B_c \) lifetime. The same function is used to smear the lifetime distribution of \( B_u \). The ratio of the areas under the two functions, with the correct \( \sigma \tau \) cuts and normalization, is used to adjust \( R_e \) for an arbitrary \( B_c \) lifetime. This contributes a 5\% systematic uncertainty in \( R_e \) for short-lived \( B_c \)'s, but falls to 0.2\% when the lifetimes are equal.

The Limit

Calculation of the 95\% confidence level limit uses the method described by [7]. This method assumes Poisson statistics for the signal and background and accounts for the uncertainty in \( N_{bg} \), the uncertainties in the estimate of \( R_e \), and the statistical uncertainty in the number of \( J/\psi + K^\pm \) obtained. The number of \( J/\psi + K^\pm \) that are lost due to the decay-in-flight of kaons relative to pions have not been included in this calculation. Such a correction would lower the limit. The 95\% C.L. limit on \( \sigma \cdot \text{BR} \) for \( B_c^\pm \rightarrow J/\psi + \pi^\pm \) versus \( B_u^\pm \rightarrow J/\psi + K^\pm \) as a function of the \( B_c \) lifetime is shown in Figure 3. Also shown is an estimate of the theoretical production ratio where it is assumed that \( B_c \) mesons are produced 1000 times less often than the other \( B \) mesons and that \( \Gamma(B_c^\pm \rightarrow J/\psi + \pi^\pm) = 3.4 \times 10^9 \text{s}^{-1} \). [8]

References

[1] C. Quigg, \( B_c \), FERMILAB-Conf-93/265-T.


Figure 1: The figure shows the three track invariant mass distribution where the third track is assumed to be a kaon. The fit is to a gaussian and a linear background with $N_{Bu} = 289 \pm 19$ in the $J/\psi + K^\pm$ peak.
Figure 2: The three-track invariant mass region from 5.9 to 7.1 GeV/c² using the same cuts as Figure 1 but assuming the third track has a pion mass. The vertical lines encompass the search region for the $B_c$ meson. The four highest bins in the search region are excluded from the fit (shown as a dotted line).
Figure 3: Shown as circular points is the 95% C.L. limit on the production of $J/\psi + \pi^+$ from $B_c^+$ relative to $J/\psi + K^+$ from $B_u^+$ as a function of the $B_c$ lifetime. Also shown is a theoretical estimate of the relative production ratio based on the assumption that the $B_c$ is produced $10^{-3}$ times less often than the other $B$ mesons and that the partial width of the $B_c$ decay to $J/\psi + \pi$ is $3.4 \times 10^9 \text{s}^{-1}$. 