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Search for the B_c Meson in Hadronic Z^0 Decays

The OPAL Collaboration

Abstract

A search for decays of the B_c meson was performed using data collected from 1990-1995 with the OPAL detector at the Z^0 peak at LEP. The decay channels $B_c^+ \to J/\psi\pi^+$, $B_c^+ \to J/\psi a_1^+$ and $B_c^+ \to J/\psi\ell^+\nu$ were investigated, where ℓ denotes an electron or a muon. We find two candidates in the mode $B_c^+ \to J/\psi\pi^+$, with an estimated background of 0.32 ± 0.11 events. The weighted mean of the mass of the two candidates is 6.32 ± 0.06 GeV/c^2, which is consistent with the predicted mass of the B_c meson. We find one candidate event in the mode $B_c^+ \to J/\psi\ell^+\nu$, with an estimated background of 0.90 ± 0.20 events. No candidate events were observed in the $B_c^+ \to J/\psi a_1^+$ decay mode. We set upper bounds at the 90% confidence level on the production rates of these processes.

This note describes preliminary OPAL results to be submitted to the XVIII International Symposium on Lepton-Photon Interactions Hamburg, 28 July - 1 August 1997.

1 Introduction

The ground state pseudoscalar mesons containing a b quark, B_u, B_d, B_s and B_c, have all but for one been observed, by experiments at CESR, DORIS, LEP and the TEVATRON. The remaining as yet unobserved state in this family of hadrons is the beauty-charm meson $B_c(\bar{b}c)$. The mass of the B_c meson is predicted to be in the range 6.24 GeV/c^2 to 6.31 GeV/c^2 [1]. The production mechanism for the $\bar{b}c$ bound states differs from that of the B_d, B_u and B_s mesons. The soft fragmentation process, involving spontaneous creation of $b\bar{b}$ or $c\bar{c}$, is severely suppressed. The predicted dominant production mechanism shown in figure 1 involves the emission and splitting of a hard gluon in the process $Z^0 \to b\bar{b}$ [2]. Perturbative QCD calculations predict a production rate of 10^{-5} to 10^{-4} B_c per hadronic Z^0 decay, with a momentum spectrum which is considerably softer than that for the light B hadrons [3]. The decay of the B_c meson is governed by the weak interaction; strong decay into a lower mass beauty meson and a charmed hadron is forbidden by energy conservation. There is a large spread in the predictions of the B_c lifetime, although it is generally agreed that it is shorter than the lifetime of the light B mesons. Theoretical calculations predict a significant branching ratio into modes involving the J/ψ meson [4].

In this article we report on a search for B_c decays in a data sample of 4.2×10^6 hadronic Z^0 decays collected with the OPAL detector at LEP. In a previous article by the OPAL collaboration [5] we reported on a study of J/ψ meson production in hadronic Z^0 decays, and the reconstruction of exclusive decays of B hadrons into modes containing a J/ψ meson, which included a candidate for the decay $B_c^+ \to J/\psi\pi^+$. [1] Here we extend the analysis of the B_c decays and search for the decay modes $B_c^+ \to J/\psi\pi^+$, $B_c^+ \to J/\psi a_1^+$ and $B_c^+ \to J/\psi\ell^+\nu$, where ℓ denotes an electron or a muon.

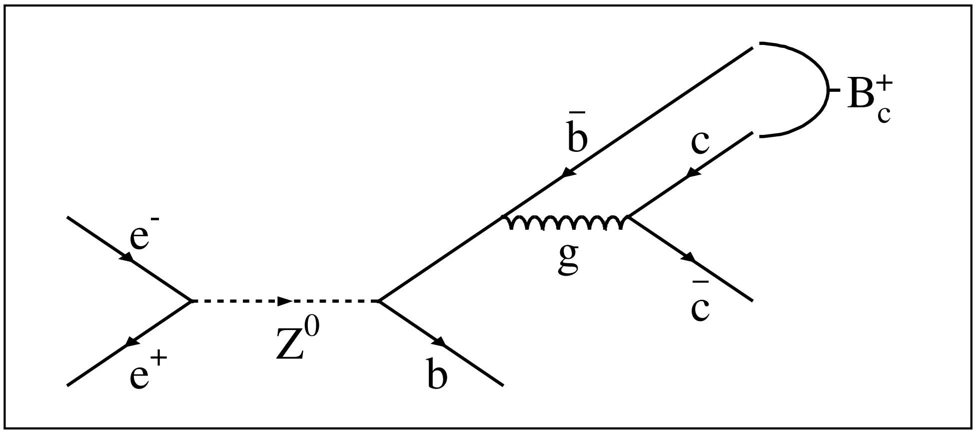

Figure 1: Feynman Diagram for the process $Z^0 \to b\bar{b} \to B_cX$

2 The OPAL Detector and the Data Sample

The OPAL detector is described in detail elsewhere [6]. Here we briefly describe the components which are relevant to this analysis. Charged particle tracking is performed by the central detector system which is located in a solenoidal magnetic field of 0.435 T. The central tracking system consists of a two layer silicon microvertex detector [7], a high precision vertex drift chamber, a large volume jet chamber and a set of planar drift chambers measuring track coordinates along z, the beam direction. The momentum resolution of the central detector in the $x-y$ plane, the plane perpendicular to the

[1] Throughout this article charge conjugate modes are implied.

beam direction, is $(\delta p_{xy}/p_{xy})^2 = (2\%)^2+(0.15\%\cdot p_{xy})^2$, where p_{xy} is in GeV/c. Particle identification is provided by the measurement of specific ionization, dE/dx, in the jet chamber. The dE/dx resolution for tracks with the maximum of 159 samplings in the jet chamber is 3.5% [8]. The central detector is surrounded by a lead glass electromagnetic calorimeter with a pre-sampler. The magnet yoke is instrumented with layers of streamer tubes which serve as a hadron calorimeter, and provide additional information for muon identification. Four layers of planar drift chambers surrounding the detector provide the tracking for muons.

3 The Data Sample and Event Selection

Data collected by the OPAL detector during 1990–1995 are used in this study, corresponding to a total of about 4.2×10^6 hadronic Z^0 decays. The selection of hadronic events has been described elsewhere [9]. The selection efficiency for the multihadronic events is (98.1±0.5)%, with a background of less than 0.1%.

For this analysis we impose the following additional requirements on charged tracks: the number of hits in the central detector used for the reconstruction of a track must be greater than 40 (this restricts the acceptance to $|\cos\theta| < 0.94$); the distance of closest approach to the beam axis in the $x - y$ plane must be less than 0.5 cm; the transverse momentum with respect to the beam direction must exceed 0.25 GeV/c; and the total momentum of the track must exceed 0.5 GeV/c. In order to obtain accurate polar angle measurements, a barrel track is required to match with a z-chamber track segment containing at least 3 hits, and a forward going track is constrained to the point where the track leaves the chamber.

A track is identified as a pion if the $\mathrm{d}E/\mathrm{d}x$ probability for the pion hypothesis, that is the probability that the specific ionization in the jet chamber ($\mathrm{d}E/\mathrm{d}x$) is compatible with a pion, exceeds 2.5% if the measured $\mathrm{d}E/\mathrm{d}x$ is lower than the expected $\mathrm{d}E/\mathrm{d}x$ for a pion, and 0.1% if it is higher. Tracks are identified as kaons if the dE/dx probability for the kaon hypothesis is greater than 5%.

Leptons are identified by imposing the following criteria. We require the track momentum $p >$ 2.0 GeV/c, and $|cos\theta| < 0.9$, where θ is the polar angle with respect to the electron beam direction. For electron identification we use a neural network algorithm [10] which uses twelve variables involving information from the central tracking system, the electromagnetic calorimeter and its pre-sampler. For the muon identification, two sets of selection criteria are used. For muon candidates combined to form J/ψ candidates in the $\mathrm{B_c^+} \to \mathrm{J}/\psi\pi^+$ and $\mathrm{B_c^+} \to \mathrm{J}/\psi \mathrm{a_1^+}$ modes we require a $\phi - \theta$ match between the extrapolated muon candidate track and a track segment reconstructed in the muon chamber, with a $\chi^2 < 3$ [11]. In addition, we require that the candidate muon track be the best match to the muon segment. When no matching to the muon segment is found, we search for a match with a track segment in the hadron calorimeter [12]. For all muon candidates combined to form $\mathrm{B_c} \to \mathrm{J}/\psi\ell\nu$ candidates we employ a "strong" muon identification [13]. In this selection we only use tracks matched with track segments in the muon detector, reject tracks identified as kaons, and apply an isolation cut by requiring that there be less than 20 track segments in the muon detector within 0.3 radians of the track. The overall efficiency for electron identification is about 77%. The efficiency for the normal muon identification is about 85%. The efficiency for the "strong" muon identification used in the $\mathrm{B_c} \to \mathrm{J}/\psi\ell\nu$ mode is 76%

Events are organised into jets of particles which are constructed using charged tracks and neutral clusters that are not associated to any charged track [14]. To form jets we use the scaled invariant mass jet-finding algorithm of JADE with a jet resolution parameter $y_{cut} = 0.04$.

We use a Monte Carlo simulation to determine the reconstruction and selection efficiencies for the various decay modes and for estimating the background level. The process $\mathrm{Z^0} \to \mathrm{b\bar{b}} \to \mathrm{B_c^+X}$ (fig. 1) and subsequent $\mathrm{B_c}$ meson decays are simulated using the JETSET 7.4 program [15]. In figure 2 is shown the prediction of reference [2] for the $\mathrm{B_c}$ momentum spectrum along with the JETSET 7.4 simulation of the $\mathrm{B_c}$ spectrum. In addition to simulating $\mathrm{B_c}$ production as described in reference [2], JETSET 7.4

includes the effect of the decay of excited levels of $\bar{\mathrm{b}}\mathrm{c}$ bound states. The two momentum distributions are similar. Also shown is the distribution for light b hadrons given by the Peterson fragmentation function with its parameter tuned to produce the measured $< x_E >$, indicating that the $\mathrm{B_c}$ spectrum is predicted to be considerably softer than that for the light b hadrons. The measured mean energy fraction ($< x_E >= E_B/E_{beam}$) for the light hadrons is $< x_E >= 0.695 \pm 0.006 \pm 0.008$ [16], while for the generated $\mathrm{B_c}$ meson we find $< x_E >= 0.54$. A sample of 2000 events was simulated for each of the following decay modes: $\mathrm{B_c^+} \to \mathrm{J}/\psi\pi^+$, $\mathrm{B_c^+} \to \mathrm{J}/\psi \mathrm{a_1^+}$, where $\mathrm{a_1^+} \to \rho^0\pi^+$ and $\rho^0 \to \pi^+\pi^-$, and the semileptonic mode $\mathrm{B_c^+} \to \mathrm{J}/\psi\ell^+\nu$, where ℓ denotes an electron or a muon.

A simulated event sample of 4×10^6 hadronic $\mathrm{Z^0}$ decays, nearly equal in size to the data sample, was used for studying the background processes. We use the JETSET 7.4 parton shower Monte Carlo generator to simulate the hadronic $\mathrm{Z^0}$ decays. For the fragmentation of heavy quarks into charmed and light b-flavored hadrons, we use the Peterson fragmentation function [17] with parameters tuned to the OPAL data [18]. All simulated events are passed through the full simulation of the OPAL detector [19]. Data and Monte Carlo simulated events are analysed using the same reconstruction programs.

4 Search for the $\mathrm{B_c}$ decays

We search for the decay modes $\mathrm{B_c^+} \to \mathrm{J}/\psi\pi^+$, $\mathrm{B_c^+} \to \mathrm{J}/\psi \mathrm{a_1^+}$, where $\mathrm{a_1^+} \to \rho^0\pi^+$ and $\rho^0 \to \pi^+\pi^-$, and the semileptonic mode $\mathrm{B_c^+} \to \mathrm{J}/\psi\ell^+\nu$. The analysis involves the reconstruction of J/ψ candidates in the leptonic mode $\mathrm{J}/\psi \to \ell^+\ell^-$, which are then combined with other tracks to form $\mathrm{J}/\psi\pi^+$, $\mathrm{J}/\psi\pi^+\pi^-\pi^+$, and $\mathrm{J}/\psi\ell^+$ combinations. The $\mathrm{J}/\psi\ell^+$ combination represents the charged track remnants of the mode $\mathrm{B_c^+} \to \mathrm{J}/\psi\ell^+\nu$. All tracks are required to be in the same jet.

4.1 Reconstruction of J/ψ Decays

The J/ψ meson decays are reconstructed in the leptonic modes $\mathrm{J}/\psi \to \mu^+\mu^-$, and $\mathrm{J}/\psi \to e^+e^-$. A pair of opposite sign electron or muon candidates in the same jet, with an invariant mass consistent with the J/ψ mass, is considered a J/ψ candidate. Muon candidates combined to form J/ψ candidates in the $\mathrm{B_c^+} \to \mathrm{J}/\psi\ell^+\nu$ mode must satisfy the additional criteria of the "strong" muon identification. Figure 3 shows the lepton pair invariant mass distributions for leptons selected with the normal lepton selection in the range 2.5 to 3.5 GeV/c^2, where the J/ψ peak is clearly visible in both e^+e^- and $\mu^+\mu^-$ modes. The peak position and width are consistent with the J/ψ mass and the expected resolution of the OPAL detector. J/ψ candidates are required to have an invariant mass within the range 2.9-3.3 GeV/c^2 for the $\mu^+\mu^-$ channel, and within the range 2.8-3.3 GeV/c^2 for the e^+e^- channel. The J/ψ candidates are kinematically constrained to the nominal J/ψ mass. We find a total of 551 $\mathrm{J}/\psi \to \mu^+\mu^-$ candidates and 354 $\mathrm{J}/\psi \to e^+e^-$ candidates using the normal lepton selection. We find 391 $\mathrm{J}/\psi \to \mu^+\mu^-$ candidates using the "strong" muon selection.

4.2 Selection of $\mathrm{B_c}$ Candidates

The dominant background to the sample of $\mathrm{B_c}$ candidates is from random combinations of J/ψ's from b hadron decays with other tracks from a b hadron decay or from the fragmentation tracks. Given the fact that at best a few events are expected in each channel, it is crucial that the combinatorial background be reduced to below the level of the expected signals. The selection criteria were developed by studying Monte Carlo simulated events containing the signal processes, as well as a simulated sample of hadronic $\mathrm{Z^0}$ events (described above). In general, a significant background suppression can be achieved by taking advantage of the hard momentum spectrum and the long lifetime of the b hadrons. However, the soft momentum spectrum of the $\mathrm{B_c}$ weakens the discrimination power of any momentum cut. Furthermore, since there is large uncertainty in the predictions of the $\mathrm{B_c}$ lifetime, we avoid any decay length cut. The criteria are described below:

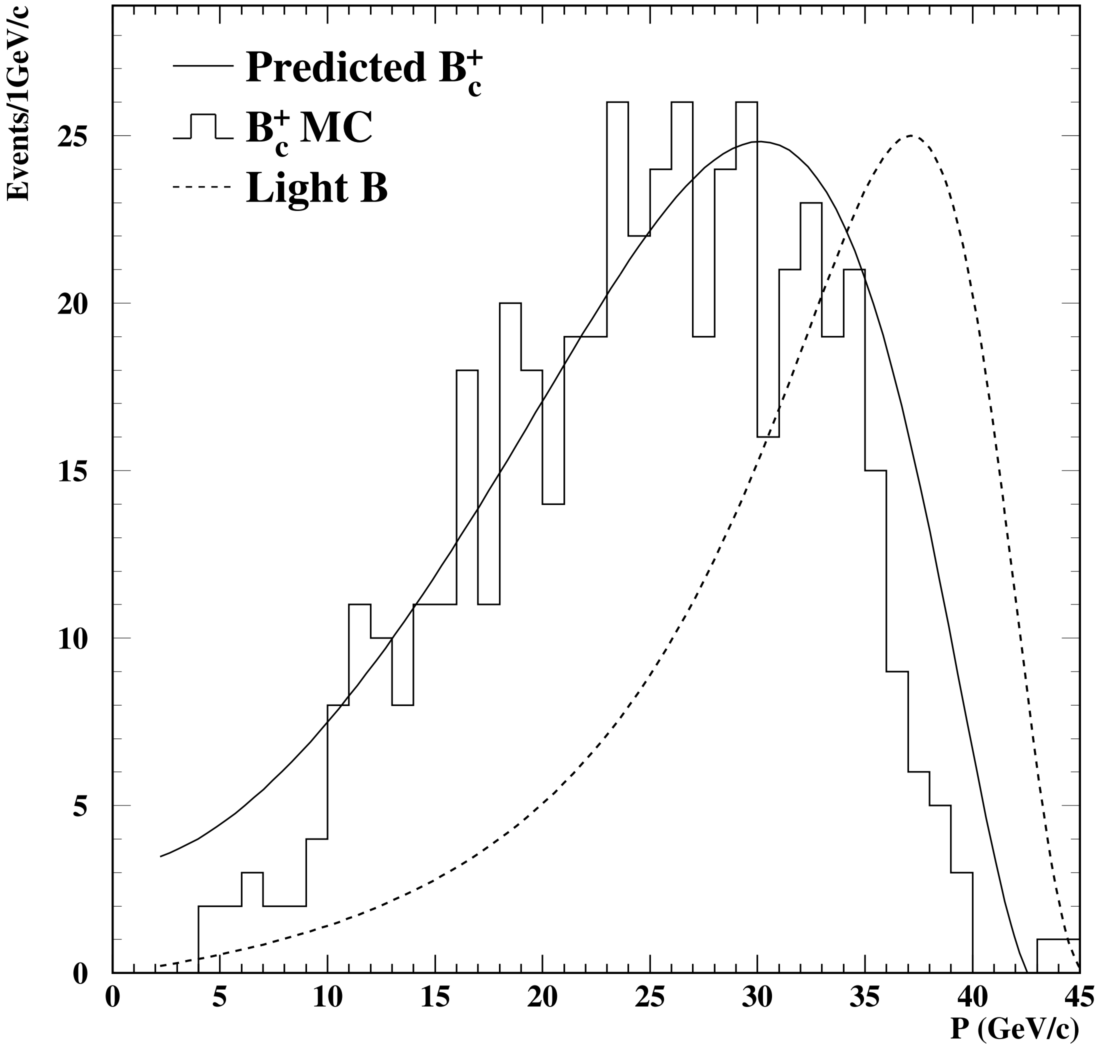

Figure 2: Momentum Spectrum of B_c mesons from the process $Z^0 \to b\bar{b} \to B_c^+X$. (a) According to the calculation of ref. 2 (Solid line). (b) According to JETSET 7.4 simulation (histogram). The momentum distribution of light B mesons in JETSET with parameters tuned to produce the measured $< x_E >$ (Dashed line).

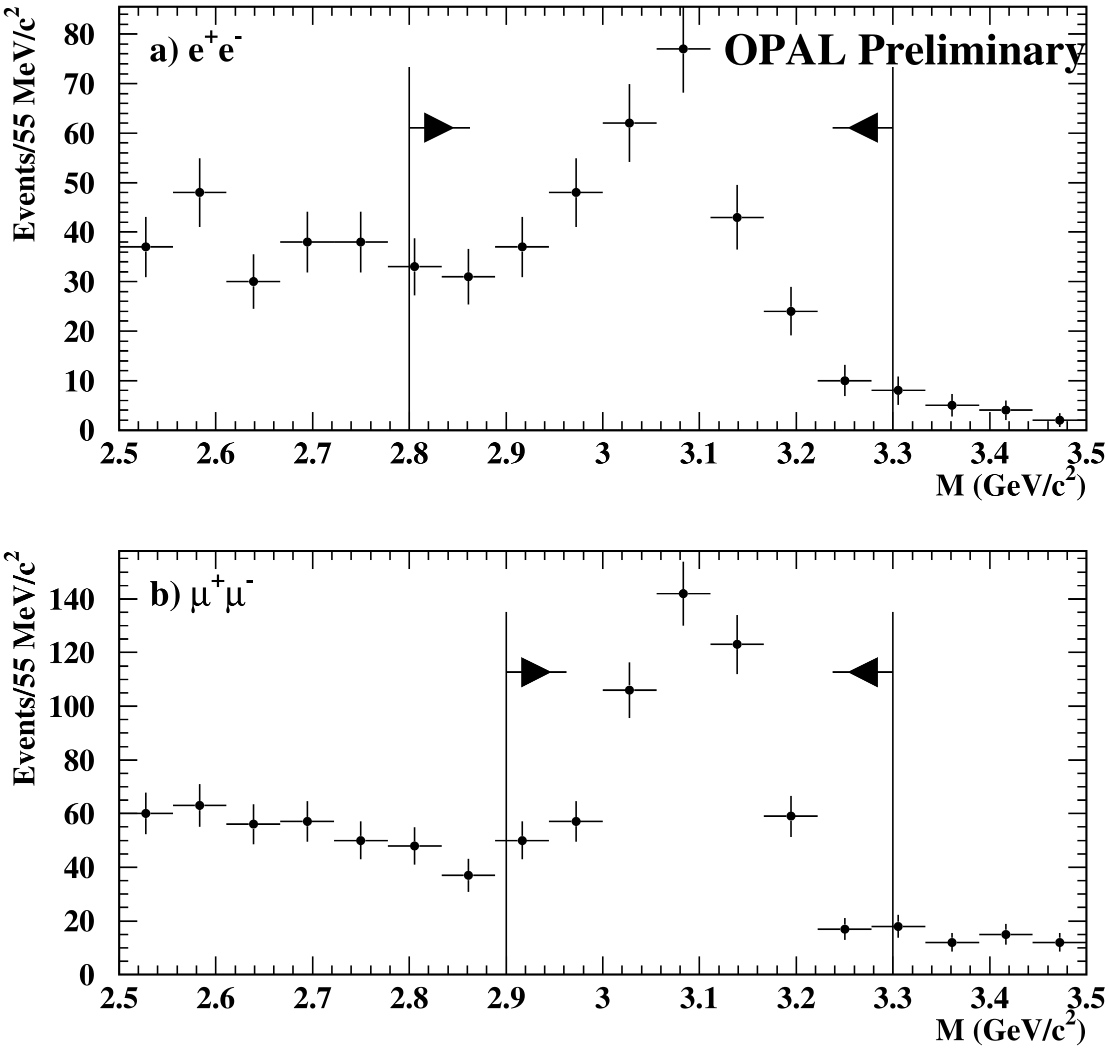

Figure 3: Invariant mass spectrum of (a) e^+e^-, and (b) $\mu^+\mu^-$ pairs. Also shown are the mass regions where the J/ψ candidates are defined.

a. For the exclusive modes, $J/\psi\pi^+$ and $J/\psi\pi^+\pi^-\pi^+$, we require that the dE/dx measurement for each pion candidate be "consistent" with a pion (as described in section 3).

b. For the inclusive mode $B_c \to J/\psi\ell^+\nu$, we impose "strong" lepton identification on all leptons. The momentum of the ℓ^+ lepton track (p) must satisfy a further requirement of $p > 4.0$ GeV/c^2.

c. For $J/\psi\pi^+\pi^-\pi^+$ combinations, we require that the three-pion combination be consistent with resulting from the decay $a_1^+ \to \rho^0\pi^+$, where $\rho^0 \to \pi^+\pi^-$. The invariant mass of the three pion combination must be consistent with the a_1 mass, $1.0 < M(\pi^+\pi^-\pi^+) < 1.6$ GeV/c^2, and the invariant mass of at least one of the two $\pi^+\pi^-$ pairs must be in the ρ^0 mass range, ($0.65 < M(\pi^+\pi^-) < 0.90$ GeV/c^2).

d. All tracks from the B_c must originate from the same decay vertex. For each B_c candidate we determine the decay vertex from the intersection of the tracks, including the tracks forming the J/ψ candidate, in the $x-y$ plane. We require the χ^2 probability of the vertex fit to exceed 1%.

e. Since the combinatorial backgrounds are largely at lower momenta, we impose a minimum momentum cut on the B_c candidates. For the $J/\psi\ell^+\nu$ mode, where the full momentum of the candidate is not reconstructed, we require the momentum of the $J/\psi\ell^+$ combination to exceed 30% of the beam energy. For the $J/\psi\pi^+$ combination we require the momentum of the B_c candidate to exceed 55% of the beam energy. For the $B_c^+ \to J/\psi a_1^+$ candidates, where the combinatorial background is more severe, the candidate momentum is required to exceed 70% of the beam energy.

f. For the exclusive modes, we take advantage of the fact that the decay products of a pseudoscalar meson are isotropically distributed in its rest frame. We define θ^* as the angle between the B_c candidate direction and the direction of the J/ψ in the B_c rest frame. Since, the combinatorial background mainly peaks near the backward direction ($\cos\theta^* = -1.0$) we require $\cos\theta^* > -0.8$.

g. For the exclusive modes, the invariant mass of the B_c candidates must be in the mass interval 6.0 GeV/c^2 to 6.5 GeV/c^2 (hereafter referred to as the signal region) which is centered at the predicted B_c mass, with a width which is about three times the B_c mass resolution (82 MeV/c^2) on each side. For the semileptonic mode, where due to the missing neutrino the full invariant mass cannot be calculated, the invariant mass of the $J/\psi\ell^+$ combination is used to define the signal region. The rarity of random combinations of three leptons in hadronic Z^0 decays combined with the high mass of the B_c produces a natural separation point between the signal and the background combinations. In figure 4 we show the invariant mass distribution for $J/\psi\ell^+$ combinations from a sample of simulated $B_c^+ \to J/\psi\ell^+\nu$ decays, along with the distribution of the combinatorial background from a simulated background event sample, equivalent in size to 30 times the data sample (see the following section for detail). Whereas the signal distribution peaks above 4.0 GeV/c^2, the background combinations are mostly at lower masses. Hence we restrict the signal region to the mass interval 4.0 to 6.5 GeV/c^2.

h. $B^+ \to J/\psi K^+$ decays can fake $B_c^+ \to J/\psi\ell^+\nu$ decays when the kaon is misidentified as a lepton. For the semileptonic mode we reject candidates that, when the third lepton candidate is assigned the kaon mass, have a reconstructed mass within 3σ ($\sigma = 57MeV/c^2$) of the measured mass of the B^+.

4.3 Estimation of Reconstruction Efficiencies and the Background Level

The reconstruction efficiencies are calculated from Monte Carlo generated event samples, with the B_c meson simulated at a mass of 6.25 GeV/c^2. The mass resolution is found to be 82 MeV/c^2 in the modes $J/\psi\pi^+$ and $J/\psi a_1^+$. The reconstruction efficiencies for these modes are $(10.3 \pm 0.7)\%$ and

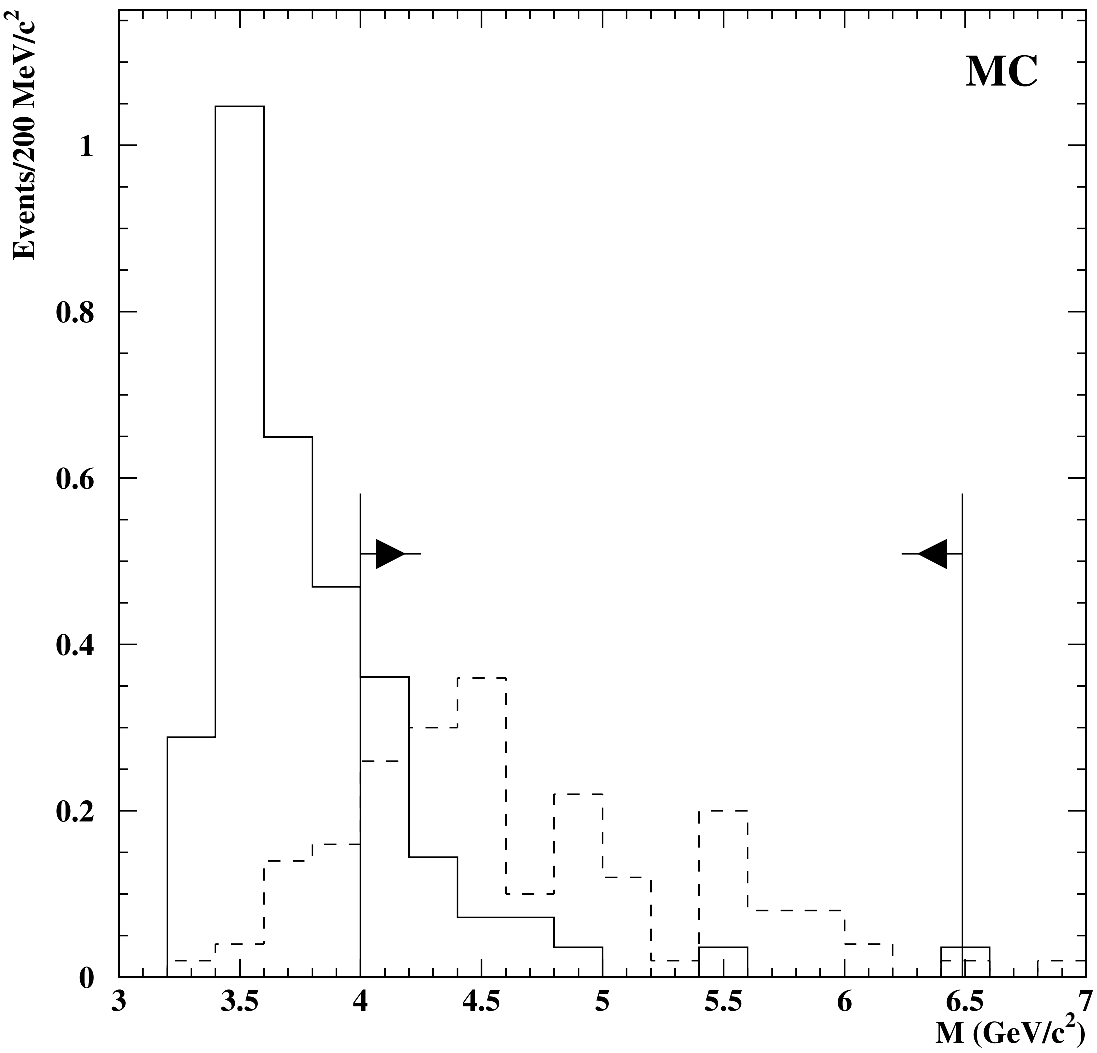

Figure 4: Invariant mass distribution of $\mathrm{J}/\psi\ell^+$ combinations for a simulated sample of $\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\ell^+\nu$ decays (dashed histogram), and combinatorial background from an enriched sample of Monte Carlo simulated $\mathrm{B} \to \mathrm{J}/\psi X$ events, normalised to the number of events expected in the data sample (solid histogram). The normalisation of the signal is arbitrary.

$(2.0 \pm 0.3)\%$, respectively, and $(5.5 \pm 0.6)\%$ for the semileptonic mode $B_c^+ \to J/\psi \ell^+ \nu$, where the errors are statistical. The reconstruction efficiency is sensitive to the B_c momentum distribution. An estimate of the size of this effect is found by comparing the efficiencies obtained for the JETSET predicted spectrum with those assuming the theoretical calculations of ref. [2]. In the $J/\psi\pi^+$ we find a difference of 2%. For the $J/\psi a_1^+$ mode, where a harder cut of $x_E > 0.7$ is applied, a difference of 14% is found. For the semileptonic mode we also find a difference of 14%. We take the systematic errors on the efficiencies to be one half of the difference for each mode.

The background level in these processes is determined by searching for B_c decays in the simulated hadronic Z^0 event sample. The invariant mass distributions of the B_c candidates which pass the above selection criteria (except the invariant mass requirement) are shown in figure 5. The signal regions for the $J/\psi\pi^+$ and $J/\psi\ell^+$ modes are empty. There is one simulated background event in the $J/\psi a_1^+$ signal region.

The background combinations below the signal region are dominated by the combinations of a real J/ψ with random tracks from a b hadron decay or from the fragmentation processes. The J/ψ mesons originate primarily from the decay of a b hadron, with a small fraction, $(4.8 \pm 1.7 \pm 1.1)\%$ [20], resulting from the fragmentation processes. In total, the simulated hadronic event sample contains 2,800 events containing a leptonic J/ψ decay. In order to improve the statistical significance of the background studies we apply the B_c search to a sample of 80,000 $B \to J/\psi X$ enriched events, where a $J/\psi \to \ell^+\ell^-$ decay is present in each event. This Monte Carlo set is equivalent to 30 times the size of the data sample. The resulting invariant mass distributions for the B_c candidates in the three modes are shown in figure 6. From these distributions we estimate the background level (see table 1) by counting the number of candidates in the signal region and normalising to the number of events expected in the data sample, using the measured rate $Br(Z^0 \to J/\psi X) = (3.9 \pm 0.2 \pm 0.3) \times 10^{-3}$ [5]. The uncertainty in the normalisation factor results in a systematic error of 9 % in the background estimates.

Decay Mode	Background Events
$B_c^+ \to J/\psi\pi^+$	$0.32 \pm 0.11 \pm 0.03$
$B_c^+ \to J/\psi a_1^+$	$1.37 \pm 0.22 \pm 0.13$
$B_c^+ \to J/\psi\ell^+\nu$	$0.90 \pm 0.18 \pm 0.08$

Table 1: Background estimates from sample of 80,000 $B \to J/\psi X$ enriched events. (First error is statistical and the second is systematic.)

5 Results and Upper Bounds on the Production Rates

In figure 7 we show the invariant mass distributions of the $J/\psi\pi^+$, $J/\psi a_1^+$, and $J/\psi\ell^+\nu$ candidates in the data sample. The shapes and overall levels of the distributions below the signal regions are consistent with the distributions obtained from the simulated background samples. In the mode $J/\psi\pi^+$ we find two events in the signal range 6.0 to 6.5 GeV/c^2. The invariant masses of the two B_c candidates are 6.29 ± 0.17 GeV/c^2 and 6.33 ± 0.063 GeV/c^2. The reconstructed decay times of the two candidates are $\tau = -0.06 \pm 0.19$ ps and $\tau = 0.09 \pm 0.10$ ps respectively. The estimated background in this mode is 0.32 ± 0.11 events. The probability for a background of 0.32 events to fluctuate to 2 is 4.1%. In the mode $J/\psi\ell^+\nu$ we find one event in the signal region. The mass of the candidate $J/\psi\ell^+$ combination is 5.76 GeV/c^2. The momentum is 15.4 GeV/c. The reconstructed decay length is 0.14 ± 0.14 cm. The estimated background in this mode is 0.90 ± 0.20 events. In the signal region above the mass of the candidate event, 5.76 to 6.5 GeV/c^2, the probability to observe one event from background is 3.6%, while the efficiency is reduced to $(0.6 \pm 0.2)\%$. There are

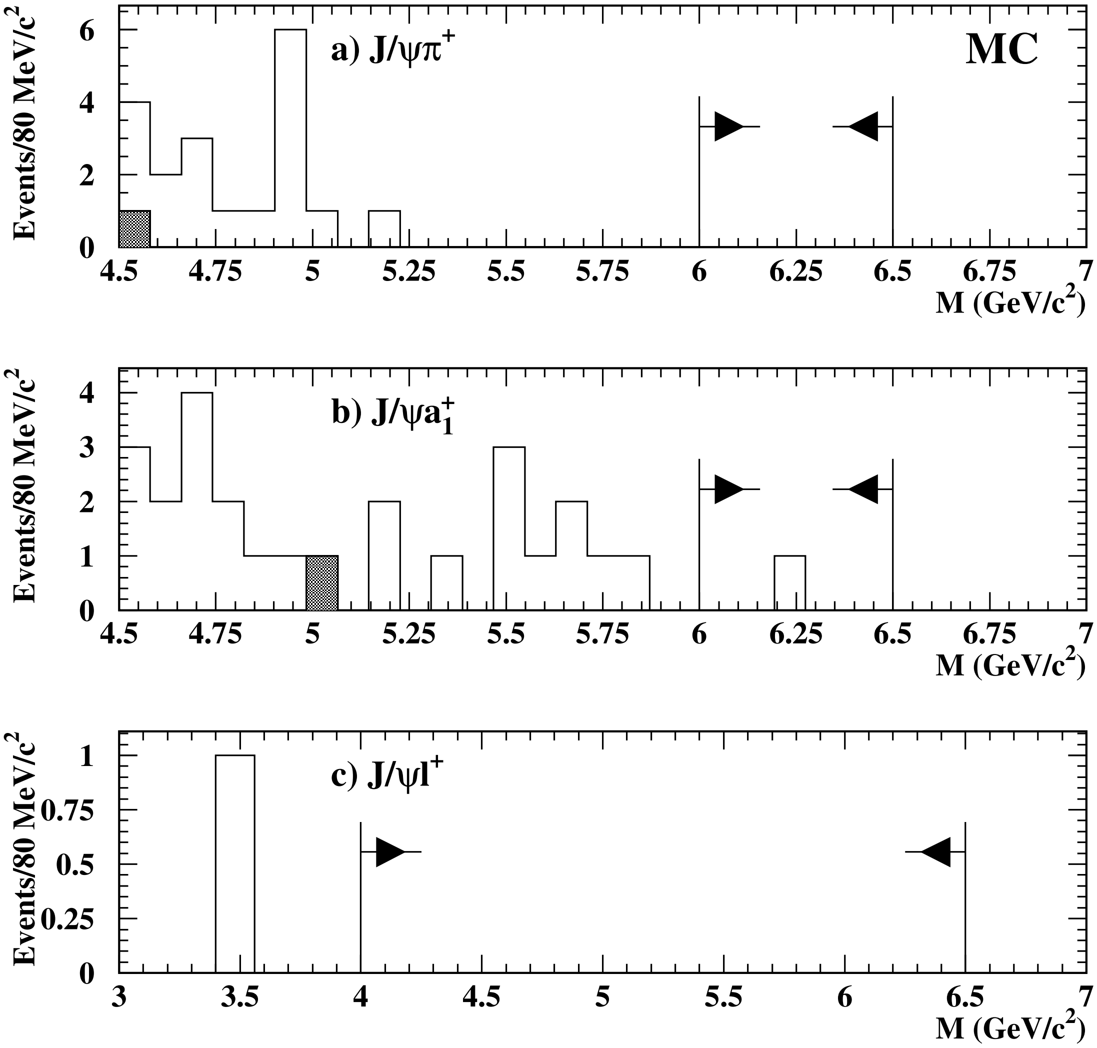

Figure 5: Invariant mass distribution of (a) $\mathrm{J}/\psi\pi^+$ combinations, (b) $\mathrm{J}/\psi\mathrm{a}_1^+$ combinations, and (c) $\mathrm{J}/\psi\ell^+$ combinations in the sample of simulated hadronic Z^0 decays, equivalent in size to the data sample. The shaded area indicates J/ψ candidates that are not real $\mathrm{J}/\psi \to \ell^+\ell^-$ decays. The open histogram shows the combinations from real $\mathrm{J}/\psi \to \ell^+\ell^-$ decays.

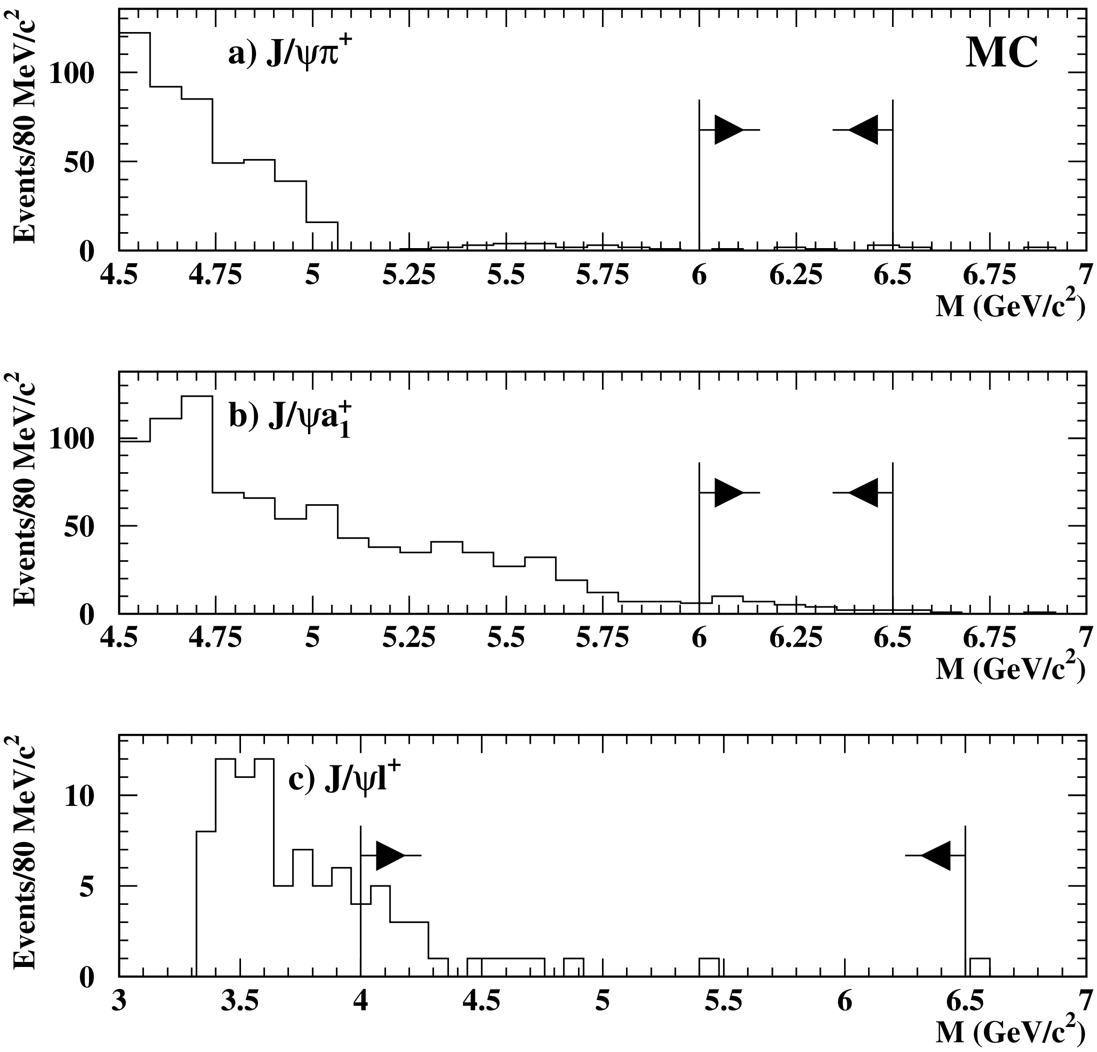

Figure 6: Invariant mass distribution of (a) $\mathrm{J}/\psi\pi^+$ combinations, (b) $\mathrm{J}/\psi\mathrm{a}_1^+$ combinations, and (c) $\mathrm{J}/\psi\ell^+$ combinations in the simulated $\mathrm{B} \to \mathrm{J}/\psi X$ enriched event sample (equivalent to 30 times the data sample).

no candidate events in the $J/\psi a_1^+$ mode in the signal region compared with an estimated background of 1.37 $\pm$ 0.25.

We determine an upper bound at 90% confidence level on the number of events in each channel by applying Poisson statistics to the number of events observed in the signal region, without background subtraction. This is then used to calculate an upper limit on the production rate from:

$$f(\bar{b} \to B_c^+) \times Br(B_c^+ \to \text{final state}) = N(\text{at } 90\% \text{ c.l.}) \times \frac{\epsilon_{had}}{(N(Z^0) \times \epsilon \times Br(J/\psi \to \ell^+\ell^-) \times 2 \times R_b)}$$

where, $N(Z^0)$ is the total number of hadronic Z^0 events in the data sample; ϵ_{had} is the hadronic event selection efficiency, 0.981 $\pm$ 0.005; ϵ is the reconstruction efficiency for each mode; $Br(J/\psi \to \ell^+\ell^-)$ is the branching ratio for the leptonic decays of J/ψ, $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$, 0.1203 $\pm$ 0.0028 [21]; and $R_b = \Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to q\bar{q})$, 0.2179 $\pm$ 0.0012 [22]. For the mode $B_c^+ \to J/\psi a_1^+$, we also account for the branching ratio $Br(a_1^+ \to \rho^0\pi^+) = 0.5$. The total systematic uncertainties on the branching ratio upper limits for each mode are shown in table 2, where the main contribution is due to the uncertainties in the reconstruction efficiencies. These systematic uncertainties are included in the following 90% confidence level upper limits using the technique of ref. [23]:

Decay Mode	Total Error
$B_c^+ \to J/\psi\pi^+$	7.3 %
$B_c^+ \to J/\psi a_1^+$	15.5 %
$B_c^+ \to J/\psi\ell^+\nu$	13.2 %

Table 2: Summary of systematic errors on branching ratio upper limit.

$$f(\bar{b} \to B_c^+) \times Br(B_c^+ \to J/\psi\pi^+) < 2.29 \times 10^{-4},$$
$$f(\bar{b} \to B_c^+) \times Br(B_c^+ \to J/\psi a_1^+) < 1.08 \times 10^{-3},$$
$$f(\bar{b} \to B_c^+) \times Br(B_c^+ \to J/\psi\ell^+\nu) < 1.60 \times 10^{-4},$$

where the branching ratio for the mode $B_c^+ \to J/\psi\ell^+\nu$ is for decay to either $J/\psi\ e^+\nu$ or $J/\psi\mu^+\nu$.

If we interpret the two candidate events in the $B_c^+ \to J/\psi\pi^+$ mode as signal we find a product branching ratio of,

$$f(\bar{b} \to B_c^+) \times Br(B_c^+ \to J/\psi\pi^+) = (8.5 \pm 6.0 \pm 0.6) \times 10^{-5}.$$

6 Conclusion

We have performed a search for the B_c meson decays with the OPAL detector at LEP. We find two candidate $B_c \to J/\psi\pi^+$ decays in a mass window around the theoretical prediction of the B_c mass, compared with an estimated background of 0.32 ± 0.11 events in this mode. The weighted average of the mass of the two candidates is 6.32 ± 0.06 GeV/c^2, which is consistent with the predicted mass of the B_c meson. We find one candidate event in the mode $B_c^+ \to J/\psi\ell^+\nu$, with a $J/\psi\ell^+$ mass of 5.76 GeV/c^2. The estimated background in this mode is 0.90 ± 0.20 events. We have also searched for the decay $B_c^+ \to J/\psi a_1^+$, but no candidate events were observed. We set upper bounds at the 90%

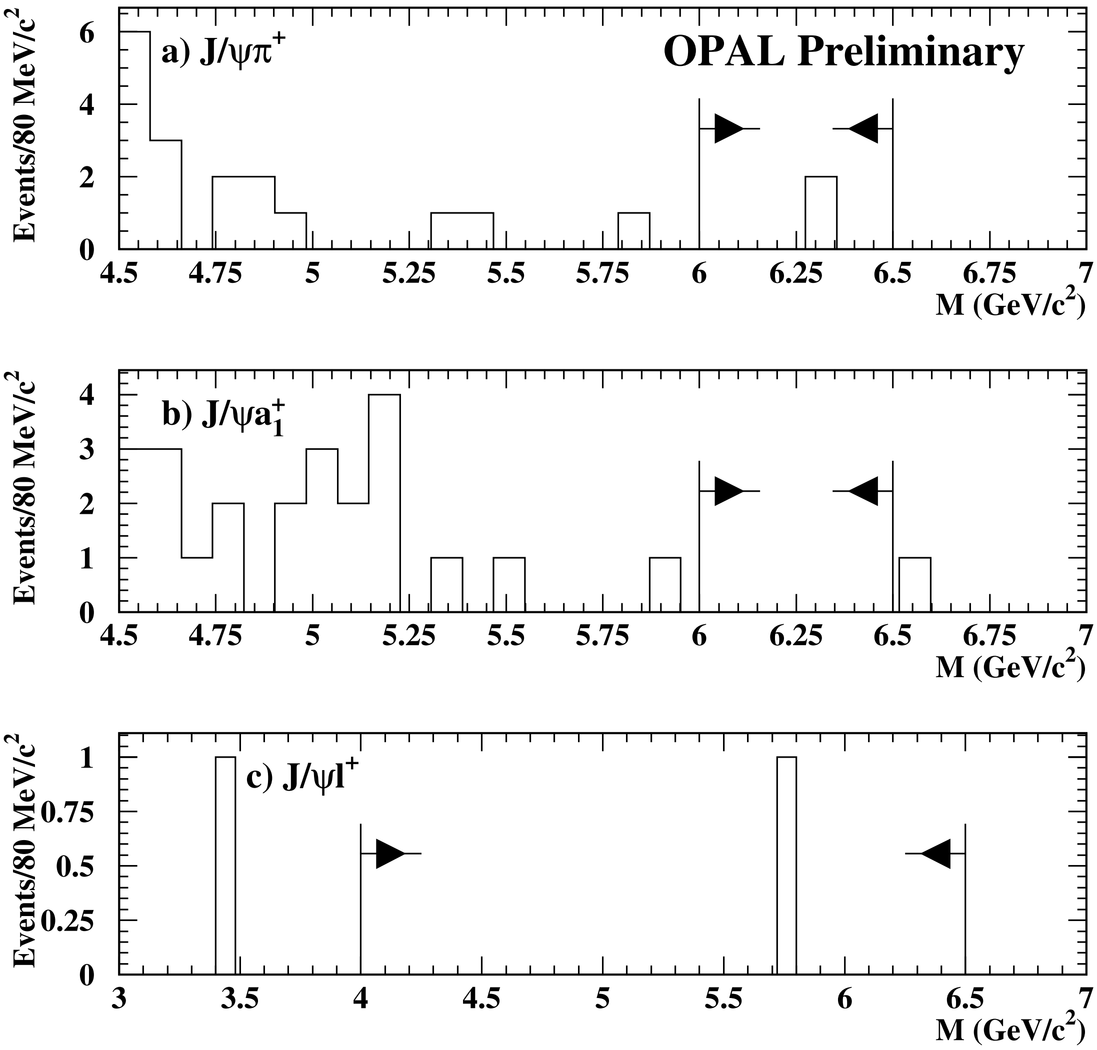

Figure 7: Invariant mass distribution of (a) $J/\psi\pi^+$ candidates, (b) $J/\psi a_1^+$ candidates, and (c) $J/\psi\ell^+$ candidates in the data sample.

confidence level on the production rates of these processes,

$$f(\bar{\mathrm{b}} \to \mathrm{B}_\mathrm{c}^+) \times \mathrm{Br}(\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\pi^+) \ < \ 2.29 \times 10^{-4},$$
$$f(\bar{\mathrm{b}} \to \mathrm{B}_\mathrm{c}^+) \times \mathrm{Br}(\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi \mathrm{a}_1^+) \ < \ 1.08 \times 10^{-3},$$
$$f(\bar{\mathrm{b}} \to \mathrm{B}_\mathrm{c}^+) \times \mathrm{Br}(\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\ell^+\nu) \ < \ 1.60 \times 10^{-4}.$$

The branching ratio limits for the $\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\pi^+$ and $\mathrm{B}_\mathrm{c}^+ \to \mathrm{J}/\psi\ell^+\nu$ mode are comparable with the limits reported by the other LEP collaborations [24][25].

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