# Search for the $b\_c$ meson in hadronic Z decays

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# Search for the $B_c$ meson in hadronic Z decays

*The ALEPH Collaboration* [1]

## Abstract

A search for the $B_c$ meson decaying into the channels $J/\psi\pi^+$ and $J/\psi\ell^+\nu_\ell$ ($\ell = e$ or $\mu$) is performed in a sample of 3.9 million hadronic Z decays collected by the ALEPH detector. This search results in the observation of 0 and 2 candidates in each of these channels, respectively, while 0.44 and 0.81 background events are expected. The following 90% confidence level upper limits are derived:

$$\frac{\mathrm{Br}(Z \to B_c X)}{\mathrm{Br}(Z \to q\bar{q})}\mathrm{Br}(B_c^+ \to J/\psi\pi^+) \quad < \quad 3.6 \times 10^{-5},$$
$$\frac{\mathrm{Br}(Z \to B_c X)}{\mathrm{Br}(Z \to q\bar{q})}\mathrm{Br}(B_c^+ \to J/\psi\ell^+\nu_\ell) \quad < \quad 5.2 \times 10^{-5}.$$

Another $B_c^+ \to J/\psi(e^+e^-)\mu^+\nu_\mu$ candidate with very low background probability, found in an independent analysis, is also described in detail.

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# 1 Introduction

The $B_c$ meson is the last ground state meson with two unlike flavour quarks still to be observed. Its properties are expected to be very different from those of the other b hadrons because it contains two non-relativistic heavy quarks of different heavy flavour. Its mass can be predicted rather accurately via potential models by interpolation between the charmonium and bottomonium spectroscopy [1]. For this analysis, the conservative theoretical range 6.20 to 6.30 GeV/$c^2$ was chosen.

The $B_c$ production rate predictions (including cascades through excited states) range from 100 to 700 $B_c$ per million hadronic Z decays [2, 3]. The $B_c$ can decay according to three main processes with comparable partial widths: annihilation, b quark spectator decay and c quark spectator decay. The predictions for the $B_c$ lifetime range from 0.4 ps to 1.4 ps [4, 5, 6]. It is therefore preferable to avoid in this analysis any lifetime related cuts. The individual branching fractions of the $B_c$ are also poorly predicted, but the presence of a c quark in the initial state favours the production of a J/$\psi$ in the final state by a factor of ten to twenty with respect to the inclusive decay of the other b hadrons.

The present analysis searches for the $B_c$ in the decays[2] $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to J/\psi\ell^+\nu_\ell$ ($\ell = e$ or $\mu$), where the J/$\psi$ decays leptonically giving a very clean signature. The branching fractions are predicted to be respectively 0.2 to 0.4% and 1 to 3% [4, 6, 7]. The number of events expected to be produced with the current ALEPH statistics and taking into account the J/$\psi$ leptonic branching ratio are in the ranges 0.1 to 1.2 and 1 to 20 events, respectively. The selection criteria were optimised to give the best expected upper limit, following the prescription of Ref. [8]. Similar searches for $B_c$ have been performed at LEP [9, 10] and at CDF [11].

# 2 The ALEPH detector

The ALEPH detector and its performance are described in detail in Ref. [12]; only a brief description of the apparatus properties is given in this section. Charged particles are detected in the central part of the detector with three concentric devices, a precision vertex detector (VDET), a multi-wire drift chamber (ITC) and a large time projection chamber (TPC). Surrounding the beam pipe, the VDET consists of two concentric layers of double-sided silicon detectors, positioned at average radii of 6.5 cm and 11.3 cm, and covering 85% and 69% of the solid angle, respectively. The intrinsic spatial resolution of the VDET is 12 $\mu$m for the $r\phi$ coordinate and between 11 $\mu$m and 22 $\mu$m for the $z$ coordinate, depending on the polar angle of the charged particle. The ITC, at radii between 16 cm and 26 cm, provides up to 8 coordinates per track in the $r\phi$ view while the TPC measures up to 21 three-dimensional points per track at radii between 30 cm and 180 cm. The TPC also serves to identify charged particle species with up to 338 measurements of the specific ionization (dE/dx). The three detectors are immersed in an axial magnetic field of 1.5 T and together provide a transverse momentum resolution of $\sigma(P_t)/P_t = 0.0006 P_t \oplus 0.005$ ($P_t$ in GeV/$c$).

[2] The charge conjugate decays are implicit throughout this note.

Electrons and photons are identified in the electromagnetic calorimeter (ECAL), a lead-proportional chamber sandwich segmented into $0.9° \times 0.9°$ projective towers which are read out in three sections in depth. Muons are identified in the hadron calorimeter (HCAL), a 7 interaction length yoke interleaved with 23 layers of streamer tubes, together with two additional double layers of muon chambers.

The analysis presented in this letter is based on 3.9 million hadronic Z decays recorded from 1991 to 1995. The selection of hadronic events is based on charged particles [13]. The interaction point is reconstructed on an event by event basis using the constraint of the position and size of the luminous region [14].

# 3 J/$\psi$ selection

The J/$\psi \to \ell^+\ell^-$ candidates are selected with criteria close to those already used in Ref. [15], starting with the identification of two leptons of opposite charge and momentum greater than 2 GeV/$c$. Electrons are identified from estimators of the longitudinal and transverse shape of the energy deposition in the ECAL and from the specific ionization estimator, when available [16]. All estimators are required to be greater than -2.5 standard deviations from the expectation for an electron. The electron momentum is then corrected for possible energy loss by adding the energy of any photon found in the electromagnetic calorimeter which is consistent with having been radiated by the electron. Muons are identified from their hit pattern in the HCAL and muon chambers [16].

Since in Z decays the $B_c$ has a softer momentum spectrum than the other b hadrons (due to the additional $c\bar{c}$ pair required in the event), J/$\psi$'s from $B_c$ decays have on average a momentum 25% smaller than those from other b hadrons; for this reason, no momentum cut is applied to the $\ell^+\ell^-$ pair. The angle between the two identified leptons is required to be smaller than 90°, and the leptons are required to form a vertex with a probability in excess of 1%. At least one of the leptons is required to have one or more three-dimensional VDET hits. J/$\psi$ candidates are retained if the $\ell^+\ell^-$ invariant mass is between 3.0 and 3.2 GeV/$c^2$. For background studies, events in which the $e^+e^-$ or $\mu^+\mu^-$ pair invariant mass lies between 2 and 2.8 GeV/$c^2$, and events in which the $e^\pm\mu^\mp$ pair invariant mass lies between 2 and 4 GeV/$c^2$, are also retained and are hereafter referred to as "sideband" events.

The efficiency of this event selection is measured on a relevant signal Monte Carlo event sample, generated with JETSET 7.4 [17]. The $B_c$ momentum spectrum in this sample agrees well with the prediction of Ref. [3]. The events are processed through a detailed detector simulation. The J/$\psi$ reconstruction efficiency is 26% for J/$\psi \to e^+e^-$ and 33% for J/$\psi \to \mu^+\mu^-$ in the $B_c^+ \to$ J/$\psi$X channels. The selected $\ell^+\ell^-$ sample is composed mainly of J/$\psi$'s from the decay of b hadrons. The remainder has two components: (*i*) genuine prompt J/$\psi$'s contributing $(4.8 \pm 2.4)$% [18], coming dominantly from gluon fragmentation [19, 20, 21], and also from c quark fragmentation [21, 22] and (*ii*) combinatorial background, which consists mainly of events in which either the two leptons come from cascade decays ($b \to \ell^- c \to \ell^+\ell^- s$) or one of the two leptons is actually a misidentified hadron. Since background (*ii*) tends to have a substantial missing energy,

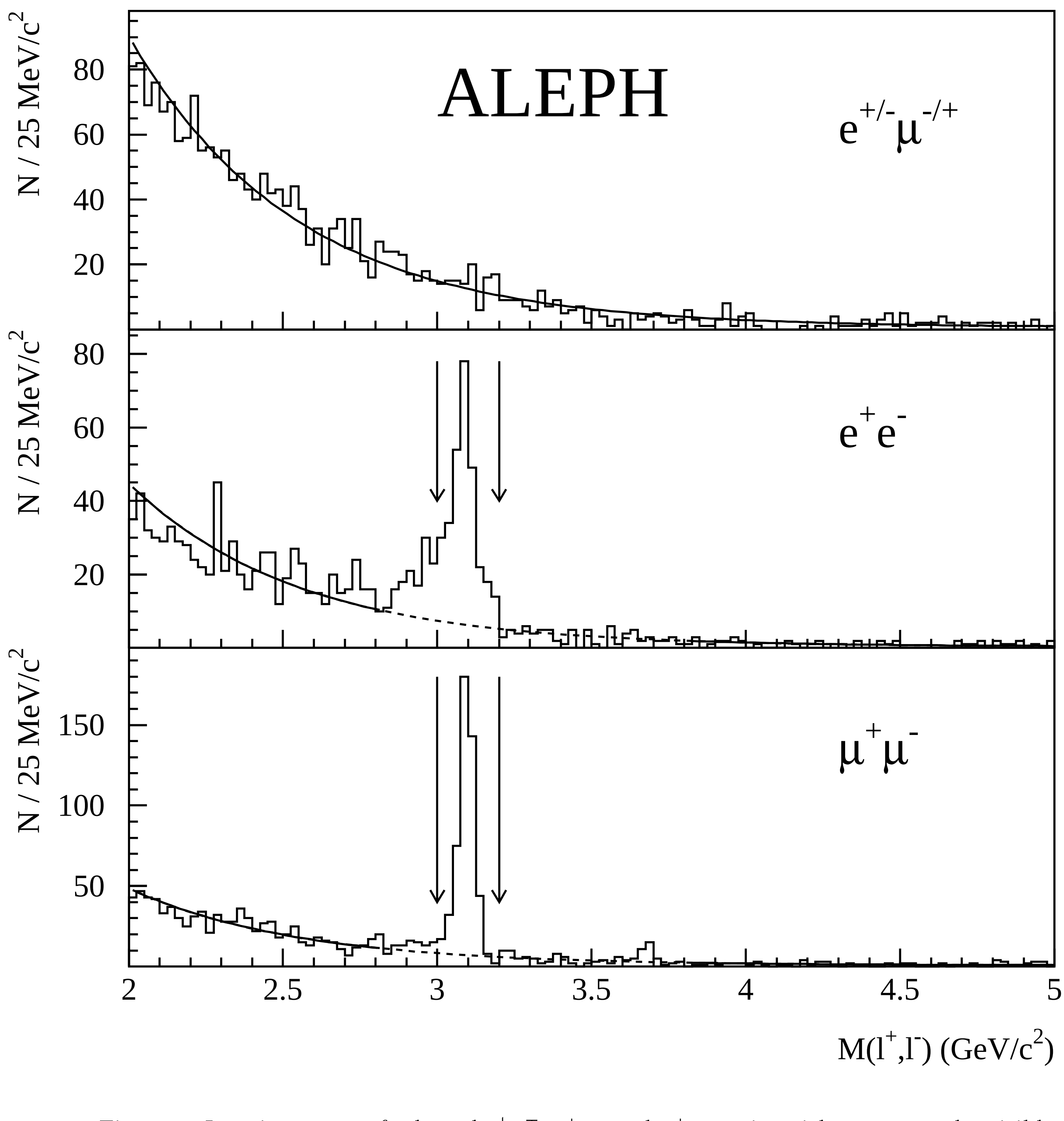


Figure 1: Invariant mass of selected $e^{\pm}\mu^{\mp}$, $e^+e^-$ and $\mu^+\mu^-$ pairs with no cut on the visible energy. The arrows define the mass window for the J/$\psi$ signal. The curves show the fit used to estimate the background below the J/$\psi$ peak.

the visible energy in the J/$\psi$ hemisphere is required to exceed 85% of the beam energy for the neutrinoless $B_c^+ \to J/\psi\pi^+$ channel.

The invariant mass distributions of the final lepton pair samples are shown in Fig. 1. Since the background in the two J/$\psi$ leptonic channels is similar, they are considered together in the following. The total number of events selected when no visible energy cut is applied is 809, with a combinatorial background fraction of 13%, estimated as in Ref. [15]. This is reduced to 695, with a combinatorial background fraction of 8%, when the visible energy cut is applied.

# 4 The $B_c^+ \to J/\psi\pi^+$ channel

Since the $B_c$ is significantly heavier than the other b hadrons, the main background to the $B_c^+ \to J/\psi\pi^+$ channel is the association of a real J/$\psi$ with a charged particle unrelated to the parent B. A requirement that the three tracks form a common vertex therefore efficiently removes most of this background. The topology of the remaining background events is kinematically similar to that of events in which the two leptons come from a cascade $b \to c\ell^- \to s\ell^+\ell^-$. This allows an evaluation of the background directly from the data using the sideband events defined previously.

## 4.1 Selection

The $B_c^+ \to J/\psi\pi^+$ candidates are selected by associating a J/$\psi$ candidate to a charged particle not identified as a lepton, with a momentum in excess of 4 GeV/$c$, a specific ionization between $-2$ and $+3$ standard deviations of that expected for a pion, and not consistent with coming from a $K_S^0$ or $\Lambda$ decay. The pion candidate is required to be within a 45° cone around the J/$\psi$ momentum direction. The total $J/\psi\pi^+$ momentum is required to be greater than 20 GeV/$c$. The $\ell^+\ell^-\pi^+$ common vertex is required to have a probability above 1%. Requiring that the $(J/\psi\pi^+)$ decay length divided by its uncertainty be greater than two would cause a loss of efficiency between 30% and 14% if the lifetime of the $B_c$ is within the range 0.4 ps to 1.4 ps; this demonstrates that a decay-length cut is to be avoided. Finally, the mass of the $B_c$ candidate, calculated at the $B_c$ vertex after constraining the $\ell^+\ell^-$ pair to the J/$\psi$ mass, is required to lie in the window 6.15 to 6.35 GeV/$c^2$. This mass window was defined by widening at both ends the theoretical mass range by twice the expected experimental resolution of 25 MeV/$c^2$.

The overall $B_c^+ \to J/\psi\pi^+$ efficiency averaged over the two J/$\psi$ leptonic channels is $(13.6 \pm 1.4)$%. The systematic uncertainties on this efficiency are detailed in Table 1. The vertex probability cut and VDET hit requirement efficiencies are estimated by comparison of these efficencies for J/$\psi$'s in data and Monte carlo simulation. The uncertainty on the lepton identification is taken to be 2% per lepton (based on Ref. [16]). The uncertainty on the $(\ell^+\ell^-)$ mass cut efficiency is estimated to be 5% for the decay $J/\psi \to e^+e^-$, from the comparison of the shape of the peak between data and Monte Carlo. The effect of a possible 100 MeV shift in the missing energy calibration [23] is measured by changing accordingly the position of the cut on missing energy. The uncertainties on the $B_c$ and $B_c^*$

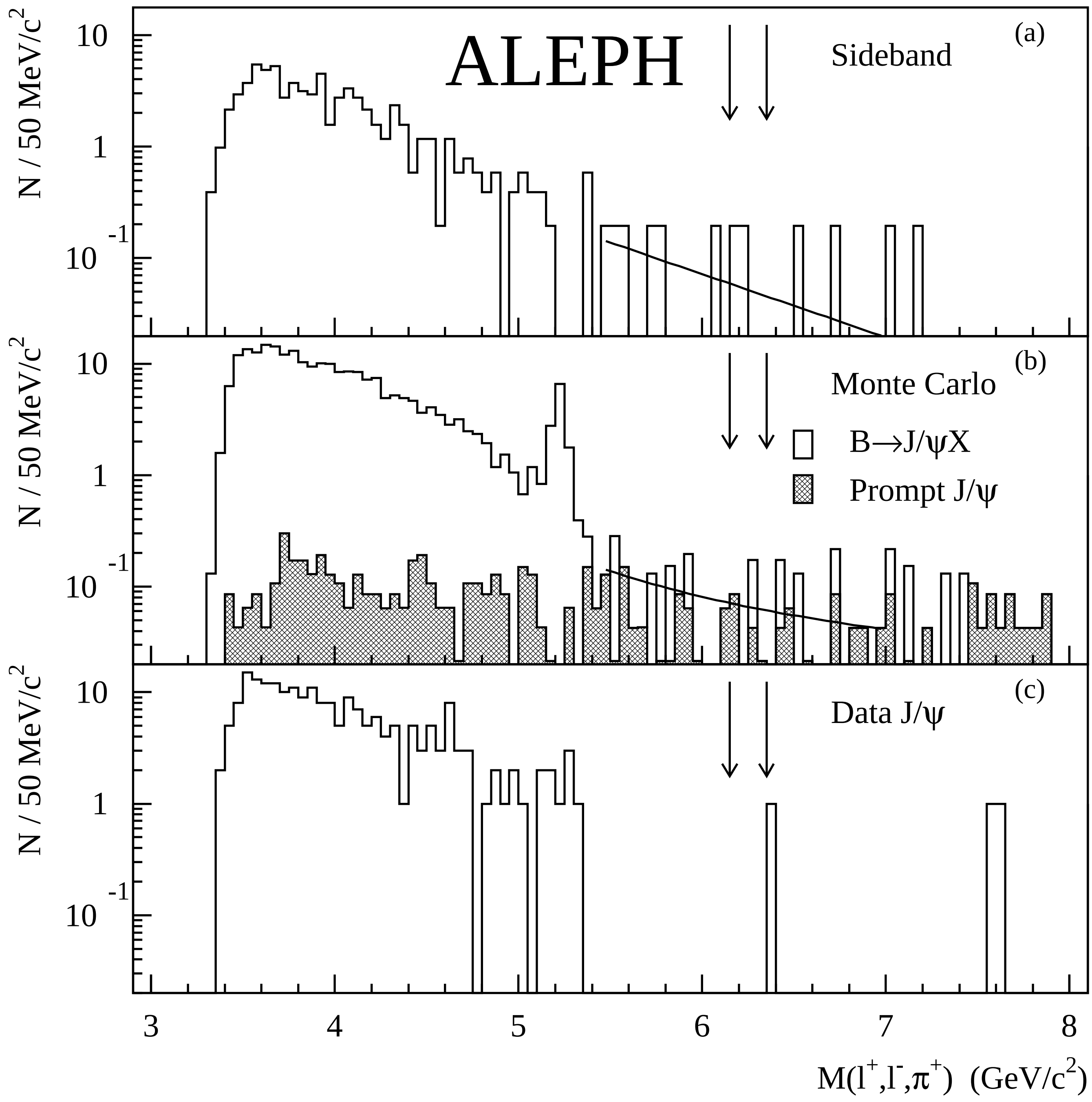


Figure 2: The $\ell^+\ell^-\pi^+$ mass spectrum for (a) the sideband events and (b) the J/$\psi$ Monte Carlo events normalized to the data; the solid lines show the result of the fits used to estimate the number of background events in the mass window shown by the arrows. Figure (c) is the data $\ell^+\ell^-\pi^+$ mass spectrum for the J/$\psi$ candidates. The excess seen in the two lower plots at a mass around 5.3 GeV/$c^2$ is due to genuine $B^+ \to J/\psi K^+$ events.

Table 1: Systematic uncertainties on the efficiencies.

| Channel | $B_c^+ \to J/\psi\pi^+$ | $B_c^+ \to J/\psi\ell^+\nu_\ell$ |
|---|---|---|
| Vertex | 4% | 4% |
| $\ell$ identification | 4% | 6% |
| $(\ell^+\ell^-)$ mass | 2% | 2% |
| Missing energy | $< 1\%$ | $< 1\%$ |
| b fragmentation | 4% | 3% |
| MC statistics | 7% | 6% |
| Total | 10% | 10% |

momentum spectra are evaluated from the difference between the predictions of JETSET 7.4 Monte Carlo simulation and that given in Ref. [3]. The uncertainties on the $B_c$ lifetime and mass have no impact.

## 4.2 Background estimation

The $B \to J/\psi X$ background is estimated using the sideband events corresponding to 5 times the number of $J/\psi$ candidates. The $\ell^+\ell^-\pi^+$ mass spectrum is shown in Fig. 2a. The number of background events is estimated by fitting the invariant mass spectrum between 5.5 and 7 GeV/$c^2$ to an exponential, and integrating the resulting function over the $B_c$ mass window. The expected number of background events is determined to be $0.29 \pm 0.08$ from the data sidebands. As a check, a consistent estimate of $0.17 \pm 0.05$ is obtained using a sample of 17000 fully simulated $B \to J/\psi X$ events, where B is not a $B_c$, corresponding to 8 times the number of $J/\psi$ candidates (see Fig. 2b).

The prompt $J/\psi$ background is estimated from simulated events. The gluon fragmentation component yields a background of $0.10 \pm 0.05$ events, while the c quark fragmentation component yields a background of $0.05 \pm 0.03$ events (see Fig. 2b).

## 4.3 Results

The mass spectrum from the data is shown in Fig. 2c. No events are seen in the mass window. One event is found with a mass of 6.39 GeV/$c^2$, which is just above the predefined window. The reconstructed decay length is $-0.05 \pm 0.13$ mm, making this event consistent with the association of a $J/\psi$ from a short-lived b hadron with a fragmentation track. The total background is expected to be $0.44 \pm 0.11$ events. Using $\mathrm{Br}(J/\psi \to \ell^+\ell^-) = (6.01 \pm 0.19)\%$ [24], the above quoted efficiency with its uncertainty and the hadronic event selection efficiency $97.40 \pm 0.24\%$ [13], the resulting 90% confidence level upper limit is

$$\mathrm{Br}_{\mathrm{had}}(Z \to B_c X)\ \mathrm{Br}(B_c^+ \to J/\psi\pi^+) < 3.6 \times 10^{-5},$$

where $\mathrm{Br}_{\mathrm{had}}(Z \to B_c X) = \mathrm{Br}(Z \to B_c X)/\mathrm{Br}(Z \to q\overline{q})$.

# 5 The $B_c^+ \to J/\psi \ell^+ \nu_\ell$ channel

The background to the $B_c^+ \to J/\psi \ell^+ \nu_\ell$ channel is primarily due to the association of a real $J/\psi$ with a fake or non-prompt lepton coming either from fragmentation or from the b hadron parent of the $J/\psi$. Additional background arises from cascade decay events in which one lepton is associated to a misidentified hadron to form a $J/\psi$, and subsequently associated with the other lepton to form the $B_c$. Finally, there is some background from prompt leptons coming either from a secondary $c\bar{c}$ pair or from the second b hadron if a very hard gluon causes the two B's to be topologically close to each other. As already mentioned for the $J/\psi\pi^+$ channel, a common vertex requirement reduces all the backgrounds where the lepton and the $J/\psi$ do not come from the same vertex. It also reduces the muon contamination from in-flight decay and the electron contamination from photon conversion. The final tagging relies on an event-by-event estimate of the parent $B_c$ mass from the missing energy in the hemisphere and from the $J/\psi\ell^+$ four-momentum.

## 5.1 Selection

Since the $B_c$ is actually tagged by the presence of a third lepton in addition to the $J/\psi$ lepton pair, a more restrictive lepton identification with respect to the two first leptons is required. For muons, the track extrapolated to the muon chambers is required to be well separated from the hits associated to the muons from the $J/\psi$ and its distance to its associated muon chamber hits is required to be less than 2.5 standard deviations. Furthermore, to reduce the high contamination from kaons in this topology, the specific ionization estimator is required to be available and more than one standard deviation away from the kaon hypothesis. These additional cuts remove 80% of the fake muons with a 20% loss in signal efficiency. For electrons, the specific ionization estimator is required to be available and the combined probability of the ECAL and specific ionization estimators is required to be in excess of 5%. These additional requirements remove 90% of the fake electrons with a 13% loss in signal efficiency. This third lepton is required to be in a 45° cone around the $J/\psi$ momentum direction and have at least one three-dimensional VDET hit. The total $J/\psi\ell^+$ momentum is required to be greater than 10 GeV/$c$. The three-lepton common vertex is required to have a probability in excess of 1%.

Finally, a consistency between the $J/\psi\ell^+$ four-momentum and the missing energy in the $J/\psi$ hemisphere is required as described below. The neutrino in the $B_c$ rest frame has a flat angular distribution, which is not biased by any of the kinematical cuts applied. Integrated over all decay angles, the average neutrino energy in the laboratory is then

$$E_\nu = \frac{E_{B_c}}{M_{B_c}} E_\nu^*,$$

where $E_\nu^*$ is the energy of the neutrino in the $B_c$ rest frame,

$$E_\nu^* = \frac{M_{B_c}^2 - M_{J/\psi\ell}^2}{2M_{B_c}}.$$

An estimator of the $J/\psi\ell\nu_\ell$ mass is therefore defined as

$$M_{B_c}^{rec} = M_{J/\psi\ell}\sqrt{\frac{E_{J/\psi\ell} + E_\nu}{E_{J/\psi\ell} - E_\nu}}. \tag{1}$$

Here, $E_\nu$ is identified as the measured missing energy in the hemisphere, corrected for the effect of the hemisphere masses [25], and is determined with a resolution of 2.7 GeV. When $E_\nu$ is larger than $E_{J/\psi\ell}$, $M_{B_c}^{rec}$ cannot be computed from Eq. 1 and is arbitrarily taken to infinity. If negative, $E_\nu$ is arbitrarily moved to 0. Removing the events below 4.8 GeV/$c^2$ keeps 89% of the signal while removing 83% of the remaining background, as shown in Figs. 3 and 4.

The overall efficiency, averaged over the $J/\psi$ leptonic channels is $(9.6 \pm 1.0)$% in the $B_c^+ \to J/\psi e^+\nu_e$ channel and $(9.8 \pm 1.0)$% in the $B_c^+ \to J/\psi\mu^+\nu_\mu$ channel. The systematic uncertainties are evaluated as for the $B_c^+ \to J/\psi\pi^+$ channel, except for the missing energy uncertainty, which has a small effect through the use of $M_{B_c}^{rec}$.

## 5.2 Background estimation

The fake lepton background can be evaluated directly from the data by counting the charged particles that can be associated to the $J/\psi$ candidate and that fulfill all the cuts except the lepton identification. This number is then scaled by a misidentification probability taken from the Monte Carlo simulation to be 0.03% for electrons with specific ionization estimator available and 0.29% for muons with specific ionization estimator available and incompatible with the kaon hypothesis by one standard deviation. The numbers of fake leptons calculated this way is $0.03 \pm 0.01$ in the electron channel and $0.13 \pm 0.03$ in the muon channel. These numbers are consistent with those obtained from 80000 $B \to J/\psi X$ Monte Carlo events, corresponding to approximately 40 times the data statistics.

The background from $J/\psi$ candidates containing a fake lepton is estimated in a similar way using the data and the corresponding misidentification probability taken from the Monte Carlo simulation: 0.16% for electrons and 0.56% for muons. The background from this source is $0.08 \pm 0.02$ for the electron channel and $0.12 \pm 0.03$ for the muon channel. The number of prompt lepton events is measured from the $B \to J/\psi X$ Monte Carlo sample to be $0.03 \pm 0.03$ in each channel, while the number of events with non-prompt (conversion or Dalitz pair) electrons is also estimated to be $0.03 \pm 0.03$. No such events are found in a sample of simulated cascade B decay Monte Carlo events. The number of prompt $J/\psi$'s associated to a lepton is estimated to be $0.21 \pm 0.10$ in the electron channel and $0.15 \pm 0.07$ in the muon channel.

To check the background from non-$J/\psi$ sources, $(e^+e^-)\mu^+$ and $(\mu^+\mu^-)e^+$ events in which the first lepton pair mass is in the range 2 to 2.8 GeV/$c^2$ were analysed in the data; no candidates were found, corresponding to a 90% upper limit of 0.31 events in both channels. The $(\mu^+\mu^-)\mu^+$, $(e^+e^-)e^+$, $(e^\pm\mu^\mp)\mu^+$ and $(e^\pm\mu^\mp)e^+$ events cannot easily be used because of the multiple combinations available.

The total number of background events expected is then $0.38 \pm 0.11$ in the electron channel and $0.43 \pm 0.09$ in the muon channel.

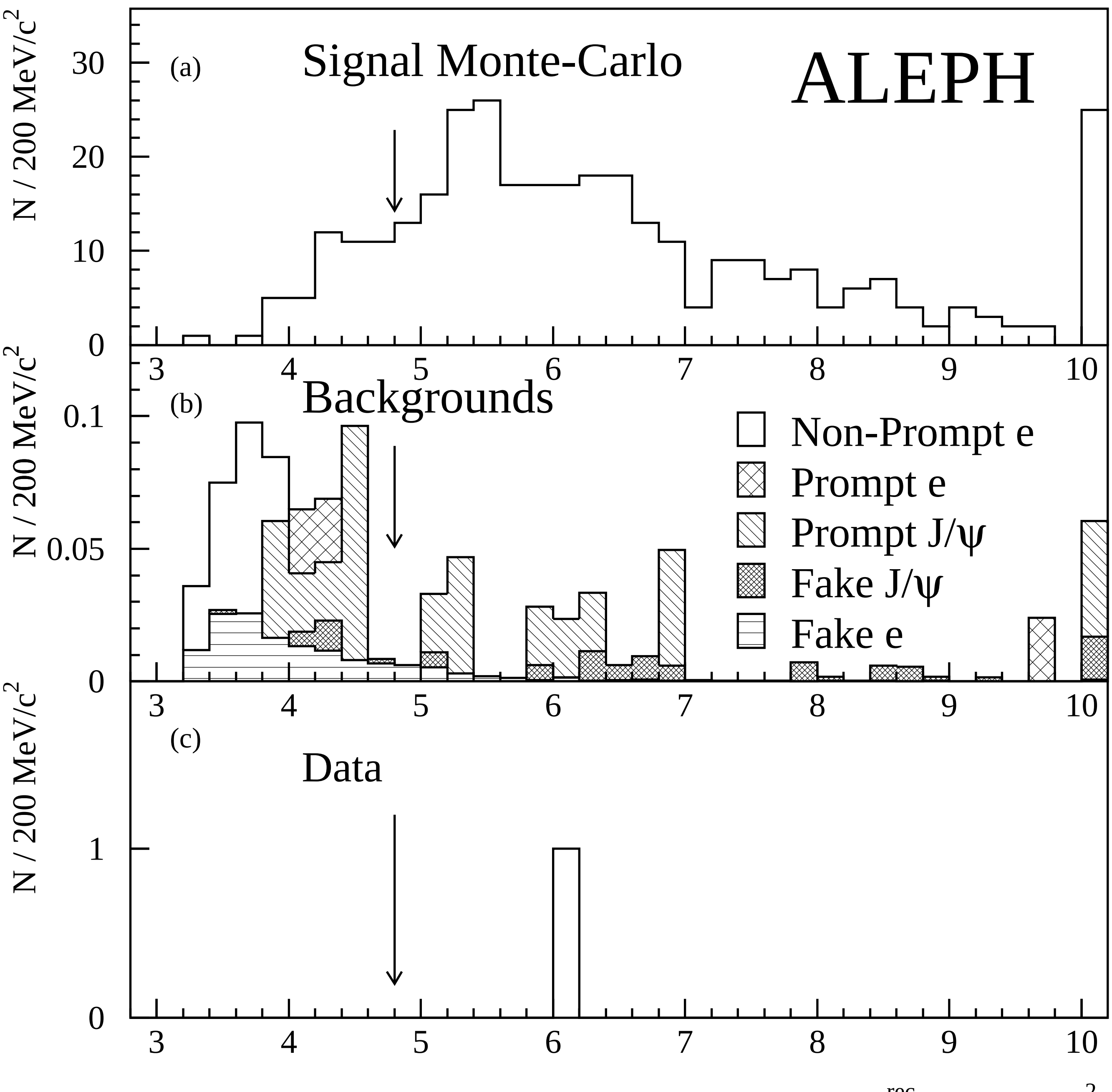


Figure 3: $M^{\rm rec}_{\rm B_c}$ spectrum in the $\rm B_c^+ \to J/\psi e^+ \nu_e$ channel for (a) Monte Carlo signal events, (b) the expected backgrounds described in the text, normalized to the data and (c) the identified electrons associated to $\rm J/\psi$ candidates in the data. The rightmost bin is an overflow bin. The arrow shows the position of the cut.

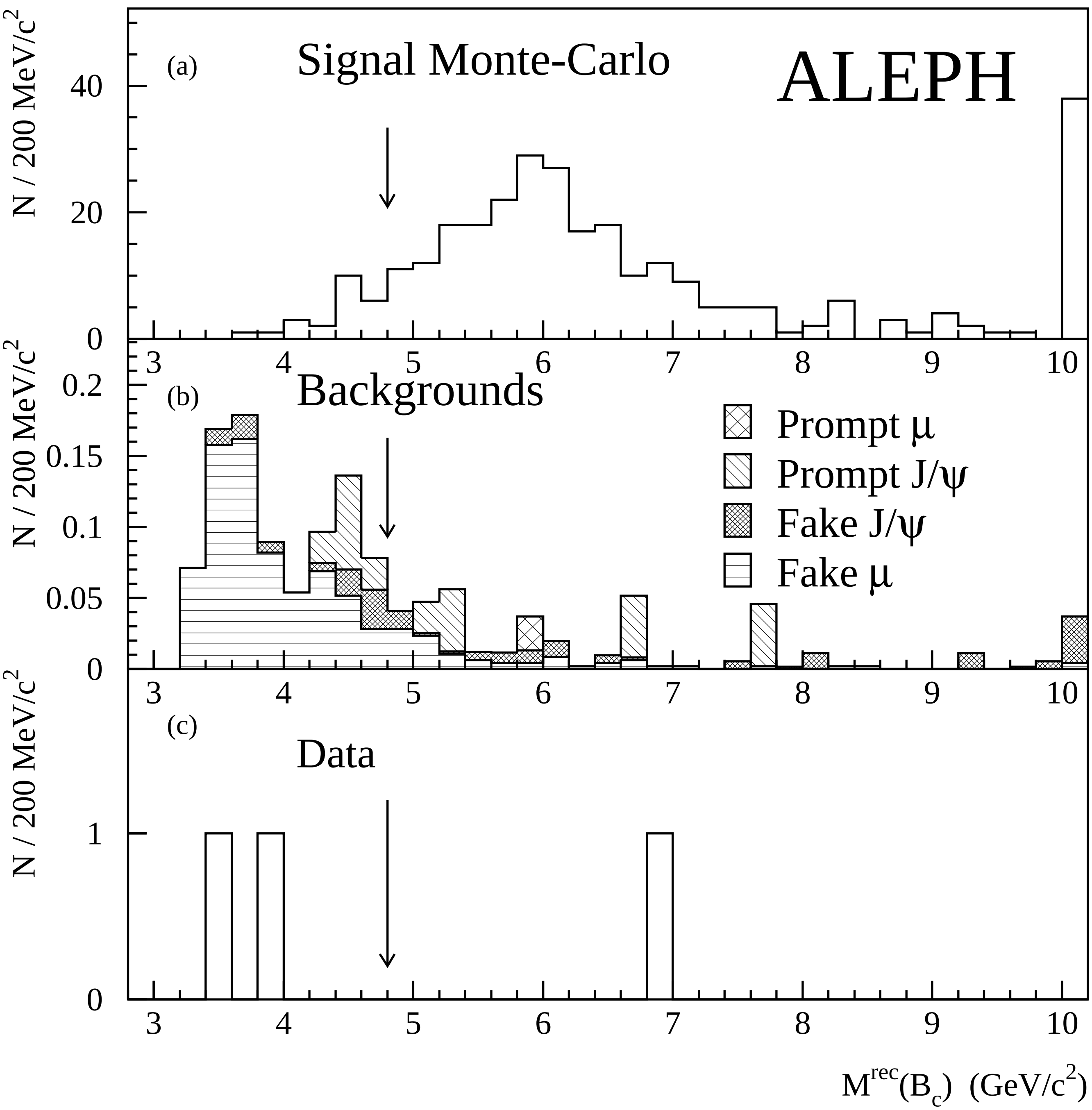


Figure 4: $M^{\rm rec}_{\rm B_c}$ spectrum in the $\rm B_c^+ \to J/\psi\mu^+\nu_\mu^+$ channel for (a) Monte Carlo signal events, (b) the expected backgrounds described in the text, normalized to the data and (c) the identified muons associated to $J/\psi$ candidates in the data. The rightmost bin is an overflow bin. The arrow shows the position of the cut.

### 5.3 Results

The mass spectra from the data are shown in Figs. 3c and 4c. One candidate is selected in the data in each channel. From simple event counting, the probability that both candidates come from a fluctuation of the background is 20%. Taking into account the expected background and the efficiency and their uncertainties, the resulting 90% confidence level upper limits are

$$\begin{aligned} \mathrm{Br_{had}(Z \to B_c X)\ Br(B_c^+ \to J/\psi e^+ \nu_e)} &< 8.2 \times 10^{-5}, \\ \mathrm{Br_{had}(Z \to B_c X)\ Br(B_c^+ \to J/\psi \mu^+ \nu_\mu)} &< 8.0 \times 10^{-5}. \end{aligned}$$

In order to qualitatively determine the viability of these $\mathrm{B_c^+} \to \mathrm{J}/\psi \ell^+ \nu_\ell$ candidates, the parameters of the two events are carefully scrutinized. Neither of the events appears to unambiguously represent the signal; each has one feature that casts some doubt on its consideration as a true $\mathrm{B_c}$ decay.

The reconstructed decay length of the $\mathrm{J}/\psi(\mu^+\mu^-)\mathrm{e}^+\nu_\mathrm{e}$ event is $4.1 \pm 0.2$ mm, enabling a precise constraint of the transverse momentum of the neutrino relative to the flight of the decaying particle to be made. The mass measurement improved with the aid of this constraint gives $5.40 \pm 0.18$ GeV/$c^2$. While this value is consistent with the mass of the $\mathrm{B}^+$, it is over four standard deviations from the predicted mass of the $\mathrm{B_c}$. For this reason the event seems unlikely to be associated with the signal. Since the $\mathrm{J}/\psi \mathrm{e}^+$ mass is only 4.5 GeV/$c^2$, the event is consistent with a decay of a B meson in a final state $\mu^+\mu^- e^+ \nu\nu$, where one of the leptons is actually misidentified or non-prompt.

The reconstructed decay vertex of the $\mathrm{J}/\psi \mu^+ \nu_\mu$ candidate is also remote from the origin, but much less significantly so. In this event, the $\mathrm{J}/\psi$ vertex probability is high, but the probability of the three-track vertex is only 2%. This suggests that the third track may actually originate from the interaction point rather than from the $\mathrm{J}/\psi$ vertex.

# 6 An additional candidate

One $\mathrm{B_c}$ candidate is found by scanning events with $\psi \mathrm{X}^\pm$ mass above the $\mathrm{B}^\pm$ mass in a different analysis which reconstructs B mesons in the decay channel $\mathrm{B}^\pm \to \psi \mathrm{X}^\pm$, where the $\psi$ is either $\mathrm{J}/\psi$ or $\psi(2S)$. A display of this event is shown in Figure 5. This event has an unmistakable $\mathrm{J}/\psi$ vertex significantly displaced from the primary vertex. The extra track is consistent with a muon hypothesis according to the dE/dx, and is very likely to be a muon given the penetration through the electromagnetic and hadronic calorimeters. This track exits the hadron calorimeter in a region without muon chamber coverage and therefore it can not have any muon chamber hits. This lack of muon chamber hits is the only reason this candidate was not selected by the previously discussed $\mathrm{B_c}$ analysis.

The two electrons forming the $\mathrm{J}/\psi$ candidate are identified by their shower profile in the ECAL. Both are energetic and have very large impact parameter significances as shown in Table 2. Fitting the two electrons to a common vertex yields a confidence level of 61%, and a mass of $3.102 \pm 0.014$ GeV/$c^2$, consistent with the $\mathrm{J}/\psi$ hypothesis.

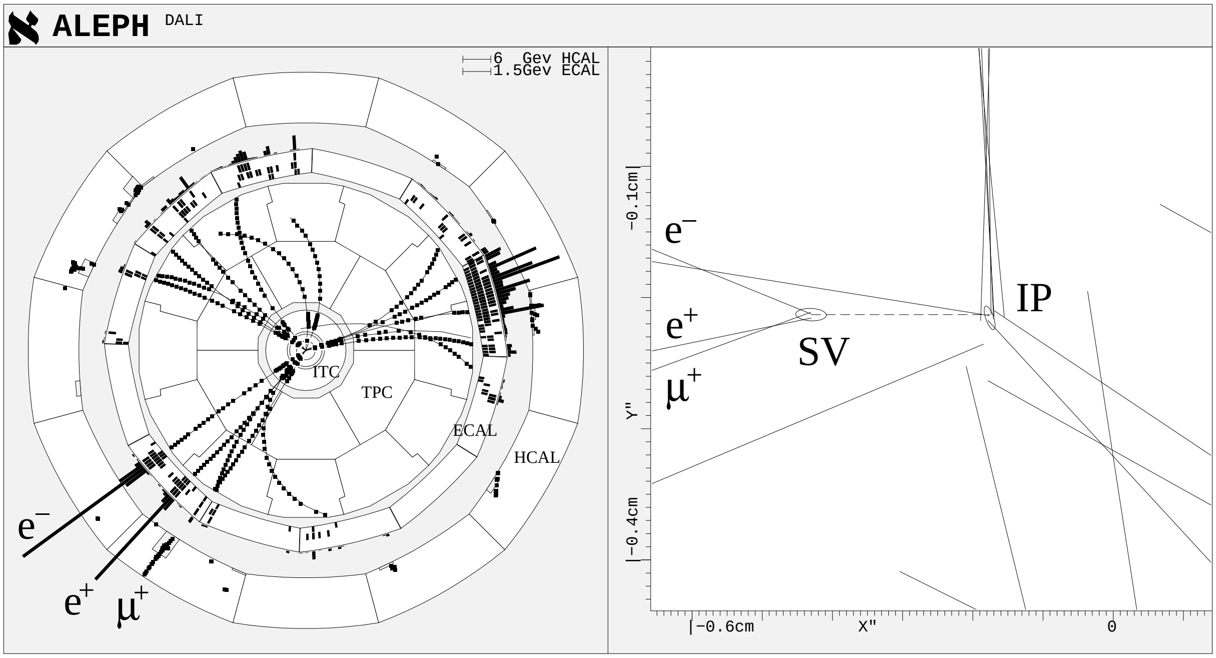


Figure 5: Event display showing the detector response and the secondary vertex (SV) of the $B_c$ candidate. The error ellipses drawn represent $3\sigma$ ellipses. Tracks with momentum less than 0.5 GeV/$c$ and hits created by tracks that loop inside the TPC are not drawn.

| Lepton | Momentum [GeV/$c$] | $\chi^2$ with P.V. |
|---|---|---|
| $e^+$ | 7.4 | 38. |
| $e^-$ | 12.1 | 287. |
| $\mu^+$ | 9.2 | 195. |

Table 2: Properties of the leptons. The $\chi^2$ with P.V. is the resulting $\chi^2$ for 2 degrees of freedom when the lepton is fit to the primary vertex.

The muon candidate is energetic and has a very large impact parameter significance as shown in Table 2. It makes a common vertex with the $J/\psi$ with a confidence level of 84%. The measured decay length is $2.55 \pm 0.08$ mm. Fitting for the mass of the three-lepton system while constraining the mass of the two electrons to the known $J/\psi$ mass gives $M_{J/\psi\mu^+} = 5.640 \pm 0.015$ GeV/$c^2$. This large mass renders the event very difficult to explain by three tracks from a B meson (other than $B_c$) or $\Lambda_b$ decay.

The event has a clear three jet structure. For each jet the lifetime tag probability [26] is calculated. It is the probability that a set of tracks all come from the interaction point. The tag probability for the jet that contains the $B_c$ candidate is $4.3 \times 10^{-5}$, making it very likely that the jet contains a hadron composed of a b quark. The tag probability for the the neighbouring jet, clockwise in Figure 5, is 0.16 and that for the remaining jet

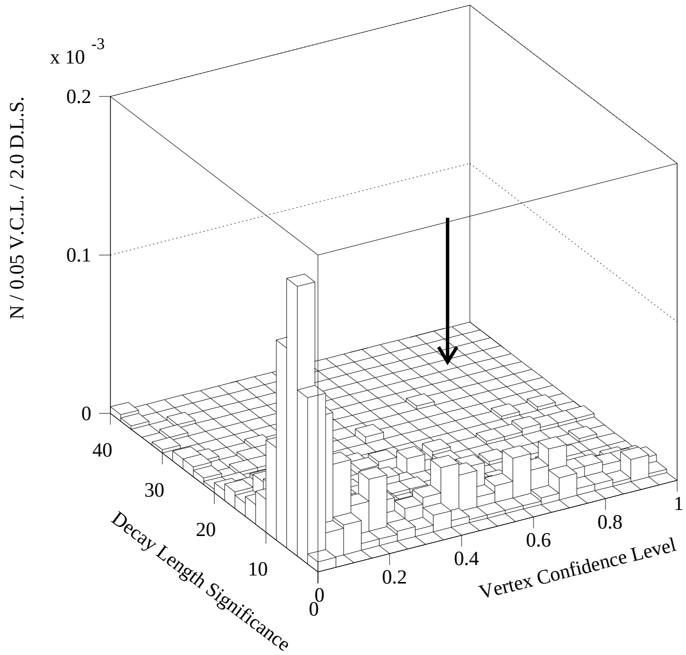


Figure 6: Background from an accidental common vertex of the J/$\psi$ and a reconstructed lepton. The decay length significance and the vertex confidence level are histogrammed, normalized to the data. The arrow indicates where the observed $B_c$ candidate would be in this histogram.

could not be reliably calculated because of confusion in the VDET hit assignment due to looping tracks in the region of the jet.

Since this event was found by scanning, its properties were known before any background estimate was made. For this reason, a totally unbiased estimate of the background would be impossible. However, an attempt was made to design an analysis which would look for a very clean signal: a J/$\psi\ell$ vertex significantly displaced from the primary vertex with a mass larger than the $B^+$ mass and with the third lepton inconsistent with coming from the primary vertex. Using this analysis, two studies are done to estimate the background probability for the candidate event.

The first considers the case in which the kaon in the decay $B \to J/\psi KX$ decays in flight to $\mu\bar{\nu}_\mu$ inside the tracking volume and the resulting badly measured track increases the J/$\psi\mu$ mass above the $B^+$ mass. The background rate from this process is found to be very small (less than $10^{-5}$).

The second considers the case in which a J/$\psi$ from a B decay accidentally forms a common vertex with a reconstructed lepton, real or fake, not coming from the B decay. In order to increase the statistics available for the Monte Carlo study, a sample of $B \to J/\psi X$ events is combined with a general $Z \to b\bar{b}$ sample. Analysis of the resulting Monte Carlo events shows that the background rate from this source is less than $2 \times 10^{-3}$ . Figure 6 shows a two-dimensional histogram of the secondary vertex confidence level and the decay length significance of the secondary vertex for all the Monte Carlo events accepted by the analysis. The histogram is normalized to the data. The dense population in the region of low values is the result of the fact that the third lepton forms an accidental common vertex and that it predominantly comes from the interaction point. The candidate indicated by an arrow in the histogram is highly unlikely to have come from this background source. Nevertheless, the background rate is conservatively estimated as simply less than all the events in the histogram, i.e., less than $2 \times 10^{-3}$.

Assuming that the candidate is a $B_c^+ \to J/\psi\mu^+\nu_\mu$ decay, the mass of the $B_c$ can be reconstructed. The neutrino momentum vector is estimated using the missing energy in the hemisphere ($= 0.2 \pm 2.5$ GeV/$c$) and the reconstructed transverse momentum with respect to the $B_c$ flight direction ($= 0.27 \pm 0.33$ GeV/$c$). Using a Monte Carlo method to reject unphysical values for the neutrino's true momentum and transverse momentum, a mass of $5.96^{+0.25}_{-0.19}$ GeV/$c^2$ is obtained for the $B_c$ candidate. This mass measurement is unaffected by any possible bias in the event selection. The measured proper decay time, $1.77 \pm 0.17$ ps, is a slightly biased representation of the lifetime in the sense that the event would not have been noticed if the decay length had been much smaller.

# 7 Conclusion

No candidates are found in the $B_c^+ \to J/\psi\pi^+$ channel, yielding the 90% confidence level experimental upper limit

$$\mathrm{Br_{had}}(Z \to B_c X)\ \mathrm{Br}(B_c^+ \to J/\psi\pi^+) < 3.6 \times 10^{-5},$$

to be compared with a theoretical expectation of 0.02 to $0.3 \times 10^{-5}$.

Two candidates are found in the semileptonic channels, yielding the 90% confidence level combined upper limit

$$\mathrm{Br_{had}}(Z \to B_c X)\ \mathrm{Br}(B_c^+ \to J/\psi\ell^+\nu_\ell) < 5.2 \times 10^{-5},$$

to be compared with a theoretical expectation of 0.1 to $2 \times 10^{-5}$.

An additional candidate consistent with a $B_c^+ \to J/\psi(e^+e^-)\mu^+\nu_\mu$ decay is also observed, where the expectation from all known background sources is less than $2 \times 10^{-3}$.

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