EUROPEAN LABORATORY FOR PARTICLE PHYSICS (CERN)

EPS0407
PA-05,14
PL-11

Search for the B_c meson in hadronic Z decays

The ALEPH Collaboration

Abstract

Out of 3.1 million hadronic Z decays collected by the ALEPH detector between 1991 and 1994, a sample of ~ 600 J/ψ candidates decaying into e^+e^- or $\mu^+\mu^-$ are selected. From these events, a search for the B_c meson decaying into the channels $J/\psi\pi^+$, $J/\psi e^+\nu_e$ and $J/\psi\mu^+\nu_\mu$ is performed. This search results in the observation of 0, 1 and 1 candidate in each of these channels respectively, with 0.32, 0.17 and 0.13 background event expected. This allows the following 90 % confidence level upper limits to be derived:

$$\frac{Br(Z \to B_c X)}{Br(Z \to q\bar{q})} Br(B_c^+ \to J/\psi\pi^+) < 4.\ 10^{-5},$$

$$\frac{Br(Z \to B_c X)}{Br(Z \to q\bar{q})} Br(B_c^+ \to J/\psi\ell^+\nu_\ell) < 7.\ 10^{-5}.$$

Contribution to the International Europhysics Conference on High Energy Physics, Brussels, Belgium, July 27-August 2, 1995

1 Introduction

The properties of the B_c meson, containing two unlike heavy quarks, are expected to be very different from those of the other b-hadrons. Its discovery and the study of its properties are some of the next challenges in B physics.

The purpose of this paper is to present a search for the B_c meson in the channels [1] $B_c^+ \to J/\psi\pi^+$, $B_c^+ \to J/\psi e^+\nu_e$, $B_c^+ \to J/\psi\mu^+\nu_\mu$ where the leptonic decays of the J/ψ give a very clean signature. This analysis is an update of the analysis presented in Ref. [1] with twice as much data; several cuts are improved according to an objective criterion which is to minimize the expected upper limit on the production rate times branching ratio as explained in Ref. [2]. This note is organized as follows: the theoretical expectation of the relevant properties of the B_c meson are briefly summarized; the common J/ψ selection is then described; finally, the selection criteria, the background estimate, and the results of the search are given for each channel.

2 Theoretical prediction for the B_c properties

Since the B_c contains two heavy quarks, its mass can be evaluated (more accurately than *e.g.* the Λ_b mass) *via* potential models by interpolation between the *charmonium* and *bottomonium* spectroscopy. A compilation of various mass estimates is given in Ref. [3]. For this analysis, the value $M_{B_c} = 6.25 \pm 0.05$ GeV/c^2 was chosen with a conservative uncertainty.

The B_c production rate predictions (including cascades through excited states) currently range from 100 to 700 B_c per million hadronic Z decays [4, 5, 6, 7]. The B_c can decay according to three main processes: annihilation, b quark spectator decay, and c quark spectator decay. For this reason, the B_c lifetime is much less accurately predicted than that of the other b-hadrons: the predictions for the B_c lifetime range from 0.5 ps [8] to 1.4 ps [9]. It is therefore preferable to avoid in this analysis any lifetime related cuts, such as a decay-length cut. The B_c various branching fractions are also poorly predicted, but the presence of a c quark in the initial state favours a J/ψ in the final state by a factor ten to twenty with respect to the inclusive decay of the other b-hadrons.

The present analysis search for the B_c in the decays $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to J/\psi\ell^+\nu_\ell$, ($\ell = e$ or μ) where the branching fractions are expected to be respectively 0.2 to 0.4 % and 1 to 3 % [8, 9, 10], which corresponds, with the current ALEPH statistics and accounting for the J/ψ leptonic branching ratio, to respectively 0.07 to 1 and 0.8 to 16 events expected.

3 J/ψ selection

Data taken from 1991 to 1994 are used, corresponding to 3.1 million hadronic Z decays. $J/\psi \to \ell^+\ell^-$ events are selected by identifying two identical leptons of opposite charge with rather loose cuts with respect to Ref. [1, 11]. Electrons are identified above 2 GeV/c

[1] The two charged conjugate decays are implicit throughout this note.

from estimators of the longitudinal and transversal shape of the energy deposit in the electronic calorimeter and from their specific ionisation estimator, when available. All estimators should be less than 2.5 σ lower than 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 above 2 GeV/c from their hit pattern in the hadronic calorimeter and muon chambers.

Since the B_c has a softer spectrum than the other b-hadrons (due to the additional necessary $c\bar{c}$ pair), the J/ψ from B_c have on average a momentum 25 % smaller than the J/ψ from other b-hadrons; for this reason, no momentum cut is applied to the $\ell^+\ell^-$ pair. The angle between the two identified leptons must be smaller than 90°, and they should form a vertex with a probability in excess of 1%. In order to have a vertex with an acceptable precision, it is also required that at least one of the leptons be associated with one or more three-dimensional vertex detector hits. J/ψ candidates are retained if the $\ell^+\ell^-$ invariant mass is between 3.0 and 3.2 GeV/c^2. For background studies, events where the e^+e^- or $\mu^+\mu^-$ pair invariant mass lies between 2 and 2.8 GeV/c^2, and events with an $e^\pm\mu^\mp$ pair with an invariant mass between 2 and 4 GeV/c^2, are also retained and are hereafter referred to as "side-band" events.

From fully simulated Monte-Carlo events $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to J/\psi\ell^+\nu_\ell$, the J/ψ tagging efficiency is 24 % for $J/\psi \to e^+e^-$ and 33 % for $J/\psi \to \mu^+\mu^-$. The selected $\ell^+\ell^-$ sample is composed mainly of J/ψ from the decay of b-hadrons. The remaining background is twofold: (*i*) a negligible (less than 1%) fraction of genuine J/ψ from gluon fragmentation [12, 13] and from $Z \to c\bar{c}J/\psi$ [14]; and (*ii*) the combinatorial background, which consists mainly of events where 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 the latter tends to have a substantial missing energy, the visible energy in the J/ψ 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 sample is shown in Fig. 1 and the relevant numbers are given in Table 1. Since the background in the two J/ψ leptonic channels is similar, they are considered together in the following.

Channel	e^+e^-			$\mu^+\mu^-$			$e^\pm\mu^\mp$
	Events	f_{bkg}	Side	Events	f_{bkg}	Side	
Standard	244	$14.1 \pm 0.9\%$	516	403	$11.6 \pm 0.7\%$	657	1529
With E_{vis} cut	213	$8.9 \pm 0.8\%$	210	340	$7.4 \pm 0.6\%$	263	634

Table 1: Detail of data sample used with standard cuts (for the $J/\psi\ell^+\nu_\ell$ channel) and with the additional cut on visible energy (for the $J/\psi\pi^+$ channel). For e^+e^- and $\mu^+\mu^-$ pairs, the number of J/ψ candidates, the fraction f_{bkg} of non J/ψ events among J/ψ candidates estimated as in Ref. [11], and the number of side-band events are given. The number of $e^\pm\mu^\mp$ is also given in the last column.

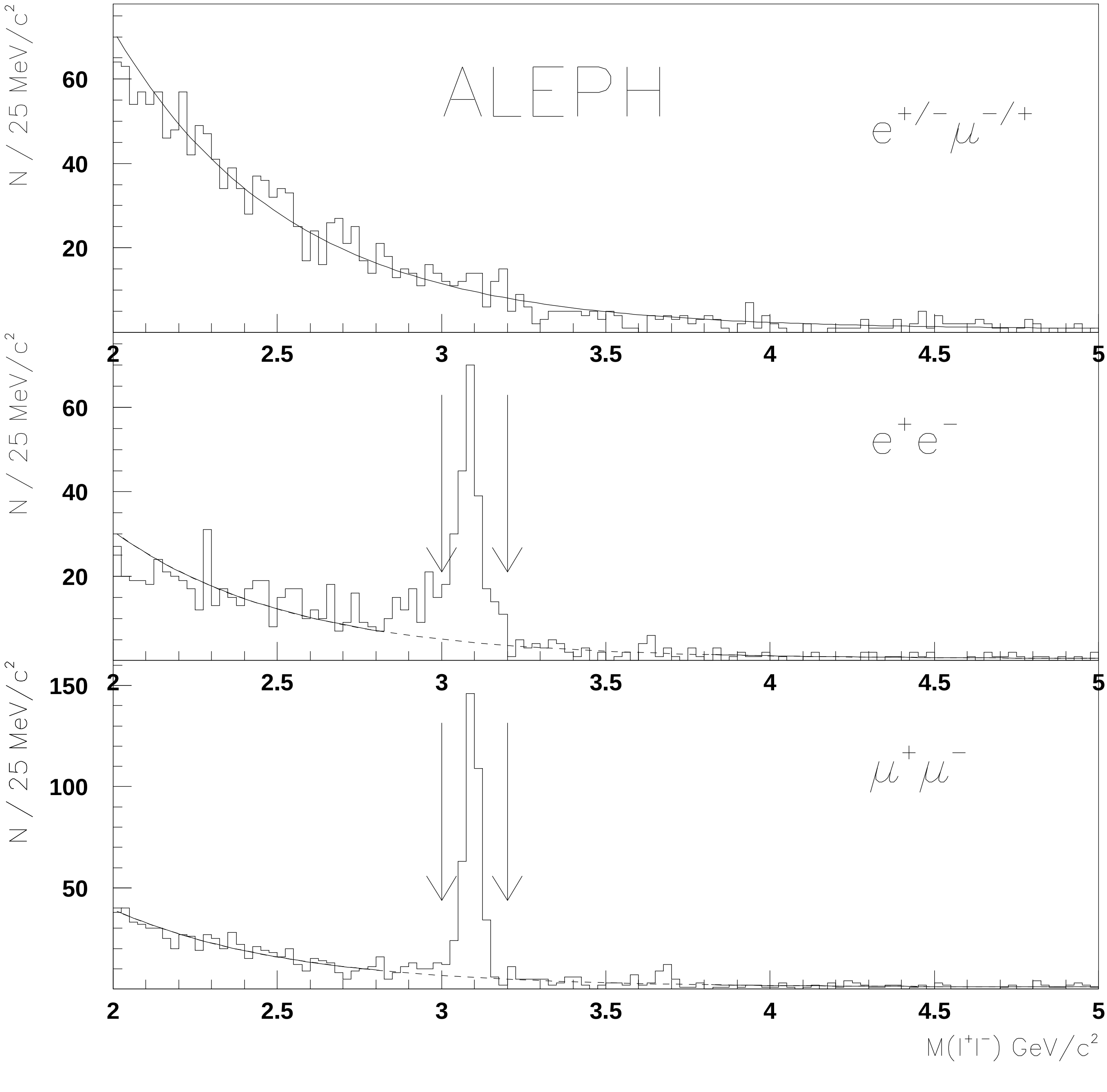

Figure 1: Invariant mass of selected $e^{\pm}\mu^{\mp}$, e^+e^- and $\mu^+\mu^-$ pairs without any visible energy cuts. The arrows define the mass window for the J/ψ signal. The solid line shows the fit used to estimate the background below the J/ψ peak.

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/ψ with a charged particle unrelated to the parent B. A requirement that the three tracks form a common vertex therefore efficiently removes this background. Moreover, the topology of the remaining background events is kinematically similar to that of events where the two leptons come from a cascade $b \to c\ell^- \to s\ell^+\ell^-$. This allows to evaluate the background directly from the data using the side-band events defined previously.

4.1 Selection

The $B_c^+ \to J/\psi\pi^+$ candidates are selected by associating a J/ψ candidate to a charged particle not identified as a lepton, with a momentum in excess of 4 GeV/c, with a specific ionisation estimator compatible with that of a pion within -2 and +3 standard deviations, and not consistent with coming from a K_s^0 or Λ decay. The pion candidate should be in a 45° cone around the J/ψ momentum direction. The total $J/\psi\pi^+$ momentum should be greater than 15 GeV/c. The $\ell^+\ell^-\pi^+$ common vertex should have a probability above 1 %. Finally, the mass of the B_c candidate, calculated at the B_c vertex by constraining the $\ell^+\ell^-$ pair to the J/ψ mass, should lie in the window 6.25 ± 0.10 GeV/c^2. The width of this mass window is defined as the sum of the theoretical uncertainty and twice the experimental resolution, in order to retain more than 97 % of the signal wherever the true B_c mass lies in the theoretical mass window. The overall efficiency averaged over the two J/ψ leptonic channels is 16 ± 1 %.

4.2 Background estimation

The background is estimated using either the side-band events corresponding to ~ 5 times the number of J/ψ candidates, or a sample of 12000 fully simulated $B \to J/\psi X$ events where B is not a B_c, corresponding to ~ 7 times the number of J/ψ candidates. The $\ell^+\ell^-\pi^+$ mass spectra are shown in Fig. 2a and 2b. 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 event turns out to be 0.32 ± 0.09 from the data side-bands and 0.26 ± 0.07 from the $B \to J/\psi X$ Monte-Carlo.

4.3 Results

The mass spectrum from the data is shown in Fig. 2c. No events are seen in the mass window. Using $R_b = 22.04 \pm 0.20\%$ [15], $Br(J/\psi \to \ell^+\ell^-) = 5.98 \pm 0.25\%$ [16] and the above quoted efficiency, this results in a 90% confidence level upper limit of

$$Br_{had}(Z \to B_c X)\ Br(B_c^+ \to J/\psi\pi^+) < 4.\ 10^{-5},$$

where $Br_{had}(Z \to B_c X) = \Gamma(Z \to B_c X)/\Gamma(Z \to q\bar{q})$.

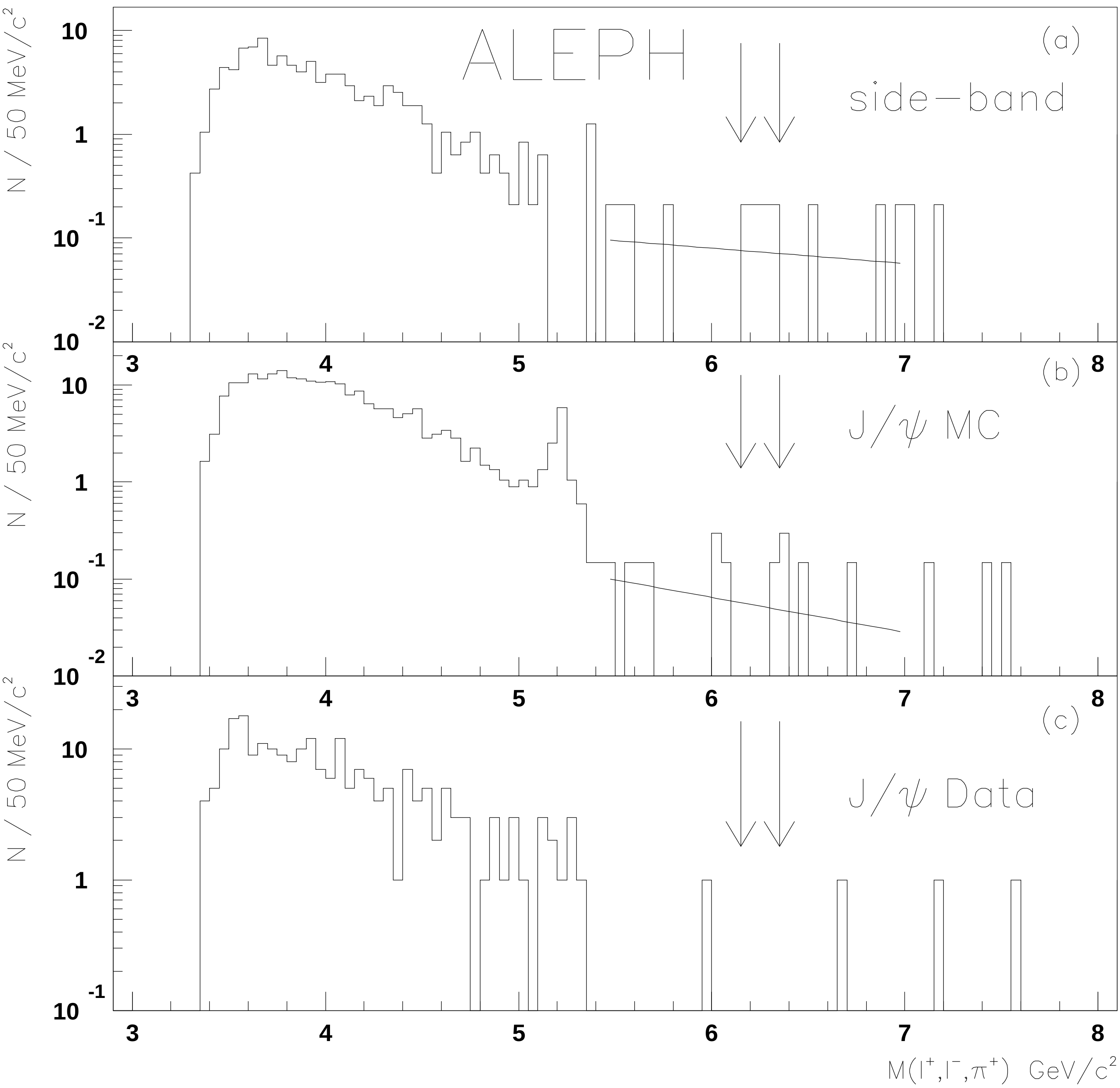

Figure 2: $\ell^+\ell^-\pi^+$ mass spectrum for the side-band events (a) and the $B \to J/\psi X$ Monte-Carlo (b) normalized to the same number of J/ψ candidates as in the data; the solid line is the fit used to estimate the number of background events in the mass window shown by the arrows. Figure (c) is the data $\ell^+\ell^-\pi^+$ mass spectrum for the J/ψ candidates.

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/ψ with a fake or non-prompt lepton coming either from fragmentation, thus not from the B vertex, or from the b-hadron parent of the J/ψ. Additional background arises from cascade decay events in which one lepton is associated to a misidentified hadron to form a J/ψ, subsequently associated to 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 to be topologically close to each other. As already mentionned for the $J/\psi\pi^+$ channel, a common vertex requirement reduces all the backgrounds where the lepton and the J/ψ 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 $J/\psi\ell^+$ 4-momentum.

5.1 Selection

Since the B_c is actually tagged by the presence of a third lepton in addition to the J/ψ lepton pair, a lepton identification tighter with respect to the two first leptons is required.

For muons, the track extrapolated to the muon chambers should be inconsistent with the muons from the J/ψ and its distance to the associated muon chamber hits should be less than 2.5 standard deviations. Furthermore, to reduce the high contamination from kaons in this topology, the specific ionisation estimator should 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 momentum cut is lowered to 1.3 GeV/c, a value chosen to avoid the region where the proton and electron expected specific ionisations are too close. The specific ionisation estimator should be available and the combined probability of the electronic calorimeter and specific ionisation estimators should be in excess of 5 %. These additional requirements remove 90 % of the fake electrons, with almost no signal efficiency loss.

This third lepton should be in a 45° cone around the J/ψ momentum direction and be associated to at least one three-dimensional vertex detector hit. The three lepton common vertex should have a probability in excess of 1%.

Finally, a consistency between the $J/\psi\ell^+$ mass and the missing energy in the J/ψ hemisphere is required as described below. The neutrino in the B_c rest frame has a flat angular distribution, which is unbiased by any kinematical cut. The neutrino energy in the laboratory frame when averaged over all decay angles is then :

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

where E_ν^* is the energy of the neutrino in the $\mathrm{B_c}$ rest frame,

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

and therefore,

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

Here, E_ν is identified to the measured missing energy in the hemisphere corrected for the effect of the mass of the hemisphere masses [17], and is determined with a resolution of 2.7 GeV. When E_ν is larger than $E_{\mathrm{J}/\psi}$, $M_{\mathrm{B_c}}^{rec}$ cannot be computed from Eq. 1 and is arbitrarily taken to infinity. If negative, E_ν is arbitrarily moved to 0. Removing the events below 4.8 GeV/c^2 keeps 87 % of the signal while removing 80 % of the background left, as shown in Fig. 3b, 3c, 4b and 4c.

The overall efficiency, averaged over the J/ψ leptonic channels and measured from 5000 Monte-Carlo signal events, is 10 ± 1 % in the $\mathrm{B_c^+} \to \mathrm{J}/\psi\mu^+\nu_\mu$ channel and 11 ± 1 % in the $\mathrm{B_c^+} \to \mathrm{J}/\psi \mathrm{e}^+\nu_\mathrm{e}$ channel. The uncertainty on the $\mathrm{B_c}$ mass contributes less than 0.1 % to the absolute efficiency error.

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/ψ candidate and fulfilling all the cuts but the lepton identification and by applying a misidentification probability taken from the Monte Carlo to be 0.02 % for electrons with specific ionisation estimator available and 0.22 % for muons with specific ionisation estimator available and incompatible with the kaon hypothesis by one standard deviation. The numbers of fake leptons calculated this way is 0.11 ± 0.03 in the muon channel and 0.02 ± 0.01 in the electron channel. These numbers are consistent with those obtained from 80000 $\mathrm{B} \to \mathrm{J}/\psi\mathrm{X}$ Monte-Carlo corresponding to ~ 40 times the data statistics.

The background from fake J/ψ candidates containing a fake lepton is also estimated using the data and the corresponding misidentification probability taken from the Monte-Carlo: 0.16 % for electrons and 0.56 % for muons. The background from this source is 0.03 ± 0.02 for $\mathrm{J}/\psi\mu^+$ and 0.04 ± 0.01 for $\mathrm{J}/\psi\mathrm{e}^+$. The number of prompt muon events is estimated from the Monte-carlo to be 0.03 ± 0.03. The number of prompt or non-prompt (conversion or Dalitz pair) electrons events is estimated to be 0.07 ± 0.04.

To check the background from non-J/ψ sources, $(\mathrm{e^+e^-})\mu^+$ and $(\mu^+\mu^-)\mathrm{e}^+$ events where the first lepton pair mass is in the range 2.-2.8 GeV/c^2 were analysed in the data; no candidates were found, corresponding to a 90 % upper limit of 0.34 events in the muon channel and 0.27 events in the electron channel. The $(\mu^+\mu^-)\mu^+$, $(\mathrm{e^+e^-})\mathrm{e}^+$, $(\mathrm{e}^\pm\mu^\mp)\mu^+$ and $(\mathrm{e}^\pm\mu^\mp)\mathrm{e}^+$ events cannot easily be used because of the multiple combinations available.

The total number of background events expected is then $N_{bkg} = 0.17 \pm 0.04$ in the muon channel and $N_{bkg} = 0.13 \pm 0.05$ in the electron channel.

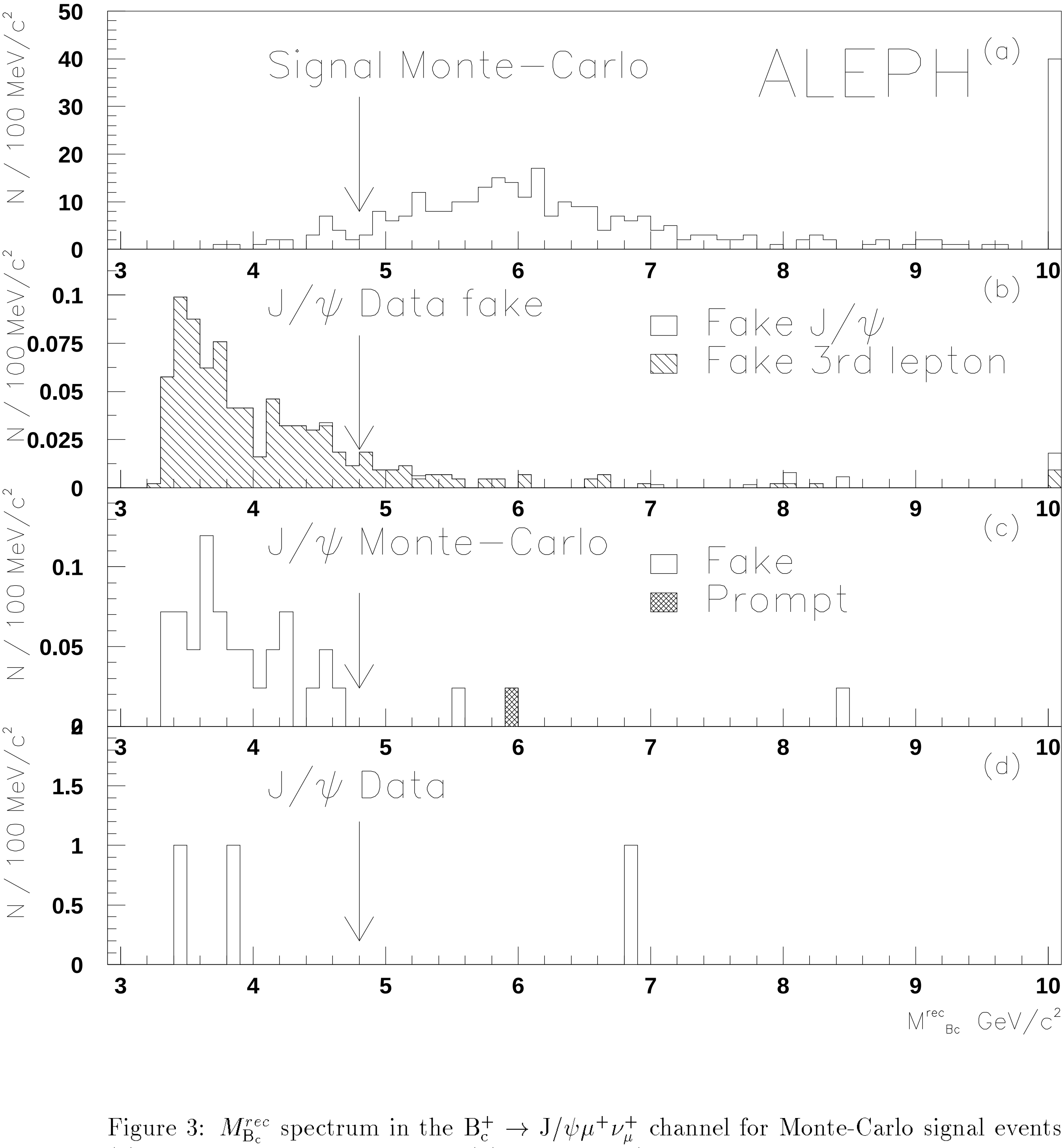

Figure 3: $M^{rec}_{\mathrm{B_c}}$ spectrum in the $\mathrm{B_c^+} \to \mathrm{J}/\psi\mu^+\nu_\mu^+$ channel for Monte-Carlo signal events (a), the fake lepton combinations (b) in the data (weighted by the muon misidentification probability), the $\mathrm{B} \to \mathrm{J}/\psi\mathrm{X}$ Monte-Carlo (c) (normalized to the same number of J/ψ candidates as in the data), and (d) the identified muons associated to J/ψ candidates in the data. The rightmost bin is an overflow bin. The arrow shows the position of the cut.

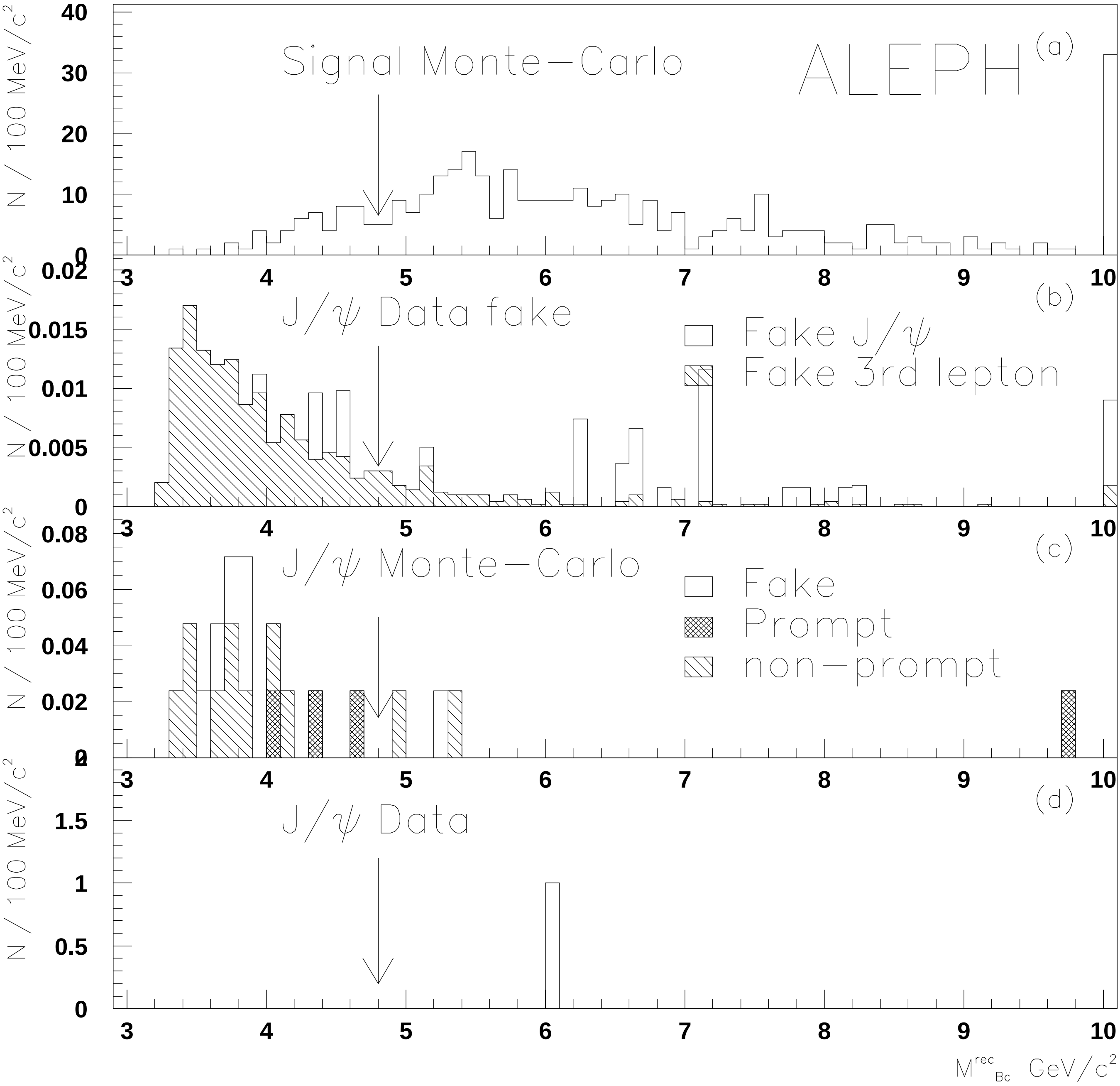

Figure 4: $M^{rec}_{\mathrm{B_c}}$ spectrum in the $\mathrm{B_c^+} \to \mathrm{J}/\psi \mathrm{e}^+ \nu_\mathrm{e}$ channel for Monte-Carlo signal events (a), the fake lepton combinations (b) in the data (weighted by the electron misidentification probability), the B $\to$ J/ψX Monte-Carlo (c) (normalized to the same number of J/ψ candidates as in the data), and (d) the identified electrons associated to J/ψ 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 Fig. 3d and 4d. One candidate is left in the data in each channel. From simple event counting, the probability that both candidates come from a fluctuation of the background is 4 %. Conservatively not subtracting the expected background, the resulting 90% confidence level upper limits are:

$$\mathrm{Br_{had}(Z \to B_c X)\ Br(B_c^+ \to J/\psi \mu^+ \nu_\mu)} < 11.\ 10^{-5},$$

$$\mathrm{Br_{had}(Z \to B_c X)\ Br(B_c^+ \to J/\psi e^+ \nu_e)} < 10.\ 10^{-5}.$$

The $J/\psi(\mu^+\mu^-)e^+$ candidate is shown in Fig. 5. The the three leptons are well identified and their momenta are 3.0, 6.4 and 9.4 GeV/c respectively. The estimated B_c mass, $M^{rec}_{B_c}$, is 6.1 GeV/c^2. Each of the three leptons tracks is unambiguously associated to two three-dimensional vertex detector hits. The three lepton common vertex has a probability of 60 % and is displaced from the primary vertex by 4.06 ± 0.15 mm. The direction of the three lepton momentum sum and that given by the vertices are incompatible by more than five standard deviations, as expected from the missing neutrino momentum. No other precisely measured tracks are compatible with the J/ψ vertex.

6 Conclusion

The results of this search are summarized in Table 2, along with the theoretical expectation. No candidates are found in the $B_c^+ \to J/\psi\pi^+$ channel, yielding an experimental upper limit

$$\mathrm{Br_{had}(Z \to B_c X)\ Br(B_c^+ \to J/\psi \pi^+)} < 4.\ 10^{-5},$$

which is a factor of fourteen above the theoretical expectation. Two candidates are found in the semi-leptonic channels, yielding a combined limit:

$$\mathrm{Br_{had}(Z \to B_c X)\ Br(B_c^+ \to J/\psi \ell^+ \nu_\ell)} < 7.\ 10^{-5},$$

which is less than a factor four above the optimistic theoretical expectation. As none of the channels is background limited, these limits are expected to decrease almost linearly with additional data, unless more candidates are found.

Channel	Efficiency	N_{bkg}	Candidate	90% CL	Theory
$B_c \to J/\psi\pi^+$	$16 \pm 1\%$	0.32 ± 0.09	0	$4.\ 10^{-5}$	$0.02 - 0.3\ 10^{-5}$
$B_c \to J/\psi\mu^+\nu_\mu$	$10 \pm 1\%$	0.17 ± 0.04	1	$11.\ 10^{-5}$	$0.1 - 2.\ 10^{-5}$
$B_c \to J/\psi e^+\nu_e$	$11 \pm 1\%$	0.13 ± 0.03	1	$10.\ 10^{-5}$	$0.1 - 2.\ 10^{-5}$

Table 2: For each of the three channels studied, the efficiency of the search, the number of background events expected (N_{bkg}), the number of candidates, the 90 % confidence level upper limit on $\mathrm{Br_{had}(Z \to B_c X)}$ times the relevant B_c branching ratio, and the theoretical allowed range.

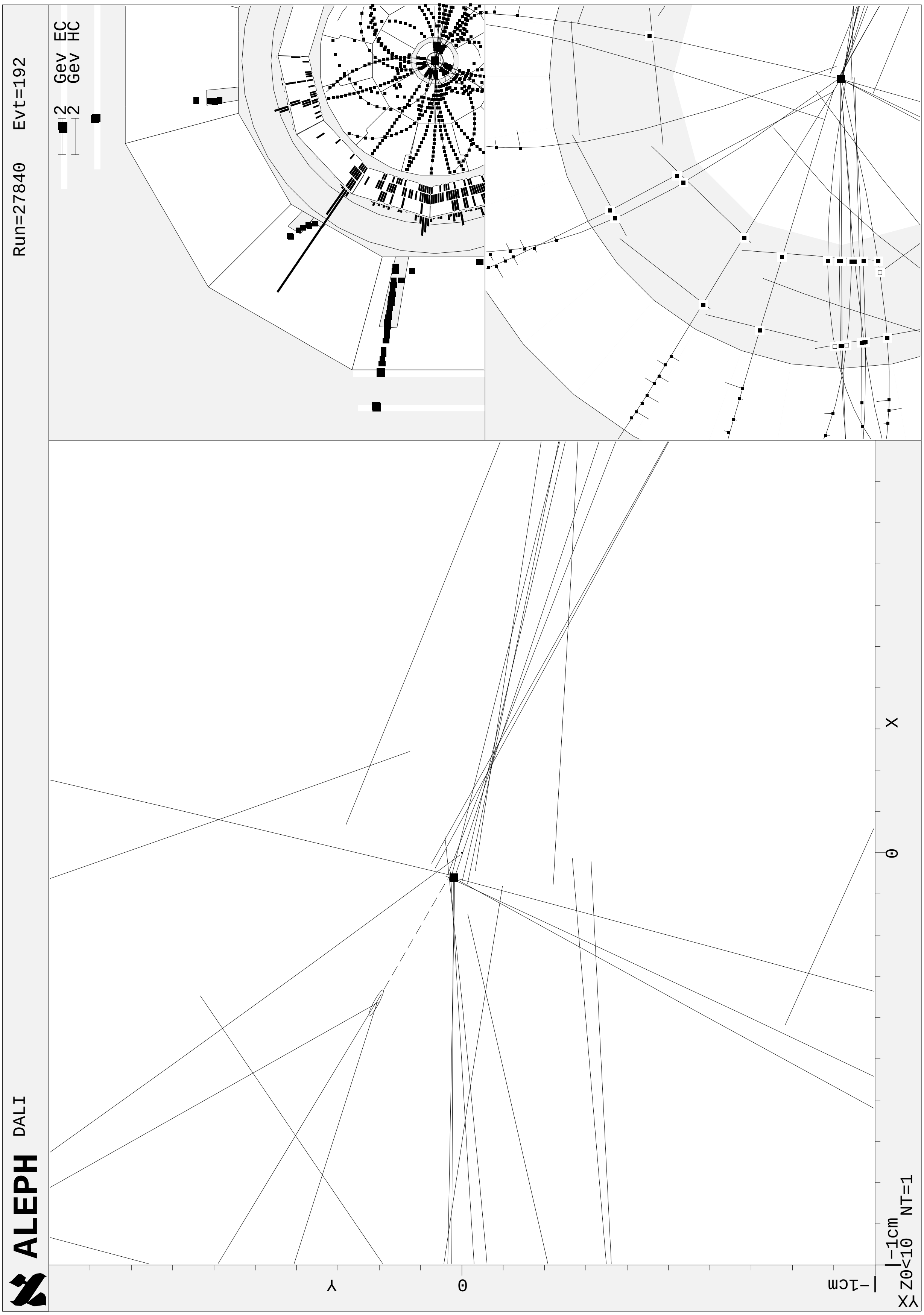

Figure 5: Different views of the $J/\psi(\mu^+\mu^-)e^+$ candidate in the plane perpendicular to the beam axis. See text for details.

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