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### Measurement of the mass of the $\Lambda_b$ baryon

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Measurement of the Mass of the  $\Lambda_b$  Baryon

The ALEPH Collaboration

## Abstract

In a data sample of four million hadronic  $Z$  decays collected with the ALEPH detector at LEP, four  $\Lambda_b$  baryon candidates are exclusively reconstructed in the  $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$  channel, with the  $\Lambda_c^+$  decaying into  $pK^- \pi^+$ ,  $p\bar{K}^0$ , or  $\Lambda \pi^+ \pi^+ \pi^-$ . The probability of the observed signal to be due to a background fluctuation is estimated to be  $4.2 \times 10^{-4}$ . The mass of the  $\Lambda_b$  is measured to be  $5614 \pm 21$  (*stat.*)  $\pm 4$  (*syst.*) MeV/ $c^2$ .

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# The ALEPH Collaboration

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# 1 Introduction

In the last few years, a great deal of progress has been made in the experimental study of the  $\Lambda_b$  baryon. Its production and lifetime have been measured in  $Z$  decays at LEP, using semi-leptonic decays [1]. The  $\Lambda_b$  lifetime is now known with a precision of  $\pm 6\%$ , which is within a factor of two of the precision of the lifetime measurements of the  $B^0$  and  $B^+$ , and comparable in precision to the  $B_s$  lifetime measurement [2].

A precise measurement of the mass of the  $\Lambda_b$  has, however, proven elusive. The PDG 94 world average of  $5641 \pm 50$  MeV/ $c^2$ , has an uncertainty which is more than twenty times bigger than that of the  $B$  mesons [3, 4]. An accurate determination of the  $\Lambda_b$  mass will provide tests of theoretical mass predictions based on potential models [5], heavy quark effective theory [6] or lattice QCD calculations [7], and will be important for future studies of the  $\Lambda_b$ .

This  $\Lambda_b$  mass measurement is based on a sample of four million hadronic  $Z$  decays collected by the ALEPH experiment during the 1991-1995 running of LEP.  $\Lambda_b$  baryons are fully reconstructed in the decay channels<sup>1</sup>  $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ , with  $\Lambda_c^+ \rightarrow p K^- \pi^+$ ,  $p \bar{K}^0$  or  $\Lambda \pi^+ \pi^+ \pi^-$ . A similar analysis has recently been reported by the DELPHI collaboration at LEP, based on the decay modes  $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$  and  $\Lambda_b \rightarrow \Lambda_c^+ a_1^-$  with  $\Lambda_c^+ \rightarrow p K^- \pi^+$ . This analysis measures the  $\Lambda_b$  mass to be  $5668 \pm 16$  (*stat.*)  $\pm 8$  (*syst.*) MeV/ $c^2$  [8].

## 2 The ALEPH Detector

The ALEPH detector and its performance are described in detail elsewhere [9]. In this section, only a brief description of the parts of the apparatus most important to this analysis is given. The critical elements are charged particle tracking, including especially the silicon vertex detector, and particle identification with ionization energy loss (dE/dx).

Charged particles are tracked with three concentric devices residing inside an axial magnetic field of 1.5 T. Just outside the 5.4 cm radius beampipe is the vertex detector (VDET) [10], which consists of silicon microstrip detectors with strip readout in two orthogonal directions. The strip detectors are arranged in two cylindrical layers at average radii of 6.5 and 11.3 cm, with solid angle coverage of  $|\cos \theta| < 0.85$  for the inner layer, and  $|\cos \theta| < 0.67$  for the outer layer. The point resolution for tracks at normal incidence is 12  $\mu\text{m}$  in both the  $r\phi$  and  $z$  projections.

Surrounding the VDET is the inner tracking chamber (ITC), a cylindrical drift chamber with up to eight measurements in the  $r\phi$  projection. Outside the ITC, the time projection chamber (TPC) provides up to 21 space points for  $|\cos \theta| < 0.79$ , and a decreasing number of measurements at smaller angles, with four points at  $|\cos \theta| = 0.96$ .

The combined tracking system has a transverse momentum resolution of  $\Delta p_t/p_t = 0.0006 \times p_t \oplus 0.005$  ( $p_t$  in GeV/ $c$ ). For tracks with hits in both VDET layers the impact parameter resolution on a track of momentum  $p$  is  $25 \mu\text{m} + 95 \mu\text{m}/p$  ( $p$  in GeV/ $c$ ).

In addition to tracking, the TPC is used for particle identification by measurement of the ionization energy loss associated with each charged track. It provides up to 338 dE/dx measurements, with a measured resolution of 4.5% for Bhabha electrons with at

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<sup>1</sup>Throughout this paper, charge-conjugate modes are also implied.

least 330 ionization samples. For charged particles with momenta above 3 GeV/c, the mean dE/dx gives  $\approx 3$  standard deviation ( $\sigma$ ) separation between pions and protons and  $\approx 1\sigma$  separation between kaons and protons.

In the following, particle identification with energy loss is specified in terms of the dE/dx estimator defined as  $\chi_a = (I_a - I_{meas})/\sigma_a$ , where  $I_{meas}$  is the measured energy loss,  $I_a$  the expected energy loss under the hypothesis that the candidate is a  $\pi$ ,  $K$ , or  $p$  and  $\sigma_a$  is the expected error on  $I_a$ . The dE/dx is defined as available if more than 50 samples are present. This occurs for 82% of the tracks and this fraction is well simulated in the Monte Carlo.

### 3 $\Lambda_b$ Reconstruction

The  $\Lambda_b$  is reconstructed using the decay  $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ , with  $\Lambda_c^+ \rightarrow pK^- \pi^+$ ,  $p\bar{K}^0$ , or  $\Lambda\pi^+ \pi^+ \pi^-$ . The world average branching ratios [3] for these channels ( $(4.4 \pm 0.6)\%$ ,  $(2.1 \pm 0.4)\%$ , and  $(2.7 \pm 0.6)\%$  respectively) combined with the expected  $\Lambda_b$  production rate ( $\approx 0.04/\text{hadronic } Z$  decay) and the  $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$  branching ratio ( $\approx 3 \times 10^{-3}$ ) leads to a small number of events to be detected. The selection procedure therefore needs to remain efficient and yet be effective at reducing combinatorial backgrounds and “reflection” backgrounds in which other decays mimic the signal when one of the decaying particles is assigned the wrong mass hypothesis.

Control of the combinatorial background is obtained by relying on the good mass resolution provided by the ALEPH tracking system and the use of decay length requirements which largely reduce the probability of selecting tracks originating from the primary vertex. The “reflection” backgrounds are suppressed by rejecting mass combinations which could be a reflection from a  $D_s^+$  or  $D^+$  meson decay and also by requirements on the dE/dx of the proton candidate. The detailed  $\Lambda_c^+$  selection cuts are described in section 3.1 and the  $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$  selection is described in section 3.2.

#### 3.1 Selection of the $\Lambda_c^+$

The backgrounds from  $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$  events are reduced by making a preselection based on the lifetime tag probability described in [11]. Events for which the probability,  $P_{uds}$ , that all the charged tracks originate from the primary vertex is greater than 1% are rejected.

In the  $\Lambda_c^+ \rightarrow pK^- \pi^+$  channel, the proton, kaon and pion candidates are required to have momenta greater than 2, 1.5 and 1 GeV/c respectively. The dE/dx measurement for a proton candidate is required to satisfy  $|\chi_\pi| > 2$  and  $|\chi_p| < 3$ . For kaon and pion candidates, the energy loss is required, when available, to be consistent with the expected value ( $|\chi_{K,\pi}| < 3$ ). To ensure precise vertex reconstruction, two of the three tracks are required to have at least one VDET reconstructed hit. The invariant mass calculated using a vertex constrained fit must be within 21 MeV/c<sup>2</sup> ( $3\sigma$ ) of the nominal  $\Lambda_c^+$  mass; to eliminate possible reflections from charmed meson decays  $D_s^+ \rightarrow K^+ K^- \pi^+$  and  $D^+ \rightarrow \pi^+ K^- \pi^+$ , all combinations with invariant mass within 21 MeV/c<sup>2</sup> ( $3\sigma$ ) of the  $D_s^+$  or  $D^+$  mass (using appropriate mass assignments for the tracks) are rejected.

In the  $\Lambda_c^+ \rightarrow \Lambda\pi^+ \pi^+ \pi^-$  channel, the  $\Lambda$  candidates are identified by their decay

$\Lambda \rightarrow p\pi^-$  using a slightly modified version of the algorithm described in [12]: to reduce the combinatorial background, the two oppositely charged tracks are required to have a total momentum greater than 3 GeV/c, and to form a vertex corresponding to a decay length of at least 3 cm from the interaction point. The TPC energy loss measurements of the pion and proton candidates, when available, are required to satisfy  $|\chi_\pi| < 3$  and  $|\chi_p| < 3$ , respectively. To reduce the possible contamination from other displaced vertices, the invariant mass of the two daughter tracks is required to be within 9 MeV/c<sup>2</sup> ( $3\sigma$ ) of the  $\Lambda$  nominal mass and incompatible with the  $\gamma \rightarrow e^+e^-$  hypothesis ( $M_{e^+e^-} > 15$  MeV/c<sup>2</sup>). If the dE/dx information for the proton candidate is consistent with that of a pion ( $|\chi_\pi| < 2$ ) or the dE/dx information is not available, an additional cut to remove  $K_s^0$ 's is applied ( $|M_{\pi\pi} - M_{K_s^0}| > 10$  MeV/c<sup>2</sup>). All three pions from the  $\Lambda_c^+$  decay are required to have momenta greater than 0.5 GeV/c and  $|\chi_\pi| < 3$  when available. Finally, the  $\Lambda_c^+$  candidate is required to have a mass within 20 MeV/c<sup>2</sup> ( $3\sigma$ ) of the  $\Lambda_c^+$  nominal mass.

In the  $\Lambda_c^+ \rightarrow p\bar{K}^0$  channel, the proton and the  $\bar{K}^0$  are required to have momenta greater than 3 and 2 GeV/c, respectively. The  $\bar{K}^0$  candidates are reconstructed in the  $K_s^0 \rightarrow \pi^+\pi^-$  channel using the same algorithm as for the  $\Lambda$  selection described previously. The two charged daughter tracks have to fulfill the condition  $|\chi_\pi| < 3$ , when the dE/dx measurements are available, and their invariant mass, with appropriate mass assignments, is required to be within 13 MeV/c<sup>2</sup> ( $3\sigma$ ) of the  $K^0$  nominal mass and incompatible with the  $\gamma$  and  $\Lambda$  hypotheses; namely,  $M_{e^+e^-} > 15$  MeV/c<sup>2</sup>, and  $|M_{p\pi} - M_\Lambda| > 5$  MeV/c<sup>2</sup> when  $|\chi_p| < 2$  for at least one of the pion candidates or their dE/dx information are not available. The decay length of the  $K_s^0$  candidate has to be greater than 1.5 cm with respect to the interaction point. The  $\Lambda_c^+$  candidate is obtained by adding a proton track to the  $K_s^0$ . The proton candidate must have at least one VDET reconstructed hit and the dE/dx measurement must be compatible with the proton but not the pion hypothesis ( $|\chi_p| < 3$  and  $|\chi_\pi| > 2$ ). To reduce combinatorial background from low momentum proton candidates, the cosine of the decay angle of the proton candidate in the  $pK_s^0$  rest frame has to be greater than  $-0.8$ . The invariant mass of the  $pK_s^0$  system is required to be within 24 MeV/c<sup>2</sup> ( $3\sigma$ ) of the  $\Lambda_c^+$  nominal mass. To remove possible reflections from the charmed meson decays  $D_s^+ \rightarrow K^+\bar{K}^0$  and  $D^+ \rightarrow \pi^+\bar{K}^0$ , all combinations with invariant mass within 24 MeV/c<sup>2</sup> ( $3\sigma$ ) of the  $D_s^+$  or  $D^+$  mass (using appropriate mass assignments for the tracks) are rejected.

### 3.2 Selection of $\Lambda_b \rightarrow \Lambda_c^+\pi^-$

The  $\Lambda_c^+$  candidates with momentum greater than 6 GeV/c are combined with charged tracks in the same hemisphere, as defined by the event thrust axis. The additional track must have momentum greater than 5 GeV/c, at least one reconstructed VDET hit, and an energy loss within  $3\sigma$  of that expected for a pion. The resulting  $\Lambda_b$  candidate is required to have a momentum greater than 30 GeV/c.

The tracks from the  $\Lambda_c^+$  are vertexed to form a  $\Lambda_c^+$  track which in turn is combined with the pion candidate to form a  $\Lambda_b$  vertex. During this last step the mass resolution on the  $\Lambda_b$  is improved by constraining the mass of the  $\Lambda_c^+$  candidate to the  $\Lambda_c^+$  world average mass [3]. The  $\Lambda\pi^+\pi^+\pi^-$  vertex is reconstructed using the three charged pions only, since most of the  $\Lambda$ 's decay after the VDET and therefore do not add a significant constraint in the vertex fit. The  $\chi^2$  probabilities of the  $\Lambda_c^+$  and  $\Lambda_b$  vertices are both required to be greater than 1%.



To reduce backgrounds due to tracks originating from the primary vertex, a requirement is made on the ratio of the projected decay length<sup>2</sup> to its error for the  $\Lambda_b$  candidate:  $R_l = l_{\Lambda_b}/\sigma_{\Lambda_b} > 4$  for the decay  $\Lambda_c^+ \rightarrow p\bar{K}^-\pi^+$  decay, and  $R_l > 2$  for the two other  $\Lambda_c$  decay channels, in which the background contamination is lower. For the  $\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^-$  channel, the three-pion projected decay length is used in place of  $l_{\Lambda_b}$  as Monte Carlo studies indicate that this quantity gives improved background rejection for the same efficiency. To ensure consistent decay topologies,  $\Lambda_b \rightarrow \Lambda_c^+\pi^-$ , followed by  $\Lambda_c^+$  decay, the requirement  $(l_{\Lambda_c} - l_{\Lambda_b})/\sqrt{\sigma_{\Lambda_b}^2 + \sigma_{\Lambda_c}^2} > -2$  is made.

After applying the full selection procedure, the final efficiencies, with branching ratios not included, are 4.8%, 7.2% and 3.6% for the  $\Lambda_c^+ \rightarrow p\bar{K}^-\pi^+$ ,  $p\bar{K}^0$  and  $\Lambda\pi^+\pi^+\pi^-$  channels respectively.

### 3.3 Results

Applying the selection criteria to the data sample, four  $\Lambda_b$  candidates are selected in the right-sign combinations ( $\Lambda_c^+\pi^-$ ) above an invariant mass of 5.4 GeV/ $c^2$  (figure 1a). Two of these candidates are in the  $\Lambda_c^+ \rightarrow p\bar{K}^-\pi^+$  channel, and there is one candidate in each of the other two modes. For the wrong-sign combinations ( $\Lambda_c^+\pi^+$ ), no candidates with mass above 5.4 GeV/ $c^2$  are found, as shown in figure 1b.

Figure 1c shows the measured values of the  $\Lambda_b$  mass for the four candidates. The errors on the mass are the event-by-event uncertainty coming from the mass constrained vertex fit. The uncertainties have been increased by 20% as studies of the uncertainty on the mass found using  $\bar{B}^0 \rightarrow D^+\pi^-$  events in data show that they are underestimated by this factor.

Table 1: Some properties of the four  $\Lambda_b$  candidates. Momenta, decay lengths, proper times and measured  $\Lambda_b$  masses are listed.

	candidate 1	candidate 2	candidate 3	candidate 4
preferred hypothesis	$\Lambda_c \rightarrow p\bar{K}\pi$	$\Lambda_c \rightarrow p\bar{K}\pi$	$\Lambda_c \rightarrow \Lambda\pi\pi\pi$	$\Lambda_c \rightarrow p\bar{K}^0$
$\Lambda_c \pi$ mass (MeV/ $c^2$ )	$5628 \pm 23$	$5622 \pm 58$	$5615 \pm 31$	$5577 \pm 41$
$\Lambda_c$ momentum (GeV/ $c$ )	22.5	8.6	24.9	9.5
$\Lambda_b$ momentum (GeV/ $c$ )	36.6	37.1	37.8	32.0
projected decay length (mm)	$2.86 \pm 0.13$	$3.50 \pm 0.20$	$0.91 \pm 0.43$	$3.60 \pm 0.58$
proper time (ps)	$1.47 \pm 0.07$	$1.77 \pm 0.10$	$0.45 \pm 0.21$	$2.10 \pm 0.34$

Table 1 summarises some relevant parameters for the four  $\Lambda_b$  candidates. The  $\chi^2$  probability for the mass distribution that the events come from a single narrow state, as expected for the  $\Lambda_b$ , is 75%.

<sup>2</sup>More explicitly,  $l_X = L_X \cdot \vec{P}_X / |\vec{P}_X|$ , where  $L_X$  is the vector drawn from the interaction point to the X vertex, and  $\vec{P}_X$  is the X momentum vector.

## 4 Background Estimate

A very approximate background estimate can be made on the data by fitting the invariant mass distribution with an exponential for the background and a Gaussian for the signal. The number of background events between 5.5 and 5.7 GeV/ $c$  extracted from such a fit is 0.3. The precision of this method is rather limited due to the low number of events, the naive assumption of an exponentially decreasing background and the presence of events like  $\Lambda_b \rightarrow \Lambda_c^+ \rho^-$  or  $\Lambda_b \rightarrow \Lambda_c^+ a_1^-$  that can populate the  $\Lambda_c^+ \pi^-$  invariant mass distribution below the true  $\Lambda_b$  mass but do not contribute to the background in the  $\Lambda_b$  mass region.

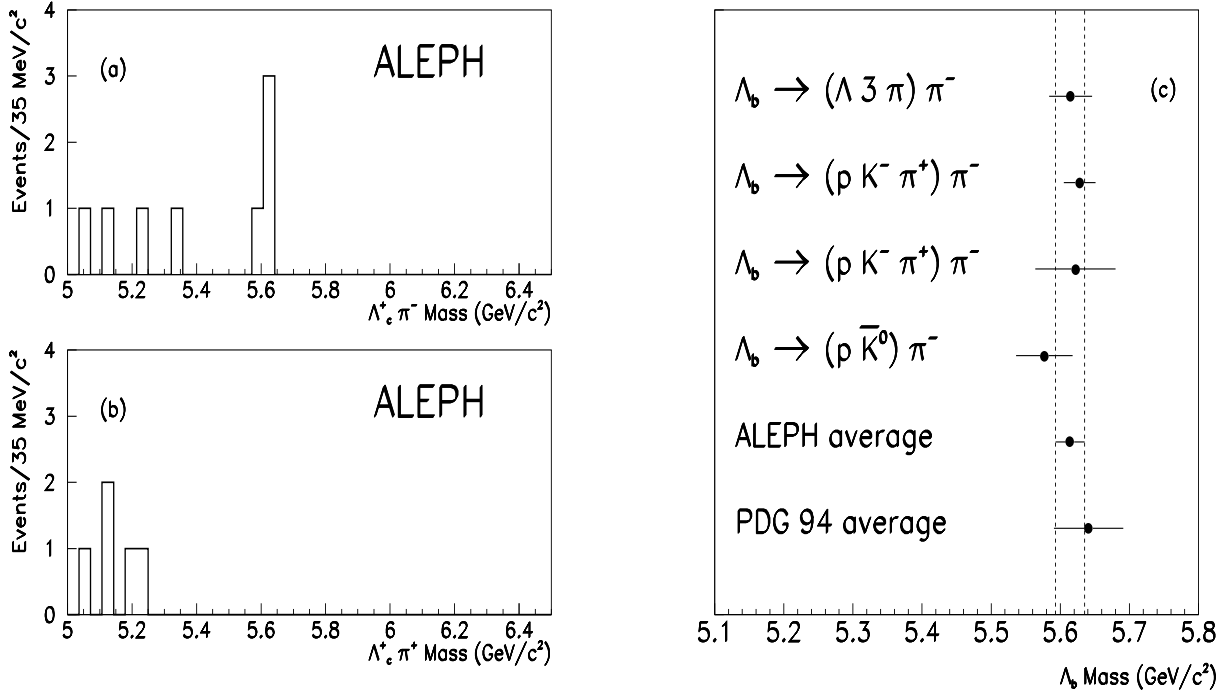


Figure 1: (a)  $\Lambda_c \pi$  invariant mass distribution for the right-sign combinations and (b) wrong-sign combinations. (c)  $\Lambda_b$  invariant masses for the four selected candidates. Also shown are the average value and the PDG 94 world average. The dotted lines indicate the  $\pm 1\sigma$  values around the ALEPH average measurement.

A more accurate method to evaluate the level of background in the  $\Lambda_b$  candidate sample is to study the number of events passing the selection requirements using dedicated high statistics Monte Carlo samples containing the backgrounds of interest. For these studies an event is defined as background if it falls in a signal region of  $\pm 100$  MeV/ $c^2$  around the  $\Lambda_b$  mass used in the Monte Carlo and is not a correctly reconstructed  $\Lambda_b$ . To further increase the statistical power of the Monte Carlo samples, various selection criteria are relaxed and the number of background events found in the signal region scaled down by the known background rejection factor of the relaxed cuts.

Using this method the following sources of background have been considered:

1. Fake  $\Lambda_c^+$  baryons from combinatorial background in  $Z \rightarrow b\bar{b}$  events.
2. Fake  $\Lambda_c^+$  baryons from combinatorial background in  $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$  events.
3. Combinations of random charged tracks with true  $\Lambda_c^+$  baryons in  $Z \rightarrow c\bar{c}$  and  $Z \rightarrow b\bar{b}$  events.
4. Reflection backgrounds from  $B^0$ ,  $B^+$  and  $B_s^0$  decays.
5. Decays from  $b$ -baryons.

Their contributions to the background estimate are summarised in table 2 and are discussed in detail in the following sections.

Table 2: The estimated number of events in each background category corresponding to the full data sample of 4 million hadronic  $Z$  decays.

Background component	$\Lambda_c^+$ decay mode		
	$\Lambda_c^+ \rightarrow pK^-\pi^+$	$\Lambda_c^+ \rightarrow pK^0$	$\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^-$
Comb. $Z \rightarrow b\bar{b}$	$0.17 \pm 0.05$	$(9 \pm 6) \times 10^{-3}$	$0.03 \pm 0.03$
Comb. $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$	$< 1 \times 10^{-3}$	$< 1 \times 10^{-3}$	$< 1 \times 10^{-3}$
$b \rightarrow \Lambda_c^+$	$(8 \pm 8) \times 10^{-3}$	$< 1 \times 10^{-3}$	$(3 \pm 3) \times 10^{-3}$
$c \rightarrow \Lambda_c^+$	$(3 \pm 1) \times 10^{-3}$	$< 1 \times 10^{-3}$	$< 1 \times 10^{-3}$
$B_s^0$ Refl.	$0.03 \pm 0.01$	$0.03 \pm 0.01$	$< 1 \times 10^{-3}$
$B^0, B^+$ Refl.	$0.05 \pm 0.01$	$0.04 \pm 0.01$	$(9 \pm 9) \times 10^{-3}$
$b$ -baryon cascade	$< 1 \times 10^{-3}$	$< 1 \times 10^{-3}$	$< 1 \times 10^{-3}$
Total Background	$0.26 \pm 0.05$	$0.08 \pm 0.02$	$0.04 \pm 0.03$
	$0.38 \pm 0.06$		

#### 4.1 Combinatorial Background: $Z \rightarrow b\bar{b}$

Analysing with the standard selection a  $Z \rightarrow b\bar{b}$  Monte Carlo sample equivalent to 8.6 million  $Z$  events gives no combinations from this source in the signal region. To get a better estimate of this background in the Monte Carlo the  $dE/dx$  requirements on the proton candidate ( $|\chi_p| < 3$  and  $|\chi_\pi| > 2$ ) are not applied. To avoid the excess of events at low mass from  $\Lambda_b$  events which are not fully reconstructed, any event originating from a  $\Lambda_b$  decay is removed. Using this procedure a total of 169 combinatorial events are found with a mass between  $4.5 - 6$  GeV/ $c^2$ , and are dominated by events in which pions from the fragmentation are selected as the proton candidate. There is also a smaller component coming from random combinations in which all tracks originate from the  $B$  decay. To be conservative these latter events are not removed from the combinatorial background estimate, even though they may be included in the reflection background estimates discussed later.

The observed mass distribution is then fitted to an exponential and the number of background events in the signal region is estimated. The rejection factors (0.026 for pions,

0.5 for kaons and 0.73 for protons) of the proton  $dE/dx$  requirements are derived from a detailed Monte Carlo simulation which is checked against data by studying protons and pions from  $\Lambda$  decays. Taking account of the relative statistics between data and Monte Carlo the number of background events is predicted to be  $0.17 \pm 0.05$  and  $(9 \pm 6) \times 10^{-3}$  for the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow p\bar{K}^0$  channels respectively.

For the  $\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^-$  channel, the cut on  $l_{\pi\pi\pi}$  is effective at reducing this background. Removing this cut in the Monte Carlo and scaling the observed number of events by the rejection power of the cut and the statistics of the Monte Carlo sample leads to an estimated background level of  $0.03 \pm 0.03$  from this source.

To check the level of combinatorial background predicted by the Monte Carlo, the number of events found when applying the loose cuts are compared in data and Monte Carlo. For all decays channels they are consistent within the statistical uncertainty.

## 4.2 Combinatorial Background: $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$

Applying the standard selection criteria to a  $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$  Monte Carlo sample equivalent to 5.6 million  $Z$  events and to a  $Z \rightarrow c\bar{c}$  Monte Carlo sample equivalent to 8.6 million  $Z$  events, no combinatorial background events are found in the signal region.

The background from  $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$  events is largely eliminated by the cut on the  $P_{uds}$  probability, the  $\Lambda_b$  decay length, and the  $\Lambda_b$  momentum. If all these three cuts are removed, zero events are found in the signal region. Scaling down by the rejection power of these cuts and the Monte Carlo statistics, the number of background events expected from these sources is less than  $1 \times 10^{-3}$  for each channel.

## 4.3 Combinatorial Background with True $\Lambda_c^+$

The number of background events coming from a true  $\Lambda_c^+$  and combined with a random pion is estimated using dedicated Monte Carlo samples containing inclusive  $\Lambda_c^+$  from all sources. The contribution of both  $Z \rightarrow b\bar{b}$  and  $Z \rightarrow c\bar{c}$  events to this part of the combinatorial background is less than  $4 \times 10^{-2}$ .

## 4.4 Reflection Backgrounds

For the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow p\bar{K}^0$  decay modes, in addition to the combinatorial background, there are reflections which can populate the  $\Lambda_b$  candidate invariant mass spectrum. This background arises when either a pion or a kaon is selected as a proton candidate. For example, in the decay  $D^+ \rightarrow K^-\pi^+\pi^+$  a misinterpretation of a  $\pi^+$  as a  $p$  can form a  $K^-\pi^+p$  mass close to the known  $\Lambda_c^+$  mass. Similarly, in the  $D_s^+ \rightarrow K^+K^-\pi^+$  decay mode it is possible to simulate a  $\Lambda_c^+$  when the  $K^+$  is misidentified as a proton. Although the selection procedure includes cuts to reject combinations consistent with  $D_s^+ \rightarrow K^+K^-\pi^+$ ,  $D^+ \rightarrow \pi^+K^-\pi^+$ ,  $D_s^+ \rightarrow K^+\bar{K}^0$  and  $D^+ \rightarrow \pi^+\bar{K}^0$  the amount of background remaining after the cuts, due to the tails of the mass distributions, remains significant. This has been evaluated with dedicated Monte Carlo samples, equivalent to 15 times the size of the data sample, and is found to be  $(1.2 \pm 0.3) \times 10^{-2}$ .

For the  $\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^+ \pi^-$  channel, possible reflection backgrounds are  $D^+ \rightarrow K_s^0 \pi \pi \pi$  and  $D_s^+ \rightarrow K_s^0 K^+ \pi \pi$  in which the  $K_s^0$  fakes the  $\Lambda$  and in the latter decay a charged kaon is misidentified as a pion. Monte Carlo studies indicate  $0.01 \pm 0.01$  background events are expected from this process.

Another possible reflection background which is not explicitly removed by the selection cuts are the Cabibbo suppressed decays  $D^+ \rightarrow K^+ K^- \pi^+$ ,  $D^+ \rightarrow K^+ \bar{K}^0$  and  $D_s^+ \rightarrow \pi^+ \pi^- K^+$ . Although the branching ratios for these decays are lower, the first two of these decays are particularly dangerous as the  $dE/dx$  cuts on the proton are less effective against a kaon faking a proton. The sum of these decays is expected to contribute  $0.04 \pm 0.02$  events to the background.

Reflection backgrounds in which the charm particle decay contains neutral particles, for example the decays  $\bar{B}^0 \rightarrow D^+ \pi^-$  with  $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$  and  $\bar{B}_s \rightarrow D_s^+ \pi^-$  with  $D_s^+ \rightarrow K^+ K^- \pi^+ \pi^0$ , or the Cabibbo suppressed versions  $\bar{B}^0 \rightarrow D^+ \pi^-$  with  $D^+ \rightarrow K^- K^+ \pi^+ \pi^0$  and  $\bar{B}_s \rightarrow D_s^+ \pi^-$  with  $D_s^+ \rightarrow K^+ \pi^- \pi^+ \pi^0$  must also be considered. Due to the presence of the neutral particle, the mass cuts against the  $D_s$  and  $D$  are no longer effective. For the same reason, the reflected mass is also shifted to lower values and is less peaked, thereby reducing the importance of this background. Monte Carlo studies indicate  $0.05 \pm 0.02$  background events from this source are expected.

Reflection backgrounds from  $B$  decays containing a  $D^*$ , such as  $\bar{B}^0 \rightarrow D^{*+} \pi^-$  with  $D^{*+} \rightarrow D^0 \pi^+$  followed by  $D^0 \rightarrow K^- \pi^+$  or  $D^0 \rightarrow K^+ K^-$ , in which the slow pion from the  $D^*$  is selected give an expected background level of  $0.008 \pm 0.002$ . Their contribution is small as they are unlikely to give a mass within the  $\Lambda_c^+$  mass region and because of the 1 GeV/ $c$  momentum cut on the pion.

Contributions from other decays, such as  $\bar{B}^0 \rightarrow D^+ \rho^-$  with  $D^+ \rightarrow K^- K^+ \pi^+$  or  $B^- \rightarrow D^0 \pi^-$  with  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  have also been found to be small and are included in the estimates.

For the  $\Lambda_b$  candidates, the deviations of the measured masses from the known  $c$  and  $b$  hadrons assuming some of the mass hypotheses discussed above are shown in table 3. It can be seen that all hypotheses corresponding to the reflections are excluded at the level of several standard deviations, except for the case of  $D^+ \rightarrow K^+ \bar{K}^0$  ( $0.72\sigma$ ). However, when combining this candidate with the pion, the resulting  $B^0$  mass is  $10\sigma$  away from the nominal  $B^0$  mass.

## 4.5 Background from $b$ -Baryons

The last source of possible background is contamination due to the hadronic decay of  $b$ -baryons. The following three decay modes have been studied:  $\Xi_b \rightarrow \Xi_c X$ ,  $\Sigma_b \rightarrow \Lambda_b X$  and  $\Lambda_b \rightarrow \Lambda_c^+ \pi^- X$ .

The production of  $\Xi_b$  in  $Z \rightarrow b\bar{b}$  decay is suppressed because an  $s$  quark has to be generated in the hadronization. In the  $\Sigma_b$  strong decay a  $\Lambda_b$  is generated and if correctly reconstructed could contribute to the signal. There is also the possibility of wrongly associating a pion from the  $\Sigma_b$  with the  $\Lambda_c^+$  from the  $\Lambda_b$  decay. This background is however suppressed by the decay length cut, since the pion comes from the primary vertex. Both  $\Xi_b$  and  $\Sigma_b$  have been studied using specific Monte Carlo samples and their contribution to the background is found to be less than  $1 \times 10^{-3}$ .

Table 3: Various mass hypotheses for the four  $\Lambda_b$  candidates have been checked. The deviations in terms of  $\sigma$  from the known hadron masses are shown for  $\Lambda$ ,  $K^0$  and  $\Lambda_c^+$ . For the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  and  $\Lambda_c^+ \rightarrow p\bar{K}^0$  channels the “reflected” masses obtained when the proton candidate is given a pion or kaon mass are also included. Similarly, for the  $\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^-$  channel the masses obtained when the  $\Lambda$  is assumed to be  $K^0$  are given. The proton candidate dE/dx estimators for the various hypotheses are also listed. The values corresponding to signal hypotheses are shown in boldface.

					candidates			
					$pK\pi$	$p\bar{K}\pi$	$\Lambda 3\pi$	$pK^0$
proton	$\chi_p$				<b>0.27</b>	<b>-0.60</b>	<b>0.97</b>	<b>0.70</b>
candidate	$\chi_K$				-0.78	-0.77	0.28	0.06
dE/dx	$\chi_\pi$				-2.34	-2.37	-0.79	-2.6
x				h	$(M_x - M_h)/\sigma_x$			
-	-	$p\pi$	$p\pi$	$\Lambda$	-	-	<b>0.09</b>	15.1
-	-	$\pi\pi$	$\pi\pi$	$K^0$	-	-	-6.82	<b>0.29</b>
$pK\pi$	$pK\pi$	$\Lambda 3\pi$	$p\bar{K}^0$	$\Lambda_c$	<b>1.01</b>	<b>-2.00</b>	<b>0.86</b>	<b>0.14</b>
$\pi K\pi$	$\pi K\pi$	$\bar{K}^0 3\pi$	$\pi\bar{K}^0$	$D$	12.9	-59.5	-2.77	-23.6
$KK\pi$	$KK\pi$	$\bar{K}^0 K 2\pi$	$K\bar{K}^0$	$D_s$	11.7	-37.1	8.49	-13.6
$KK\pi$	$KK\pi$	-	$K\bar{K}^0$	$D$	25.9	-22.9	-	0.72
$(\pi K\pi)\pi$	$(\pi K\pi)\pi$	$(\bar{K}^0 3\pi)\pi$	$(\pi\bar{K}^0)\pi$	$B^0$	6.04	-39.5	5.00	-18.7
$(KK\pi)\pi$	$(KK\pi)\pi$	$(\bar{K}^0 K 2\pi)\pi$	$(K\bar{K}^0)\pi$	$B_s^0$	4.41	-28.0	18.2	-14.1
$(KK\pi)\pi$	$(KK\pi)\pi$	-	$(K\bar{K}^0)\pi$	$B^0$	8.24	-24.1	-	-10.2

The possibility of contamination from  $\Lambda_b \rightarrow \Lambda_c^+ \pi^- X$  decays in which neutral and/or charged particles are missed in the reconstruction is also unlikely. These would give entries in the mass distribution at least a pion mass below the  $\Lambda_b$  mass and thus would not enter the signal region. In addition, for this type of process the momentum of the reconstructed  $\Lambda_b$  candidate peaks at 20 GeV/ $c$  and is therefore suppressed by the 30 GeV/ $c$  cut on the  $\Lambda_b$  momentum.

## 5 $\Lambda_b$ Mass Measurement

The expected total number of background candidates from all sources is  $0.38 \pm 0.06$ . Taking into account the different contribution of each channel to the background, the probability that this background fluctuates to produce the four observed candidates is estimated to be  $4.2 \times 10^{-4}$ . The statistical significance of the observed mass peak therefore is  $3.3\sigma$ , where the obvious mass clustering of the candidates has not been taken into account.

To calculate the  $\Lambda_b$  mass and its uncertainty a fast Monte Carlo is used in which many simulated experiments are generated. For each experiment the number of background events is decided according to a Poisson distribution whose mean is the background estimate. These background events are then removed from the four candidates observed in the data. The probability of removing a certain event is weighted according to the predicted background levels of its decay channel. For the remaining signal events the mass is randomly picked from Gaussian distributions whose mean and sigma are those of the selected candidate. The mass of the  $\Lambda_b$  for one experiment is then just the weighted mean of the signal events. Using this procedure on many fast Monte Carlo experiments the resulting distribution of  $\Lambda_b$  masses is found to have a mean of 5614 MeV/ $c^2$  with an rms of 21 MeV/ $c^2$ . A simple weighted average of the four candidates, neglecting a possible background contribution, would give  $5616 \pm 16$  MeV/ $c^2$ .

To evaluate the systematic error on the mass due to the uncertainty of the background estimate, the mean of the expected background level is varied by one sigma. The maximum deviation of the mean of the  $\Lambda_b$  mass distribution is found to be 1 MeV/ $c^2$ .

The main source of systematic error on the mass comes from the mass scale calibration. This uncertainty is estimated from fully reconstructed charmed and beauty mesons to be 0.12% [13]. This corresponds to a 4 MeV/ $c^2$  systematic error on the  $\Lambda_b$  mass value measured after the  $\Lambda_c^+$  mass constrained fit. Other sources of systematic error such as the alignment of the ALEPH tracking system and the possibility of interchange of ambiguous hits in the various tracking detectors have been found to be negligible. The measured value of the  $\Lambda_b$  mass is

$$M_{\Lambda_b} = 5614 \pm 21 (stat.) \pm 4 (syst.) \text{ MeV}/c^2. \quad (1)$$

## 6 Conclusions

In a data sample of four million hadronic  $Z$  decays recorded with the ALEPH detector at LEP, four candidate  $\Lambda_b$  decays are fully reconstructed in the decay mode  $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ . Based on the background estimate of  $0.38 \pm 0.06$  events, the statistical significance of the

observed peak is at the  $3.3\sigma$  level. From the four events, the mass of the  $\Lambda_b$  baryon is measured to be  $M_{\Lambda_b} = 5614 \pm 21(stat.) \pm 4(syst.) \text{ MeV}/c^2$ .

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