Search for exclusive decays of the Λ_b baryon and measurement of its mass

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DELPHI Collaboration

Abstract

A search for fully reconstructed Λ_b^0 beauty baryons is performed using about 3 million Z decays collected with the DELPHI detector at LEP. The analysis relies on the combined use of the accurate tracking and of the hadron identification capabilities of DELPHI. A total of four events has been found, three in the $\Lambda_c^+ \, \pi^-$ channel and one in the $\Lambda_c^+ \, a_1^-$ channel over a small background. The Λ_b^0 beauty baryon mass is measured to be (5668 ± 16 (stat.) $\pm$ 8 (syst.)) MeV/c^2 .

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1 Introduction

Signals of exclusive decays of the Λ_b^0 beauty baryon have been searched for by several experiments at hadron colliders and at the large electron positron collider LEP. The UA1 collaboration reported an excess of events in the channel J/ψ Λ^0 corresponding to a Λ_b^0 mass of $(5640 \pm 50 \pm 30)$ MeV/c^2 [1], but the result has not yet been confirmed by a similar analysis performed by experiments at the Tevatron. Searches at LEP for Λ_b^0 events in this channel have been unsuccessful so far. The SFM collaboration has published evidence for the Λ_b^0 beauty baryon in the $pD^0\pi^-$ and $\Lambda_c^+\pi^-\pi^+\pi^-$ channels, with a mass of respectively $(5640\ ^{+100}_{-200})$ MeV/c^2 and $(5650\ ^{+150}_{-200})$ MeV/c^2 [2]. Evidence for Λ_b^0 beauty baryon production has been obtained at LEP through the partial reconstruction of its semileptonic decay modes [3].

The mass of the Λ_b^0 beauty baryon predicted by potential models ranges from 5600 to 5900 MeV/c^2 [4]. Recent calculations from lattice QCD give values from 5590 to 5728 MeV/c^2 [5]. A calculation in the framework of Heavy Quark Effective Theory (HQET) gives the prediction of (5625 ± 2) MeV/c^2 [6] in the static limit, neglecting some terms proportional to $1/M$ where M is the bottom or charm quark mass. An accurate measurement of the Λ_b^0 mass would test these predictions.

In this letter the results of the measurement of the Λ_b^0 mass using the data collected by the DELPHI experiment are presented. The search for fully reconstructed Λ_b^0 decays was performed in the channels $\Lambda_c^+\ \pi^-$, $\Lambda_c^+\ a_1^-$ and J/ψ Λ^0 .[1] These channels, analogous to those used for the measurement of the B_s^0 mass [7], were selected because the branching ratios are expected to be large and because of the strong background rejection obtained in these channels, due to the presence of a fully reconstructed charmed particle (Λ_c^+ or J/ψ) in the final state.

The analysis used the full statistics collected in the DELPHI experiment from 1991 to 1994, corresponding to about 3 million Z hadronic decays. The Λ_b^0 reconstruction relies on the combined use of the accurate tracking and of the hadron identification capabilities of DELPHI. The silicon Microvertex detector enables a precise primary vertex and secondary b and c hadron vertex reconstruction. On the basis of the Cherenkov photons in the Ring Imaging CHerenkov (RICH) detector and the specific ionization dE/dx measured in the Time Projection Chamber (TPC), the proton and kaon in the final state were identified and backgrounds were significantly reduced.

This letter is organized as follows. After a brief description of the DELPHI detector, particle identification and event selection criteria, the Λ_b^0 reconstruction in the different channels is discussed in section 3. Section 4 contains a discussion of the Λ_b^0 candidates and the measurement of the Λ_b^0 mass, while the conclusions are presented in section 5.

2 Particle identification and event selection

A description of the DELPHI apparatus can be found in reference [8]. Only the silicon Microvertex detector and the Barrel RICH will be briefly described here because of their importance for this analysis. A single sided read-out silicon Microvertex detector, consisting of three layers, measured points in the $R\phi$ coordinate [2] and was operational for the data taken from 1991 to 1993. In 1994, two layers were equipped with detector modules with double sided readout. A single hit resolution of 7.6 μm in the $R\phi$ coordinate

[1] Throughout the paper charge-conjugate states are implicitly included.

[2] In the DELPHI coordinate system, z is along the electron direction, x points towards the center of LEP and y points upwards. The polar angle to the z axis is θ, the azimuthal angle ϕ and the radial coordinate $R = \sqrt{x^2 + y^2}$.

was achieved, similar to the resolution obtained from 1991 to 1993, and 9 μm in the z coordinate [9], for high momentum tracks perpendicular to the beam pipe.

The Barrel RICH detector [10] consists of two radiators in which the Cherenkov photons are produced, one filled with liquid C_6F_{14} freon and the other with gaseous C_5F_{12} freon. The information on the measured Cherenkov angle and the observed number of photons from the two radiators is combined to identify heavy particles (protons and kaons) from 2 GeV/c up to 30 GeV/c . Using loose cuts, a mean rejection factor of around 8 is achieved for light particles (pions, muons and electrons) with an average identification efficiency of 70 % for heavy particles. Efficiencies and rejections were measured using tagged particle samples, such as kaons from D^0 decays, protons from Λ decays and well identified muons. Details on the method used for particle identification and results on the performance of the RICH detector can be found in refs. [11] and [12]. The specific ionization dE/dx, measured in the TPC, is also used to reject light particles in the momentum region from 3 GeV/c to 30 GeV/c . A mean rejection factor of about 5 is achieved for light particles with an efficiency of 60 % for heavy particles. Muons were identified using the information in the Muon Chambers and the energy deposited in the Hadron Calorimeter.

Hadronic events were selected by requiring five or more charged particles and a total energy of the charged particles larger than 11 GeV assuming all particles to be pions. The hadronic event selection efficiency was estimated from simulation to be 95.0 %. A total of about 3 million hadronic events were selected from the combined 1991-1994 data.

3 Λ_b^0 reconstruction

The search and reconstruction of Λ_b^0 beauty baryons was performed in the $\Lambda_c^+\ \pi^-$, $\Lambda_c^+\ a_1^-$ and $J/\psi\ \Lambda^0$ channels. Candidate Λ_b^0 beauty baryons were accepted in a 200 MeV/c^2 invariant mass interval in the range from 5.53 GeV/c^2 to 5.73 GeV/c^2 . This interval is centred around the Λ_b^0 mass predicted by HQET, and includes most of the other Λ_b^0 mass predictions.

3.1 The $\Lambda_c^+\ \pi^-$ and $\Lambda_c^+\ a_1^-$ channels

The Λ_c^+ baryon was reconstructed in the $pK^-\pi^+$ decay mode. Both the proton and the kaon had to be identified as heavy particles in the RICH detector. Therefore only the subset of data for which the Cherenkov detector was fully operational, corresponding to 2.2 million hadronic events, was used. The momenta of the kaon and proton were both required to be above 2 GeV/c , and at least one of them should be above 3 GeV/c . The measurements of the specific ionization dE/dx were used to reject cases in which they identified both the kaon and the proton as light particles. The ability to tag the proton and kaon resulted in a significant suppression of background. The a_1^- was reconstructed in its decay into $\rho^0\pi^-$ giving in the final state $\pi^-\pi^+\pi^-$.

To allow for an optimal reconstruction of vertices, all charged particles were required to have momenta above 1 GeV/c and at least one associated hit in the silicon Microvertex detector. In the $\Lambda_c^+\ a_1^-$ channel the momentum cut was lowered to 0.5 GeV/c for one of the particles from the a_1^- , because of the higher multiplicity of the final state.

By adding a pion to the identified proton and kaon, Λ_c^+ candidates were formed. The tracks were fitted to a common vertex and the fit χ^2 probability was required to be larger than 1 %. The Λ_c^+ candidate was accepted if its momentum was larger than 5 GeV/c and its invariant mass was between 2.235 and 2.335 GeV/c^2 .

A b-tagging algorithm was applied to reduce the background from light quark and charm decays of the Z . This algorithm uses the significance of the impact parameters of the reconstructed tracks in the event and gives the probability for the hypothesis that all of them originate at the Z production point. Events with bottom quarks give a sharp peak at low probabilities due to the displaced secondary vertices in the decay chain of the bottom quark [12]. A cut at probabilities less than 10 % was used, giving an efficiency for b quarks of 85 %, for light quarks of 12 % and for charm quarks of 38 %. The Z production point was determined in a vertex fit imposing as a constraint the average beam spot determined over a longer period.

The combinatorial background was further reduced by requiring a well reconstructed chain of secondary decay vertices. The Λ_c^+ candidate was extrapolated and combined with either one pion or three pions in the same hemisphere to form the Λ_b^0 decay vertex. Events were rejected if a track with a momentum above 3 GeV/c , compatible within three standard deviations with the Λ_b^0 or Λ_c^+ secondary vertex, was not used in the vertex fit. The primary vertex was redetermined by intersecting the extrapolated Λ_b^0 particle with the beam spot. The decay distance between the Λ_b^0 vertex and the primary vertex was required to be larger than the associated error. Because of the hard fragmentation of the b quark, the reconstructed Λ_b^0 candidate was required to have an energy of at least 25 GeV .

Finally, a global mass constrained fit was performed, imposing the Λ_c^+ mass and recomputing the secondary and primary vertices, including both geometrical and kinematic constraints [7]. The fit in the $\Lambda_c^+ \pi^-$ channel has 7 degrees of freedom, that in the $\Lambda_c^+ a_1^-$ channels has 12. The probability of the fit had to be larger than 1 %.

The response of the detector was simulated [12] using Z decays into hadrons generated with the JETSET 7.3 Parton Shower program [13]. The reconstruction efficiencies for the different channels were measured using simulated Λ_b^0 events. The efficiency was estimated to be about 5 % in the $\Lambda_c^+ \pi^-$ channel, and about 1.5 % in the $\Lambda_c^+ a_1^-$ channel.

Four Λ_b^0 candidates were found, three in the $\Lambda_c^+ \pi^-$ channel and one in the $\Lambda_c^+ a_1^-$ channel, in the invariant mass range from 5.53 GeV/c^2 up to 5.73 GeV/c^2 (Figure 1a). The vertex display of the Λ_b^0 candidate in the $\Lambda_c^+ a_1^-$ channel is shown in Figure 2.

3.2 The J/ψ Λ^0 channel

The J/ψ Λ^0 channel allows for an almost background-free reconstruction of the Λ_b^0 by tagging the decay J/$\psi \to \mu^+\mu^-$ combined with a long flying Λ^0 decaying into a proton and a pion. Identified oppositely charged pairs of muons having an invariant mass within 150 MeV/c^2 of the world average J/ψ mass and a total momentum above 10 GeV/c were taken as J/ψ candidates.

Candidate Λ^0 's were reconstructed from pairs of oppositely charged particles consistent with originating from one common secondary vertex. No momentum cut was applied for these tracks. The track with the higher momentum was assigned the proton mass, the other the pion mass. The Λ^0 momentum was required to be above 1 GeV/c with the $p\pi^-$ vertex displaced by at least 1 cm in the $R\phi$ plane and the invariant mass in the interval between 1.108 and 1.128 GeV/c^2 . The angle between the Λ^0 flight direction and its momentum vector had to be less than 2 degrees.

Kinematical reflections from $K_s^0 \to \pi^+\pi^-$ decays were removed by requiring that either the proton was identified as a heavy particle or the invariant mass was more than three standard deviations away from the K_s^0 mass when attributing pion masses to both particles.

Finally, the Λ_b^0 decay vertex, reconstructed from the pair of muons and the Λ^0 , was required to be separated from the primary vertex by more than the error on the separation, and the energy of the Λ_b^0 had to be greater than 20 GeV .

After applying the global mass constrained fit, as described above, no events were found at invariant masses above 5.3 GeV/c^2 . The efficiency for reconstructing a Λ_b^0 in this decay mode was estimated by simulation to be 6.9 %. This result implies a 90 % confidence level upper limit on the branching ratio for the decay $\Lambda_b \to J/\psi\ \Lambda^0$ at $0.007 \times (0.10/f_{\Lambda_b})$, where f_{Λ_b} is the probability that a b quark hadronizes producing a beauty baryon Λ_b^0 .

4 Λ_b^0 mass measurement

The masses of the four Λ_b^0 candidates selected in the $\Lambda_c^+\ \pi^-$ and $\Lambda_c^+\ a_1^-$ channels are compatible within their errors (see Figure 3). Their weighted average is (5668 $\pm$ 16 (stat.)) MeV/c^2 with a χ^2 per degree of freedom of 3.3/3. Some properties of the Λ_b^0 candidates, namely the reconstructed mass and error, the unconstrained Λ_c^+ mass, the Λ_b^0 energy, its proper time, and the global fit probability are listed in Table 1.

	Decay mode	Λ_b^0 mass (MeV/c^2)	Λ_c^+ mass (MeV/c^2)	$E(\Lambda_b)$ (GeV)	$t(\Lambda_b)$ (ps)	Fit prob.
1	$\Lambda_c^+\ \pi^-$	5662 ± 43	2263 ± 13	34.1	0.25 ± 0.21	0.32
2	$\Lambda_c^+\ \pi^-$	5676 ± 33	2296 ± 14	29.0	0.10 ± 0.05	0.07
3	$\Lambda_c^+\ \pi^-$	5623 ± 31	2302 ± 11	40.4	0.23 ± 0.07	0.40
4	$\Lambda_c^+\ a_1^-$	5693 ± 24	2286 ± 13	35.2	0.43 ± 0.07	0.14

Table 1: Properties of the four Λ_b^0 candidates.

It is important to make sure that the observed Λ_b^0 candidates do not originate from background sources. The possible B meson reflections in the Λ_b^0 sample, the combinatorial background, the lifetime of the Λ_b^0 candidates, the effect of partially reconstructed Λ_b^0 decays, and the systematic error are discussed in the following.

	Decay mode	$(KK\pi)\pi(a_1)$ mass (MeV/c^2)	$KK\pi$ mass (MeV/c^2)	$(K\pi\pi)\pi(a_1)$ mass (MeV/c^2)	$K\pi\pi$ mass (MeV/c^2)
1	$\Lambda_c^+\ \pi^-$	5468 ± 43	1863 ± 13	5408 ± 43	1718 ± 13
2	$\Lambda_c^+\ \pi^-$	5469 ± 33	1648 ± 14	5382 ± 33	1346 ± 14
3	$\Lambda_c^+\ \pi^-$	5391 ± 31	1787 ± 11	5294 ± 31	1505 ± 11
4	$\Lambda_c^+\ a_1^-$	5412 ± 24	1876 ± 13	5309 ± 24	1709 ± 13

Table 2: Reflection properties of the four Λ_b^0 candidates.

In principle, the observed Λ_b^0 candidates could originate from kinematical reflections, in particular of fully reconstructed B_d^0 meson decays into $D^+\ \pi^-$ (a_1^-) or B_s^0 meson decays into $D_s^+\ \pi^-$ (a_1^-), with wrong masses assigned to the D^+ or D_s^+ decay products. Therefore the reflected $KK\pi\pi(a_1)$ (B_s^0) , $K\pi\pi\pi(a_1)$ (B_d^0), $KK\pi$ (D_s^+) and $K\pi\pi$ (D^+) masses were calculated for all the candidates. The values of the reflected masses, choosing in each case the combination closest to the world average D_s^+ or D^+ mass [14], are given in Table 2. It is observed that the $KK\pi$ and $K\pi\pi$ mass values are not compatible (by more than 7 standard deviations) with the D_s^+ or D^+ mass. In events 1 and 4, the $KK\pi$ mass is compatible with the $D^+ \rightarrow KK\pi$ hypothesis, but the corresponding $KK\pi(a_1)$ masses are incompatible by more than 4 standard deviations with the B_d^0 mass. Therefore none of the candidates is compatible with a fully reconstructed B meson decaying into a charmed particle.

There are two main classes of combinatorial background. The first is due to partially reconstructed B decays, either from genuine B baryons or from B mesons with a misidentified particle. This background is mainly confined below the Λ_b^0 mass. The second class of background is due mainly to b quark events with an accidental association of a primary track to the b vertex. This background has a flatter mass distribution and becomes dominant above the B_d^0 meson mass. The background in the Λ_b^0 mass region was therefore evaluated above 5.3 GeV/c^2 .

The combinatorial background was studied both on real and simulated data. The rejection factors of the selection cuts were compared for real data and simulation. The agreement was better than 20 %.

After all cuts, only one background event was found in the real data in the $\Lambda_c^+ \pi^-$ channel in the invariant mass region from 5.3 to 6.5 GeV/c^2 excluding the mass acceptance interval for Λ_b^0 candidates. This corresponds to a background density of 0.2 events per 200 MeV/c^2 . No background events were observed in the data in the $\Lambda_c^+ a_1^-$ channel. The same procedure was applied to 1.8 million simulated hadronic events, but using the entries in the whole invariant mass range from 5.3 GeV/c^2 to 6.5 GeV/c^2 for the background estimate. The simulation predicted (0.4 $\pm$ 0.3) background events per 200 MeV/c^2 for the $\Lambda_c^+ \pi^-$ channel and (0.2 $\pm$ 0.2) events per 200 MeV/c^2 for the $\Lambda_c^+ a_1^-$ channel (see Figure 1b).

More precise estimates of the background density were obtained by relaxing the particle identification criteria and the cuts on the final fit probability and the Λ_b^0 flight, using the mass region centred around the Λ_b^0 mass from 5.3 to 6 GeV/c^2 . The total background density in the $\Lambda_c^+ \pi^-$ and $\Lambda_c^+ a_1^-$ channels from data was (0.48 $\pm$ 0.16) events per 200 MeV/c^2 and from simulation (0.60 $\pm$ 0.20) events per 200 MeV/c^2 . The two estimates are compatible within the errors. To evaluate the effect of the background, a simulation study was performed on the data using the higher of these estimates. The probability was evaluated for the hypothesis that all candidates are background and for the hypothesis that at least one candidate comes from background. It was concluded that the probability of getting all four candidates from a background fluctuation is 0.2 %. The probability to have at least one background event in the sample is 30 %. The most likely situation is that all four candidates are signal.

Changing the width of the acceptance window from 200 MeV/c^2 to 400 MeV/c^2 would not change the background density and the probability for all the events to be background would become 0.4 %. Disregarding the estimation of the background level, the probability of four background events being consistent with a single mass value in a 200 MeV/c^2 wide window is about 1 %.

The average proper time of the Λ_b^0 candidates of 0.22 ps is low with respect to the measured Λ_b^0 lifetime of $1.21^{+0.21}_{-0.18}$ ps [15] in DELPHI. A simulation program, used to evaluate the probability to get this set of events with an average proper time as small as this or lower with a generated lifetime of 1.2 ps, gave a probability of 0.5 %. This corresponds to a total probability of about 2.5 %, taking into account that one selects one out of the five variables listed in Table 1. The hypothesis that the low average lifetime of the candidates might be due to the presence of additional background in the data sample was therefore investigated further. After relaxing cuts, the proper time and invariant mass distributions of data and simulation were compared and found to agree within 20 %, both in shape and normalization. In the simulation, 94 % of the background comes from b quarks, 5 % from charm quarks and 1 % from the other quarks. This high beauty quark content was confirmed in the real data by comparing the b tagging probability distributions in the simulation and the data. The proper time distribution of the background was measured on the data. It has an exponential shape with an average lifetime of 0.9 ± 0.1 ps, as expected for a sample containing 94 % beauty quarks. Data and simulation agree on the proper time distribution. Relaxing the Λ_b^0 flight cut increased the background by only about 10 %, both in data and simulation. Thus there is no evidence for an unidentified low lifetime background. On a sample of simulated Λ_b^0 beauty baryons it was checked that the Λ_b^0 lifetime after the whole analysis chain agreed within 10 % with the simulated value. Therefore the lifetime of the Λ_b^0 signal and background differ by only 30 %. This means that the probability to get an average proper time of 0.22 ps or lower assuming that all candidates are background, ie not taking into account the probability that all candidates are background of 0.2 %, is still as low as 1.5 %. It is concluded that the low average lifetime is due to a downward statistical fluctuation and not to the presence of background.

The measured Λ_b^0 mass would be shifted if partially reconstructed Λ_b^0 decays were present in the event sample. The Λ_b^0 beauty baryon would be partially reconstructed if it decayed into $\Sigma_c^+ \pi^-$ and the Σ_c^+ subsequently decayed into $\Lambda_c^+ \pi^0$, since the π^0 would not be reconstructed in this analysis. A simulation study showed that this would cause a mass shift of 200 MeV/c^2 and a broadening of the mass peak from the typical mass resolution of about 30 MeV/c^2 to about 90 MeV/c^2 . The four events in Figure 3 are compatible with the mass resolution expected for fully reconstructed Λ_b^0 beauty baryons. To evaluate the effect of partially reconstructed decays, a likelihood fit was performed on the data. The fraction of $\Lambda_b^0 \to \Sigma_c^+ \pi^-$ decays, left free in the fit, was found to be zero with an upward error of 0.12. The Λ_b^0 mass was found to be (5668 ± 16) MeV/c^2 in agreement with the average mass value quoted above. Another fit was performed assuming that all the events are partially reconstructed. The fitted mass increased to $(5864\ ^{+45}_{-40})$ MeV/c^2 , outside the considered mass range. A simulation program was used to evaluate the probability that all the events are partially reconstructed. The hypothesis is excluded at 92 % confidence level.

The Λ_b^0 mass measurement is sensitive to a systematic error in the mass scale. Comparing the mass values observed for charmed mesons in these data with the world averages [14], indicated a systematic uncertainty of less than 0.15 % on the mass scale. This corresponds to a 5 MeV/c^2 systematic mass scale error on the Λ_b^0 mass after the globally constrained fit. The expected and observed mass errors of fully reconstructed charmed mesons were also studied and found to agree within 10 %.

A possible background event in the sample can affect the mass measurement. Therefore each candidate in turn was removed from the sample and the average mass was recalculated each time. The spread on this average of 6 MeV/c^2 is quoted as the systematic error due to a possible background contribution. Changing from a 200 MeV/c^2 wide acceptance window to one 400 MeV/c^2 wide would not affect the mass measurement. Thus, the total systematic error on the mass measurement is 8 MeV/c^2 .

In summary, four Λ_b^0 events have been reconstructed with an estimated background density of (0.6 ± 0.2) events per 200 MeV/c^2 . The Λ_b^0 mass is measured to be (5668 ± 16 (stat.) $\pm\, 8$ (syst.)) MeV/c^2 .

5 Conclusions

A search for fully reconstructed Λ_b^0 decays has been performed in the $\Lambda_c^+ \pi^-$, $\Lambda_c^+ a_1^-$ and $J/\psi \Lambda^0$ channels. No events have been found in the $J/\psi \Lambda^0$ channel and an upper limit at 90 % confidence level is obtained for the branching ratio of the decay $\Lambda_b \to J/\psi \Lambda^0$ of $0.007 \times (0.10/f_{\Lambda_b})$, where f_{Λ_b} is the probability that a b quark hadronizes producing a beauty baryon. This can be compared to the measurement of UA1 of the same branching ratio of (0.018 ± 0.006 (stat.) ± 0.009 (syst.)) $\times (0.10/f_{\Lambda_b})$ [1].

In total, four fully reconstructed Λ_b^0 events have been found, three in the $\Lambda_c^+ \pi^-$ decay channel, and one in the $\Lambda_c^+ a_1^-$ channel. The events have been selected identifying the proton and the kaon in the RICH detector. These events are not compatible with a kinematical reflection from a fully reconstructed B_d^0 or B_s^0 meson. The events have an unexpectedly short mean lifetime. However, the proper time distribution expected for the background is similar to that expected for the signal and detailed comparison of data and simulation with relaxed cuts gave no indication of any unidentified low lifetime background. The total background density is estimated from simulation to be (0.6 ± 0.2) events per 200 MeV/c^2 . It is excluded at the 99.8 % confidence level that all four events are due to a background fluctuation. Further, it is excluded at 92 % confidence level that all the events are partially reconstructed Λ_b^0 beauty baryons.

Using these four events, the Λ_b^0 beauty baryon mass is measured to be (5668 ± 16 (stat.) ± 8 (syst.)) MeV/c^2 , where the systematic error comes from the uncertainty on the mass scale and a possible background contribution.

The measured Λ_b^0 mass is consistent with the UA1 result ($5640 \pm 50 \pm 30$) MeV/c^2 [1], with most of the predictions of potential models ranging from 5600 to 5900 MeV/c^2 [4], and with the calculations from lattice QCD giving values from 5590 to 5728 MeV/c^2 [5]. It is, however, significantly higher than the prediction of (5625 ± 2) MeV/c^2 [6], calculated in the framework of HQET in the static limit neglecting some terms proportional to the inverse heavy quark masses.

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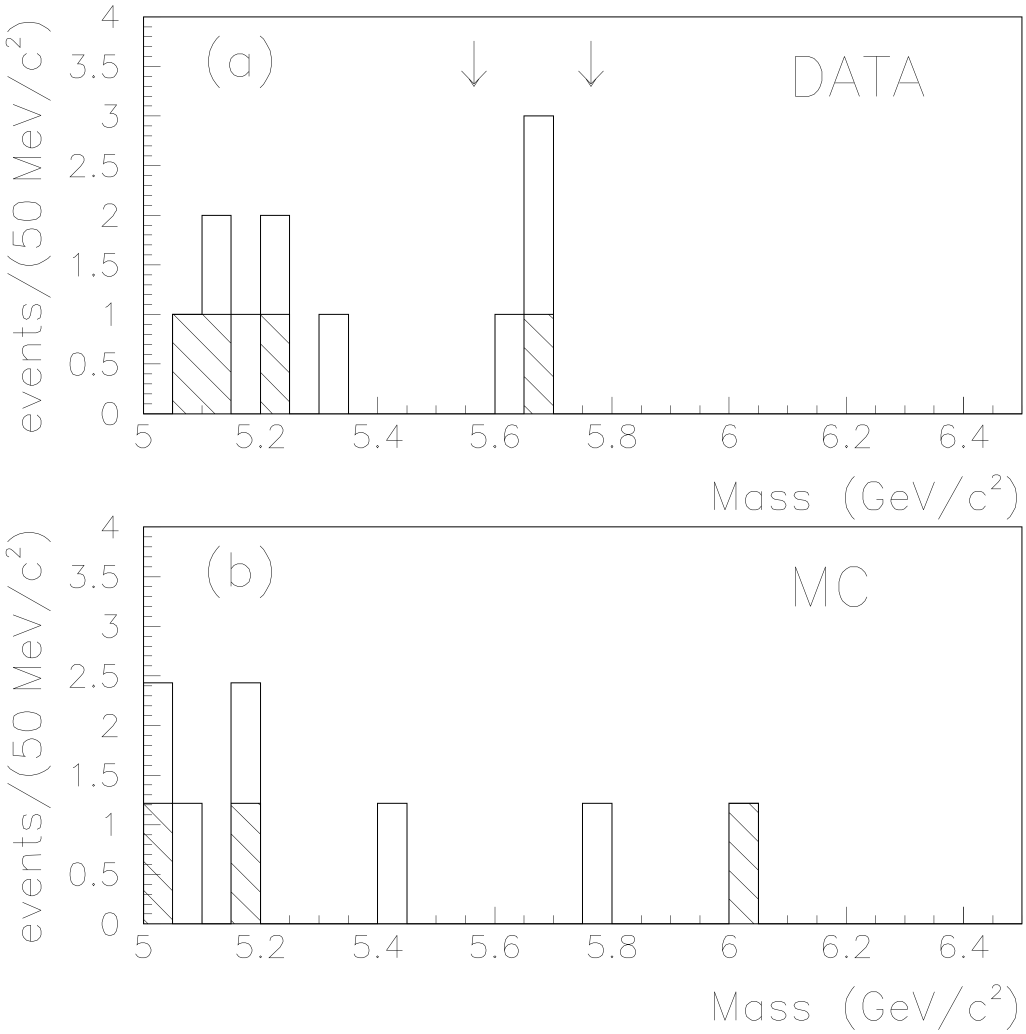

Figure 1: Invariant mass distributions for the channels $\Lambda_b^0 \to \Lambda_c^+ \, \pi^-$ and $\Lambda_b^0 \to \Lambda_c^+ \, a_1^-$ for real data (a) and the estimated background distribution from simulation (b). The hatched area corresponds to events in the $\Lambda_b^0 \to \Lambda_c^+ \, a_1^-$ channel only. The Λ_b^0 mass range is indicated with arrows.

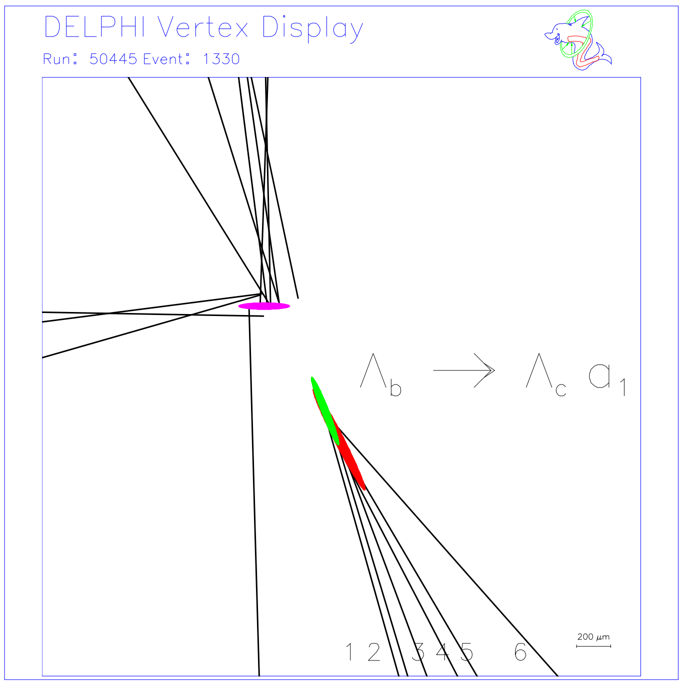

Figure 2: Display of the vertex region for the $\Lambda_b^0 \to \Lambda_c^+ \ a_1^-$ candidate, showing the Λ_b^0 and Λ_c^+ decay vertices and the primary vertex. The Λ_b^0 flies 790 μm. The error ellipses correspond to 1.5 standard deviations. Tracks 1,2 and 6 are the pions from the a_1^- . Tracks 3,4, and 5 are the kaon, pion, and proton from the Λ_c^+ .

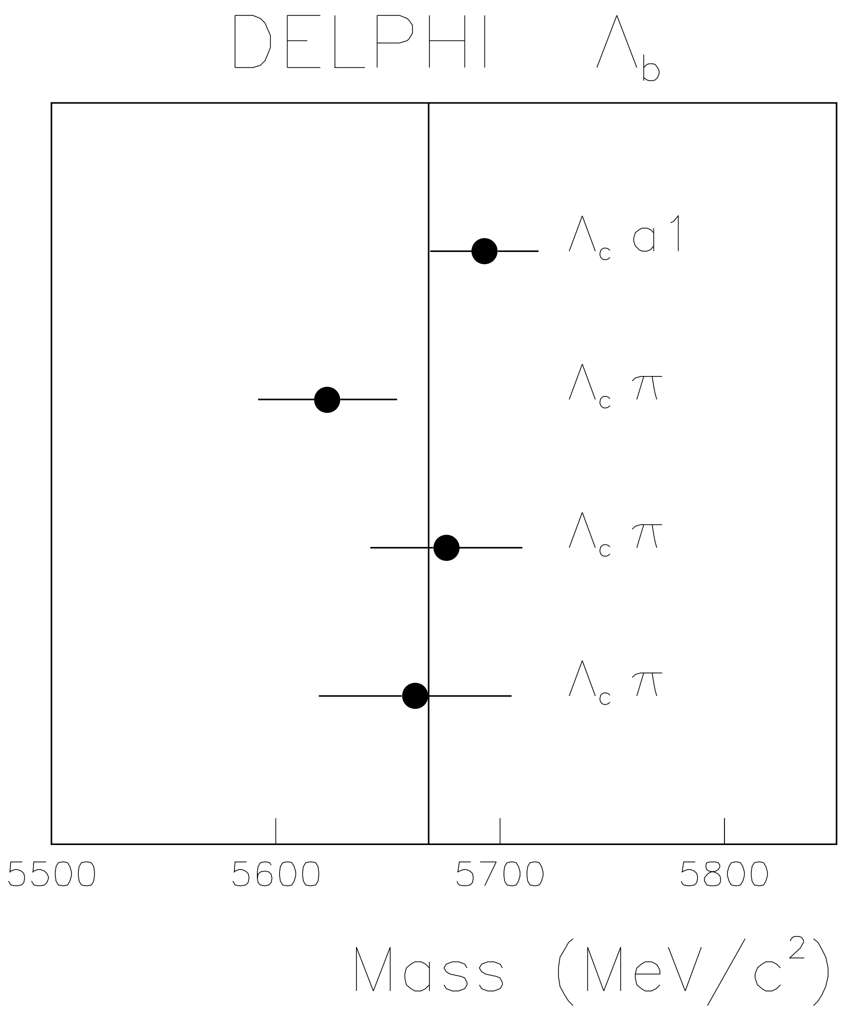

Figure 3: The masses of the four Λ_b^0 candidates in the channels $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \to \Lambda_c^+ a_1^-$.