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Evidence for b Baryons in Z Decays

The ALEPH Collaboration

Abstract

In 160,000 hadronic Z decays recorded with the ALEPH detector at LEP, the yields of $\Lambda\ell^-$ and $\Lambda\ell^+$ combinations have been measured. The observed excess of $\Lambda\ell^-$ over $\Lambda\ell^+$ of 53 ± 13 is interpreted as evidence for b baryons and their semileptonic decay. Assuming that three body decay processes such as $\Lambda_b \to \Lambda_c^+\ell^-\overline{\nu}$ dominate the semileptonic decay of b baryons, this excess corresponds to a product branching ratio $Br(b \to \Lambda_b) \cdot Br(\Lambda_b \to \Lambda_c^+\ell^-\overline{\nu}) \cdot Br(\Lambda_c^+ \to \Lambda X) = (0.95 \pm 0.22\ (stat) \pm 0.21\ (syst))\%$, where Λ_b and Λ_c^+ denote the bottom and charm baryons respectively.

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Introduction

During the last ten years, significant progress has been made in the study of the decay dynamics of the B mesons[1]. Less, however, is known experimentally [2] about the production or decay rates of b baryons. Theoretically, b baryons [3, 4, 5, 6] provide interesting tests of the spectator model of b-hadron decays and heavy flavour spectroscopy.

In this letter, a study of the decay $\Lambda_b \rightarrow \Lambda_c^+ \ell^- \overline{\nu}$ followed by the decay $\Lambda_c^+ \rightarrow \Lambda X$ is reported. Here and throughout this letter charge conjugate reactions are also included. The Λ_b is expected to be the lightest [3, 7] and most copiously produced b baryon. The Σ_b is expected to be heavier than the Λ_b by more than a pion mass; consequently it is expected to decay via strong interaction to Λ_b [1]. In principle, this study is also sensitive to semileptonic decays of Ξ_b and Ω_b involving Λ in the final state via a charmed baryon. However, since Ξ_b and Ω_b contain one or more strange quark, their production rates compared to Λ_b are expected to be suppressed. Here and throughout this paper, Λ_b and Λ_c^+ refer to bottom and charm baryons.

The technique described in this letter takes advantage of the large decay rate [8] of Λ_c^+ to Λ. Due to the kinematics of its decay, in the lab frame, the decay $\Lambda \rightarrow p\pi^-$ can be unambiguously differentiated from the $\overline{\Lambda} \rightarrow \overline{p}\pi^+$. Hence an observable correlation exists between the charge of the lepton from the semileptonic decay of Λ_b and the charge of the decay products of the Λ from the subsequent decay of Λ_c^+. The signature, therefore, of the semileptonic decay of Λ_b is the presence of a $\Lambda\ell^-$ pair on the same side [2] of an event. As a result of the hard fragmentation of the b hadrons and their relatively large mass, the decay products of the semileptonic decays of b hadrons emerge with high momenta and high transverse momenta ($p_\perp$) with respect to the jet direction. These features can be used to distinguish the $\Lambda\ell^-$ combinations from Λ_b decay from different possible sources of background.

This study is based on a sample of 160,000 hadronic Z decays recorded with the ALEPH detector at centre-of-mass energies near 91.2 GeV during the 1990 running of LEP.

The ALEPH Detector

The ALEPH detector has been described in detail elsewhere [9]; only a brief description is presented here. Charged tracks are measured over the range $|\cos\theta| < 0.95$, where θ is the polar angle, by an inner cylindrical drift chamber (ITC) and a large cylindrical

[1] If the mass difference between Σ_b and Λ_b is less than a pion mass, Σ_b will decay either electromagnetically to Λ_b or it will decay via weak interaction. In the latter scenario, semileptonic decays of Σ_b will involve either Λ_c^+ or Σ_c, which in turn will decay into Λ_c^+.

[2] At LEP energies, the b hadrons carry away, on average, 70% of the beam energy; consequently the b and $\bar{b}$ hadron jets are well seperated. In this analysis the Λ and the lepton were considered to be on the same side of the event if the opening angle between them is less than 45^o.

time projection chamber (TPC). These chambers are immersed in a magnetic field of 1.5 Tesla and together measure the momentum of charged particles with a resolution of $\delta p/p = 0.0008 p\,(\mathrm{GeV}/c)^{-1} \oplus 0.003$ [9, 10]. The TPC also provides up to 330 measurements of the specific ionization (dE/dx) of each charged track. For electrons in hadronic events, the dE/dx resolution is 4.6% for 330 ionization samples. The electromagnetic calorimeter (ECAL), which surrounds the TPC and is inside the coil of the superconducting solenoid, is used to measure electromagnetic energy and, together with the TPC, to identify electrons. It is a lead-proportional tube calorimeter with cathode-pad readout which has a resolution for electromagnetic showers of $\delta E/E = 0.017 + 0.19/\sqrt{E}$, with E in GeV. It covers the angular region $|\cos\theta| < 0.98$ and is finely segmented into projective towers, each subtending an solid angle of approximately 0.8° by 0.8°. These pads are read out in three longitudinal segments corresponding to thicknesses of approximately 4, 9, and 9 radiation lengths. Muons are identified with the hadron calorimeter (HCAL), composed of the iron of the magnet return yoke interleaved with 23 layers of streamer tubes, and the muon chambers, an additional two layers of streamer tubes surrounding the calorimeter. The tubes of the HCAL have a pitch of 1 cm and measure, in two dimensions, tracks from penetrating particles within the angular range $|\cos\theta| < 0.985$. The energy of hadronic showers is measured by means of a cathode pad readout arranged in projective towers, each subtending an solid angle of approximately 3.8° by 3.8°, with an energy resolution of $\delta E/E = 0.85/\sqrt{E}$, with E in GeV. The muon chambers, covering the same angular range as the HCAL, are streamer tubes read out by cathode strips both parallel and perpendicular to the tubes. Therefore each layer provides a three-dimensional coordinate for charged tracks which penetrate the 7.5 interaction lengths of material between the interaction point and the muon chambers.

The selection of hadronic events is based on charged tracks. Each event is required to have at least five "good" charged tracks, where a "good" track is one that passes through a cylinder of 2 cm radius and 10 cm length around the interaction point, has $|\cos\theta| < 0.95$, and has at least four TPC hits. The sum of the track energies is required to be greater than 10% of the centre-of-mass energy. This selection has an efficiency of 97.4%, and the background from $\tau\bar{\tau}$ and two-photon events is estimated to be less than 0.65%. [11]

Leptons are identified in the ALEPH detector by matching a charged track measured in the TPC and ITC with either an energy deposit consistent with being from an electron in the ECAL, or a pattern of hits in the HCAL and muon chambers consistent with being from a muon. The details of lepton identification, the jet clustering method and the definition of $p_\perp$ have been discussed elsewhere [12, 13].

The Λ candidates are identified by their decay $\Lambda \rightarrow p\pi^-$, using an algorithm which vertexes two oppositely-charged tracks with at least 4 hits each in the TPC. The decay length of the topologically displaced vertex is calculated with respect to the average fill-by-fill beam spot. In this analysis, only those vertices with a decay length greater than 5 cm are considered. In cases where TPC dE/dx information is available, the measured specific ionization of the track is required to be within three standard deviations of the correct particle hypothesis. All vertices which are consistent with the $K_s^0 \rightarrow \pi^+\pi^-$ or $\gamma \rightarrow e^+e^-$ mass hypotheses within two standard deviations (10 MeV/c^2 and 15 MeV/c^2, respectively) of the corresponding mass are rejected. The Λ detection efficiency in the 3.0-20.0 GeV/c momentum range is approximately 55%. The measured Λ mass resolution of approximately 2.5 MeV/c^2 is consistent with the expectation based on a Monte Carlo simulation of the TPC and ITC performance.

$\Lambda\ell$ Correlations in Hadronic Z Decays

There are five possible sources of $\Lambda\ell$ combinations on the same side of a hadronic Z decay. They can be classified on the basis of the resulting charge correlation between the Λ and the lepton.

$$\Lambda_b \rightarrow \Lambda_c^+ \ell^- \overline{\nu}, \quad \Lambda_c^+ \rightarrow \Lambda X \qquad (1)$$
$$\overline{B} \rightarrow \Lambda_c^+ X \ell^- \overline{\nu}, \quad \Lambda_c^+ \rightarrow \Lambda X \qquad (2)$$
$$b \rightarrow \Lambda_c^+ X, \quad \Lambda_c^+ \rightarrow \Lambda \ell^+ X \qquad (3)$$
$$c \rightarrow \Lambda_c^+ X, \quad \Lambda_c^+ \rightarrow \Lambda \ell^+ X \qquad (4)$$
$$\text{Accidental Combinations} \qquad (5)$$

Processes (1) and (2) lead to $\Lambda\ell^-$ combinations, while processes (3) and (4) are sources of $\Lambda\ell^+$ combinations. In addition, Λ baryons are produced copiously in the process of hadronization of quarks. Sometimes such a Λ can pair up with a prompt lepton (e.g., from semileptonic decays of heavy flavours) or a misidentified hadron (fake lepton) and produce a $\Lambda\ell$ combination. Process (5) listed above refers to this possibility. If there is no dominant correlation between the Λ and the lepton charge from this process, the $\Lambda\ell^-$ and $\Lambda\ell^+$ pairs are expected to be observed with equal rates within the assumptions on fragmentation distributions discussed at the end of this section.

These five processes have characteristic kinematic features. The $p_\perp$ of the lepton from process (1) is on average relatively large compared with (2), since baryon number conservation in process (2) implies that the rest frame momentum of the lepton, in such a decay of the B meson, is small. The expected transverse momentum spectra of the leptons in the lab frame, based on a Monte Carlo simulation of processes (1) and (2), are displayed in Fig. 1(a) and Fig. 1(b) respectively. A cut on the lepton transverse momentum of 1.0 GeV/c removes about 90% of the $\Lambda\ell^-$ combinations from process (2). Furthermore, no experimental evidence exists for process (2)[3]. The lepton from processes (3) and (4), due to its origin in the semileptonic decay of the Λ_c^+, also has a softer $p_\perp$ spectrum than process

[3] The ARGUS collaboration has searched for the process $\overline{B} \rightarrow p\ell^- X$ and placed an upper limit of $\text{Br}(\overline{B} \rightarrow p\ell^- X) \leq 0.16\%$ at 90% confidence level [14]. Assuming that at least half of the Λ_c^+ decays produce a proton in the final state, this implies that the process $\overline{B} \rightarrow \Lambda_c^+ X \ell^- \overline{\nu}$ occurs at a rate less than 0.32% at 90% confidence level of which a further 90% can be eliminated with a cut on the lepton $p_\perp$. Hence this decay mode is not a significant background to the process (1).

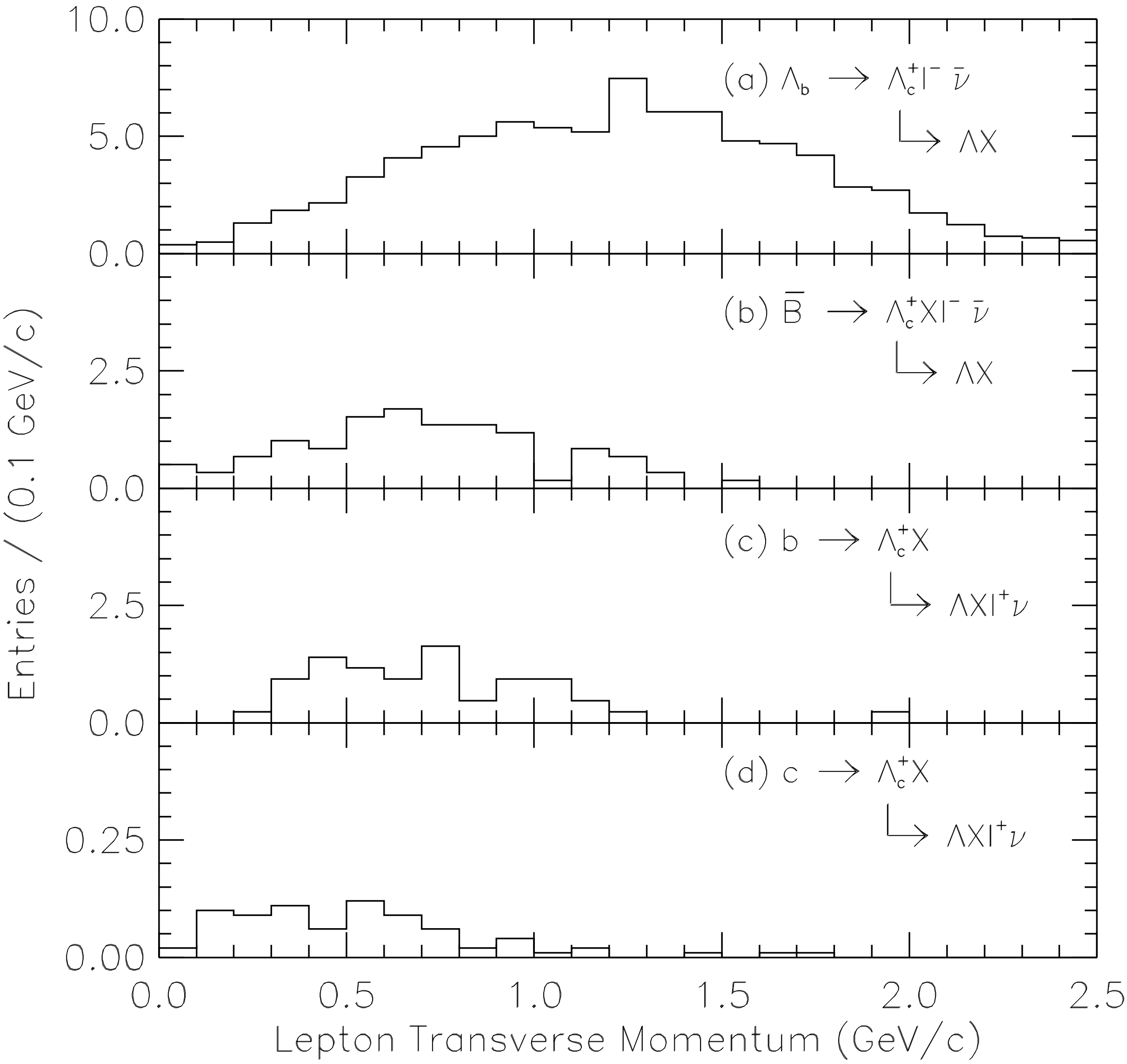

Figure 1: The predicted lepton transverse momentum spectrum for the process (a) $\Lambda_b \rightarrow \Lambda_c^+ \ell^- \overline{\nu}$, (b) $\overline{B} \rightarrow \Lambda_c^+ X \ell^- \overline{\nu}$, (c) $b \rightarrow \Lambda_c^+ X$, $\Lambda_c^+ \rightarrow \Lambda \ell^+ X$, (d) $c \rightarrow \Lambda_c^+$, $\Lambda_c^+ \rightarrow \Lambda \ell^+ X$. All cuts mentioned in the text have been applied. In the normalization of the production rate of process (1) relative to the rest a product branching ratio $Br(b \rightarrow \Lambda_b) \cdot Br(\Lambda_b \rightarrow \Lambda_c^+ \ell^- \overline{\nu}) \cdot Br(\Lambda_c^+ \rightarrow \Lambda X)$ of 1% was assumed. The branching ratio for the process $\overline{B} \rightarrow \Lambda_c^+ X \ell^- \overline{\nu}$ of 0.32 % was used.

(1). The predicted transverse momentum spectra for these two processes are illustrated in Fig. 1(c) and Fig. 1(d), respectively. The $p_\perp$ distribution in each case is shown after other cuts, described in the following paragraphs, on the momentum of the lepton and the Λ were applied.

The rate and the momentum spectrum of the Λ produced during hadronization of heavy quarks has not been measured at LEP energies. Therefore, the contribution of $\Lambda\ell^-$ from process (5) must be estimated from data. A measurement of the level of accidental combinations in the $\Lambda\ell^-$ yield can be obtained from the yield of the $\Lambda\ell^+$ sample, provided the $\Lambda_c^+ \to \Lambda\ell^+ X\nu$ contribution is removed. This can be achieved by requiring the lepton to have more than 5 GeV/c of momentum and $p_\perp$ greater than 1.0 GeV/c. This eliminates more than 95% of all $\Lambda\ell^+$ combinations from processes (3) and (4), leaving process (5) as the largest source of $\Lambda\ell^+$ combinations. Therefore, any excess of the $\Lambda\ell^-$ over the $\Lambda\ell^+$ yield is evidence for semileptonic decays of b baryons. This interpretation is based on the assumption that the momentum spectra of Λ and $\overline{\Lambda}$ from fragmentation which accompany a b hadron are the same. This assumption has been tested with a sample of about 220,000 hadronic Z decays generated by the JETSET 6.3 Monte Carlo program [15] with a simulation of the ALEPH detector characteristics. The ratio of the yields of $\Lambda\ell^-$ to $\Lambda\ell^+$ combinations resulting from accidental combinations was found to be 1.18 ± 0.23. Further estimates were made at the event generator level (without any detector simulation). An inequality between the yields of $\Lambda\ell^-$ and $\Lambda\ell^+$ combinations can arise if a natural correlation exists between the b hadron and the Λ produced in the event in the process of fragmentation. This possibility was investigated using a sample of approximately 10^6 $Z \to b\bar{b}$ events generated with the JETSET 6.3 Monte Carlo where the b-baryon production rate was set to 9%. In this sample, the ratio of $\Lambda\ell^-$ over $\Lambda\ell^+$, where the lepton originated in the semileptonic decay of a b hadron (selected with momentum greater than 5.0 GeV/c and $p_\perp$ greater than 1.0 GeV/c) and the Λ (with momentum greater than 3.0 GeV/c) was produced in the process of fragmentation, was found to be 0.80 ± 0.01. In the extreme case where the b quark hadronized only into b mesons and never into b baryons, this ratio of $\Lambda\ell^-$ over $\Lambda\ell^+$ from accidental correlations was found to be 1.41 ± 0.02. Since the b baryon production rate is not precisely known and the detailed nature of the hadronization process in heavy flavour decays is not accurately measured, the ratio of $\Lambda\ell^-$ over $\Lambda\ell^+$, arising from accidental correlations, was taken to be 1.0 ± 0.4 in this analysis.

Data Analysis and Results

The Λ candidates were required to have a momentum greater than 3.0 GeV/c in order to suppress the contribution of Λs produced in the hadronization process. The lepton candidates were required to have momentum greater than 5.0 GeV/c and $p_\perp$ greater than 1.0 GeV/c. The angle between the Λ and the lepton was required to be less than 45^o. The yield of the same side $\Lambda\ell^-$ combinations is shown in Fig. 2(a) where the invariant mass distribution of the $p\pi^-$ combinations is plotted. This spectrum should be compared with that from the $\Lambda\ell^+$ yield which is shown in Fig. 2(b). The two mass distributions were fitted simultaneously to a single Gaussian representing the signal, and a second order Chebychev polynomial was used in each case to parametrize the combinatorial background. The fitted mass and the width of the two distributions were found to be 1.1163 ± 0.0004 and 0.008 ± 0.0012 GeV/c^2 respectively, consistent with expectations based on a Monte Carlo simulation of the decay (1). A total of 73 ± 11 $\Lambda\ell^-$ and 20 ± 7 $\Lambda\ell^+$ combinations were observed. In the $\Lambda\ell^+$ combinations, the contribution from processes (3) and (4) was estimated to be 1.5 ± 2. This implies an excess in the yield of the $\Lambda\ell^-$ correlation over $\Lambda\ell^+$ of $54.5 \pm 13.0(stat) \pm 8.2(syst)$. The systematic error quoted here corresponds to the uncertainty in the relative yields of $\Lambda\ell^-$ and $\Lambda\ell^+$ from accidental combinations discussed in the last section. This excess is interpreted as due to the semileptonic decays of b baryons.

In order to translate the observed excess into a product branching ratio $Br(b \to \Lambda_b) \cdot Br(\Lambda_b \to \Lambda_c^+ X \ell^- \overline{\nu}) \cdot Br(\Lambda_c^+ \to \Lambda X)$, a model for the decay process must be considered. Assuming that the three-body decay process, such as $\Lambda_b \to \Lambda_c^+ \ell^- \overline{\nu}$ dominates the semileptonic decay of b-baryons, an overall detection efficiency of $8.3 \pm 1.3\%$ was estimated [4]. The partial decay width for the process $Z \to b\bar{b}$ has been measured[16] to be 0.385 ± 0.023 GeV. This observed excess of $\Lambda\ell^-$ correlations can be translated into a product branching ratio $Br(b \to \Lambda_b) \cdot Br(\Lambda_b \to \Lambda_c^+ \ell^- \overline{\nu}) \cdot Br(\Lambda_c^+ \to \Lambda X) = 0.95 \pm 0.22(stat) \pm 0.21(syst)$ %.

Conclusion

A technique sensitive to the semileptonic decays of b baryons has been demonstrated. In the analysis of 160,000 hadronic events, an excess of $\Lambda\ell^-$ combinations over $\Lambda\ell^+$ of 53 ± 13 has been observed. This provides evidence for the existence of b baryons in Z decays, the first evidence for their semileptonic decay and the first measurement of the product branching ratio $Br(b \to \Lambda_b) \cdot Br(\Lambda_b \to \Lambda_c^+ \ell^- \overline{\nu}) \cdot Br(\Lambda_c^+ \to \Lambda X) = 0.95 \pm 0.22(stat) \pm 0.21(syst)$ %.

[4] The JETSET 6.3 prescription was used to model the semileptonic b-baryon decay as well as the decay $\Lambda_c^+ \to \Lambda X$. The possibility that the Λ_c^+ in the semileptonic decay of the b baryon could arise from Σ_c or Λ_c^* decay is included in the simulation.

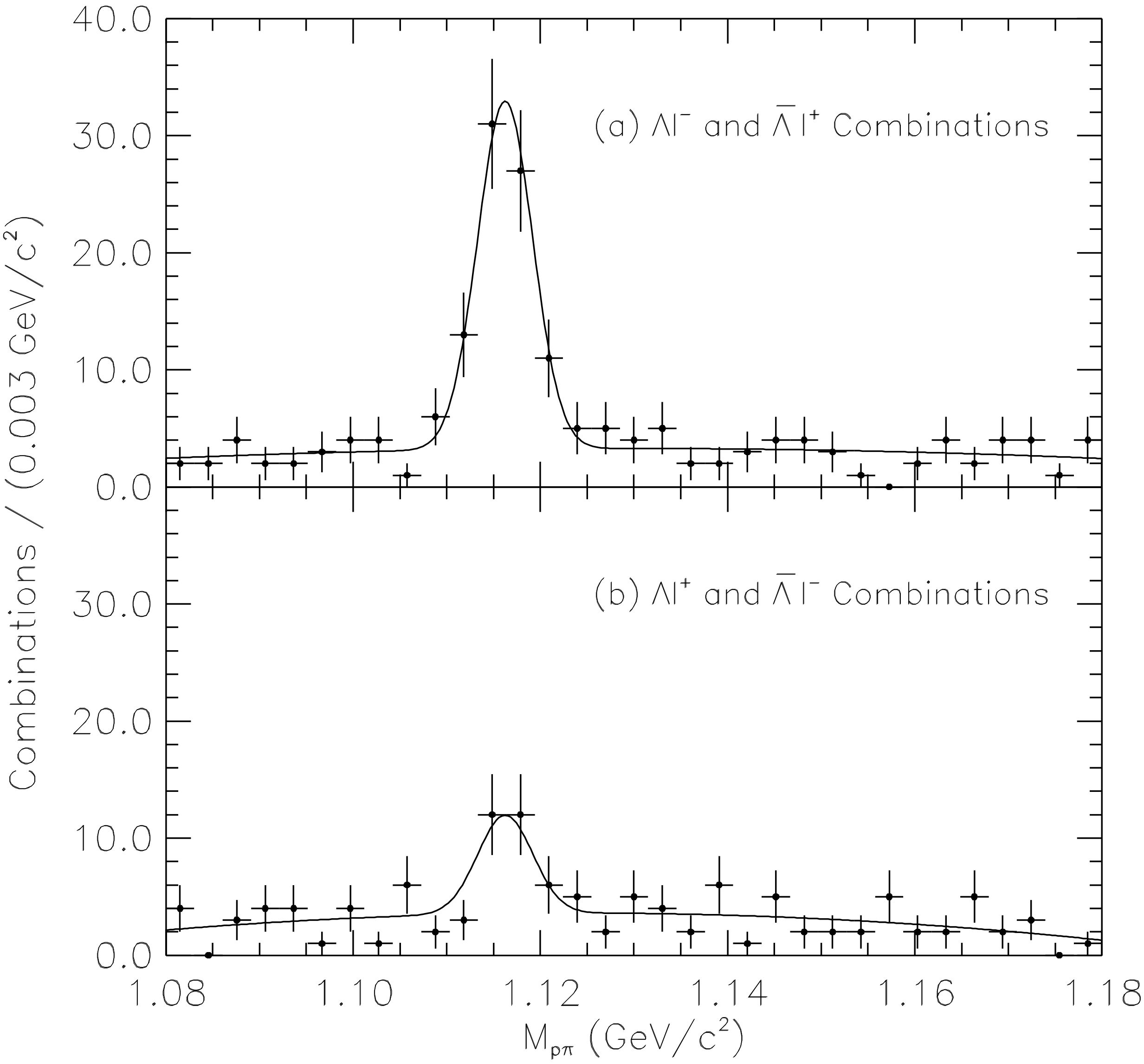

Figure 2: The Λ yield in the (a) $\Lambda\ell^-$ and $\overline{\Lambda}\ell^+$ combinations and (b) $\Lambda\ell^+$ and $\overline{\Lambda}\ell^-$ combinations. The process $\Lambda_b \to \Lambda_c^+\ell^-\overline{\nu}$ contributes only to the yield in Fig. 2(a). The contribution of the accidental combinations to the yield in Fig. 2(a) is measured from Fig. 2(b).

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