Production of strange B-baryons decaying into $\Xi^{\mp}$ - $l^{\mp}$ pairs at LEP


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DELPHI Collaboration

Abstract. An excess of events containing, in a jet, a same-sign $\Sigma^\pm - \ell^\pm$ pair as compared to those with an opposite-sign $\Sigma^\pm - \ell^\pm$ pair has been observed in an analysis of 1.7 million hadronic $Z^0$ decays collected by the DELPHI detector at LEP between 1991 and 1993 inclusive. The probability for this signal to come from non $B$-baryon decays is less than $5 \times 10^{-4}$. The measured production fraction corresponds to:

$$\mathcal{P}(b \rightarrow \text{baryon}) \times BR(\text{baryon} \rightarrow \Sigma^- \ell^- X) = (5.9 \pm 2.1 \pm 1.0) \times 10^{-4},$$

per lepton species, averaged for electrons and muons and assuming that the two channels have an equal contribution. Semileptonic decays of $A_b$ baryons can account for less than 10% of these events and the major part of the signal has to originate from $\Xi_b$ semileptonic decays. Using the subsample of these events where the $\Sigma^-$ trajectory has been measured in the Vertex Detector, the lifetime of $B$-baryons producing a $\Sigma^-$ in their semileptonic decay final state is found to be:

$$\tau(B \rightarrow \Sigma^- \ell^- X) = 1.5^{+0.7}_{-0.4} \pm 0.3 \text{ ps}.$$
device, is a cylinder of 30 cm inner radius, 122 cm outer radius and 2.7 m length. For polar angles between 39° and 141° it provides up to 16 space points along the charged particle trajectory.

The Vertex Detector (VD) [5] is very important in this analysis. It is made of three concentric shells of Si-strip detectors at radii of 6.3, 9 and 11 cm covering the central region between 43° and 137°. The shells surround the beryllium beam pipe of internal radius 5.3 cm and wall thickness 1.45 mm. Each shell consists of 24 modules with about 10% overlap in azimuth between the modules. Each module holds 4 detectors with strips parallel to the beam direction. The silicon detectors are 300 μm thick and have a diode pitch of 25 μm. The read-out strips (50 μm pitch) are AC coupled and give a 5 μm intrinsic precision on the coordinates of the charged particle tracks, transverse to the beam direction.

Hadronic Z⁰ decays have been isolated from all registered events by applying standard selection criteria [6]. Correcting for the 5% losses induced by these cuts, the sample amounts to 1.7 million hadronic Z⁰ decays which have been registered by DELPHI from 1991 to 1993.

Simulated events have been produced using the Lund parton shower model in the JETSET 7.3 program [7] with fragmentation and decays as treated there. The parameters were optimized by DELPHI and the events were passed through the DELphi detector Simulation, DELSIM [8] and processed with the same event reconstruction as the data. The samples are described in section 7.

### 3 Lepton identification

Muons are identified by combining the muon chamber hits with the tracking information. The tracks of charged particles are extrapolated to the muon chambers and then associated and fitted to the hits. Information from the muon chambers alone allows a measurement of the position and direction of a track element. These are then compared to the corresponding parameters of the extrapolated track and a χ² test is used to determine the association of the track with the muon chamber hits.

The electron candidates are identified by combining the electromagnetic shower information from the HPC with the particle ionization loss, dE/dx, measured by the TPC. A sizeable fraction of electrons come from photon conversion. They are partially rejected if two oppositely charged particles form a secondary vertex where the invariant mass is zero within measurement errors.

The global identification efficiencies for muons and electrons with momenta larger than 3 GeV/c, and the corresponding probabilities for a hadron to be misidentified as a lepton, are given in Table 1. These values have been obtained using the detailed simulation code of the DELPHI detector, DELSIM [8], and have been checked on real data using selected events samples such as K⁰ → π⁺π⁻, Z⁰ → μ⁺μ⁻, converted photons before the HPC, γγ → ℓ⁺ℓ⁻ and hadronic τ decays [9].

### 4 Reconstruction of Ξ⁺ hyperons

The two algorithms which have been used to reconstruct the decay of a cascade hyperon:

\[ Ξ⁺ → Λ π^- \]

are described in Sects. 4.1 and 4.2.

#### 4.1 The Ξ⁺ trajectory is measured in the VD

The first method, called “HT” (Hyperon Tracking) in the following, applies to decays that occur after the last layer of the VD. Due to their large lifetimes, charged hyperons are often seen in the three layers of the VD. For a Ξ⁺ of 5 GeV energy, the probability that it decays after the VD outer layer is larger than 50%. Most such particles will not travel far enough into the main tracking detector, the TPC, to be reconstructed, and in this case the VD hits cannot be associated to tracks reconstructed in the event. A Ξ⁺ track candidate is defined as a set of 3 hits in the VD, not associated to any track, pointing towards the main interaction vertex. In this way, only relatively energetic hyperons are kept. The soft pion produced in the Ξ⁺ decay is searched for in the central tracking system and the Ξ⁺ decay vertex is obtained using the Ξ⁺ and the pion trajectories. The Λ⁰ decay position is searched for inside a cone, whose point is located at the Ξ⁺ decay vertex, the axis of which is the direction of flight of the Ξ⁺. The pion candidate from the Λ decay must have a momentum between 0.1 and 3 GeV/c with an impact parameter larger than 2.5 mm relative to the event main vertex; the momentum of the proton candidate has to be larger than 1 GeV/c. The χ² probability that the proton and pion make a vertex has to be larger than 1% with the mass of the \( p - \pi \) system constrained to the Λ mass. Finally, the Ξ⁺, π and Λ are required to form a common vertex and to satisfy the constraints on momentum conservation with a χ² probability larger than 1%. The efficiency of this algorithm has been measured using simulation and found to be (2.0 ± 0.1)% for Ξ⁺ momenta larger than 3 GeV/c. This number and its error include the branching fraction of the Λ⁰ → p π channel (64%), the limited solid angle covered by the VD (≈ 73%), the various track reconstruction efficiencies and the correction to account for differences in the efficiency of the VD between data and the simulation.

From a sample of 1.7 million hadronic Z⁰ decays, 548 ± 36 Ξ⁺ have been reconstructed, within an interval of ± 10 MeV/c² centered on the nominal Ξ⁺ mass (1321.3 MeV/c²) [10]; the Λ π mass distribution is shown in Fig. 1.4. The fitted mass and width of the signal are respectively 1321.2 ± 0.2 MeV/c² and 7.8 ± 0.6 MeV/c². These values have been obtained by fitting a Breit–Wigner distribution to account for the signal and a first order polynomial for the background. The algorithm isolates the Ξ⁺ sample with a purity of (92 ± 3)%. As the Ξ⁺ track is measured in the VD, these events can also be used to search for secondary vertices from heavy flavour decays.
4.2 Only \( \Xi^\mp \) decay products are measured

The second method, referred to as "\( \Lambda \pi \)", is more traditional in its approach. The \( \Lambda \) is reconstructed first and is combined with a charged pion of appropriate electric charge. The candidate proton from the \( \Lambda^0 \) decay must have a momentum larger than 0.5 GeV/c and the associated pion candidate a momentum larger than 0.1 GeV/c. The impact parameter of the pion relative to the primary vertex, measured in the plane transverse to the beam direction, has to be larger than two times its measurement error. The same selection criteria have been applied to the corresponding parameters of the candidate pion from the \( \Xi^\mp \) decay. The vertex fits at the \( \Lambda^0 \) and \( \Xi^\mp \) decay vertices must have a \( \chi^2 \) probability larger than 1%. It is also required that the \( \Xi^\mp \) hyperon decay vertex be at least 1 cm in the transverse plane (and the \( \Lambda^0 \) decay vertex be at least 2 cm), from the primary vertex. The efficiency of this second algorithm for \( \Xi^\mp \) particles of momentum larger than 3 GeV/c, including branching ratios and solid angle acceptances as in Sect. 4.1, is (7.0 \( \pm \) 0.1)\% and 2175 \( \pm \) 97 have been reconstructed (Fig. 1.b).

The inclusive production rate of the \( \Xi^\mp \) has been measured using the "\( \Lambda \pi \)" algorithm:

\[ N((\Xi^- + \Xi^+)/Z^0 \rightarrow \text{hadrons}) = 0.0257 \pm 0.0012 \text{(stat.)} \pm 0.0020 \text{(syst.)} \]

and found to be in agreement with previously published results [11].

The main source of systematic uncertainty comes from the use of the simulation to account for the fraction of the momentum distribution, below 2 GeV/c, for which there is no acceptance in this analysis. An uncertainty of 30% has been assumed on this correction. The momentum distribution of the reconstructed \( \Xi^\mp \) agrees with the expectations from the simulation, and the measured mean decay length, 4.8 \( \pm \) 0.4 cm, agrees with published results (4.91 cm)[10]. From the number of \( \Xi^\mp \) reconstructed using the "\( \Lambda \pi \)" algorithm and the efficiencies of the two algorithms one expects 621 \( \pm \) 42 \( \Xi^\mp \) from the "HT" algorithm: this value agrees with the number quoted in Sect. 4.1 showing that the relative efficiency between the two algorithms is acceptable.

The overall \( \Xi^\mp \) reconstruction efficiency, for particles of momentum larger than 3 GeV/c found by either or both of the two algorithms is:

\[ e(\Xi^\mp) = (8.3 \pm 0.2)\% \]

5 Possible sources of \( \Xi^\mp - \ell \) pairs in the same jet

The different mechanisms contributing to the production of a \( \Xi^\mp - \ell \) pair in the same jet are reviewed. As mentioned in the introduction, B-baryon direct semileptonic decays contribute mainly to right-sign pairs. It is shown that, on quite general grounds, one expects an excess of events in the wrong-sign pair sample from all other mechanisms. The expected number of events from the simulation, are given in section 7 for heavy baryon semileptonic decays. In the final analysis, direct semileptonic decays of B hadrons have been selected by requiring that the lepton transverse momentum, measured relative to the direction of the jet (particles were clustered into jets according to the LUCLUS algorithm with default parameters) after having removed the lepton from it, be larger than 1 GeV/c. Possible sources of background have to be envisaged mainly in this domain.

Two main classes of events are considered, depending on the origin of the \( \Xi^\mp \) hyperon.

5.1 \( \Xi^\mp \) hyperons from decays

Leptons from weak decays are produced at secondary vertices, whereas misidentified hadrons can come also from the event primary vertex.

Only heavy flavour baryon semileptonic decays contribute events with a \( \Xi^\mp - \ell \) and with the lepton produced by semileptonic decay of a heavy hadron. Semileptonic B meson decays can be neglected because, due to the small available phase space, the lepton momentum, in the B centre of mass system, is lower than 1 GeV/c.

- Strange B-baryons:

The two \( \Xi_b \) baryonic states are expected to decay in the following way (Fig. 2.a):

\[ \Xi_b^- \rightarrow \Xi_b^0 \ell^- \bar{\nu}_\ell X, \quad \Xi_b^0 \rightarrow \Xi_b^+ \ell^- \bar{\nu}_\ell X. \]

As the production of excited \( \Xi_c \) states in the semileptonic decays of \( \Xi_b \) baryons will mainly give a \( \Xi_c^+ \) state, the production rate of \( \Xi^\mp - \ell^- \) is proportional to the inclusive semileptonic branching fraction of \( \Xi_b \) baryons times the inclusive branching fraction of \( \Xi_c^+ \) baryons to \( \Xi^\mp \) hyperons. In the simulation, the probability to obtain a \( \Xi^\mp - \ell^- \) from a direct \( \Xi_b \) baryon semileptonic decay, in a b jet is:
Fig. 2. Schematic description of processes contributing to the production of \( \Xi^- \ell^+ \) pairs in which the \( \Xi^- \) originates from heavy flavour decays: (a) direct semileptonic decays of \( \Xi_b \) baryonic states; (b) direct semileptonic decays of a \( \Lambda_b \) with production of a \( \Xi_c K \) hadronic system; (c) direct semileptonic decays of a \( \Lambda_b \) in which the produced \( \Lambda_c \) decays into \( \Xi X \); (d) direct semileptonic decays of \( \Xi_c \) states

\[
\mathcal{P}(b \to \Xi_b \to \Xi^- \ell^- X) = \mathcal{P}(b \to \Xi_b) \\
\times \mathcal{P}(\Xi_b \to \Xi_c \ell^- X) \times \mathcal{P}(\Xi_c \to \Xi^- X) \times \mathcal{P}(\Xi_c \to ^0 \Xi_c \ell^- X) = 1.7 \times 10^{-4}.
\]

It has been assumed that the semileptonic branching fraction of heavy hadrons into an electron or a muon is the same and the notation \( I \) refers to only one of the lepton categories. Semileptonic decays with emission of an \( \ell^- \) lepton are assumed to be relatively suppressed and are not considered.

The value of the semileptonic branching fraction is a reasonable assumption because similar values are expected for all \( B \) hadrons, but the two other quantities are largely uncertain and have still to be determined by experiments.

- \( \Lambda_b \) semileptonic decays
  A much larger contribution to the \( \Xi^- \ell^+ \) final state is expected from \( \Xi_b \) baryons than from \( \Lambda_b^0 \) states, even if their initial production rate is smaller. Semileptonic decays of \( \Lambda_b^0 \) (Fig. 2.b) can contribute to \( \Xi^- \ell^+ \) candidates through the decay chain:

\[
\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_l X. \\
\to \Xi^- K^+ \pi^+
\]

The branching ratio for this decay of the \( \Lambda_c \) was measured by the CLEO collaboration [12] to be \( (0.34 \pm 0.13 \%) \) assuming \( \text{BR}(\Lambda_c \to pK^- \pi^+) = (4.3 \pm 1.0 \pm 0.8 \%) \) [13]. It has been measured also by CLEO [12] that \( (42 \pm 12 \%) \) of the \( \Lambda_c \to \Xi^- K^+ \pi^+ \) decays were due to the two-body decay \( \Lambda_c \to \Xi^0 K^+ \) which has a branching fraction of \( (0.23 \pm 0.11 \%) \). Other possibilities to produce a \( \Xi^- \) in a \( \Lambda_c^+ \) decay require the production of at least an additional pion. Because of the very small Q value of these decays, the contribution from such configurations should not exceed the previous one unless they are favoured dynamically by the production of resonances in the final state. These effects, which can produce enhancement factors of two to three times on the decay rates, as observed in D decays, are unlikely in this case because there is not enough available phase-space to produce a \( \rho^+ \) or a \( K^+ \) at its pole mass value.

A large effect from \( \Xi^- \) states is also unlikely because \( \Xi^- \) contributes only to about 50% of the \( \Xi^- K^+ \pi^+ \) as noticed previously. In the simulation the production of \( \Xi^0 \) from \( \Lambda_b \) decays amount to 0.3%, a value which is consistent with the expected contribution from the decay \( \Lambda_c^+ \to \Xi^- K^+ \pi^+ \) alone, and the probability to have this final state in a \( \Lambda_b \) quark jet is:

\[
\mathcal{P}(b \to \Lambda_b^0 \to \Xi^- \ell^- X) = \mathcal{P}(b \to \Lambda_b^0) \\
\times \mathcal{P}(\Lambda_b^0 \to \Lambda_c^+ \ell^- X) \times \mathcal{P}(\Lambda_c^+ \to \Xi^- X) \times \mathcal{P}(\Lambda_c^+ \to \Xi^- X) = 2.3 \times 10^{-5}.
\]

Direct semileptonic decays of a \( \Lambda_b \) with a \( \Xi_c \) and a kaon produced in the accompanying system (Fig. 2.c) are expected to be negligible (as in the search for the \( B_s \) meson using the \( D_s - \ell^+ \) final state, where semileptonic decays with a \( D_s \) and a kaon in the final state, from non-strange \( B \)-hadrons could be neglected [2]).

- At lower transverse momenta of the lepton, several decay mechanisms contribute, as:
  - semileptonic decays of \( \Xi_c \) baryons produced in charmed jets (Fig. 2.d)
  
  \[
  c \to \Xi_c \to \Xi^- \ell^+ X
  \]
  - cascade decays of B mesons into baryon-antibaryon pairs like:
  \[
  B \to \Xi_c \Lambda_c X \text{ with } \Xi_c \to \Xi^- X' \text{ and } \Lambda_c \to \ell^- X''
  \]
  - fake leptons

These three processes give a negligible contribution when the \( P_t \) of the lepton is required to be larger than 1 GeV/c.

5.2 \( \Xi^- \) hyperons from fragmentation

\( \Xi^- \) are produced during the hadronization of the quark jets and are a source of background. They require the emission of an \( s - \bar{s} \) quark pair and of a diquark-antidiquark pair containing at least one strange quark. As the \( \Xi^- \) and the lepton both are required to have a momentum larger than 3 GeV/c, it is probable that the \( \Xi^- \) and the hadron producing the lepton are close in rapidity, and therefore only those cases will be dealt with in the qualitative description given below. The expected contribution from these mechanisms,
If the lepton comes from a non-strange $B$ semileptonic decay, the $\Xi^{\mp}$ are less energetic because they have to be produced further down the hadronization chain. The contributions to right-sign and wrong-sign pairs should also be rather symmetric in this case (Fig. 3.c, d).

- The lepton originates from a charmed hadron decay: if the charmed hadron is produced in a $B$ hadron cascade decay the previously quoted mechanisms have to be considered but the sign of the lepton is reversed and its transverse momentum relative to the jet axis will be usually smaller.

If the charmed hadron comes from the fragmentation of a primary charm quark, in case of $D_s$ semileptonic decays, there will be a contribution to wrong-sign $\Xi^{\mp} - \ell^\mp$ pairs only.

- Contribution from fake leptons: because of the quark content of the $\Xi^{-}$ it will be more probable to get a $\Xi^{\mp}$ accompanied by a kaon or a pion of opposite charge which can be identified as a muon. An excess of background is then expected in wrong-sign $\Xi^{\mp} - \mu^\pm$ pairs (Fig. 3.e).

From the above list it appears that all mechanisms in which the $\Xi^{-}$ is produced in the jet hadronization and is accompanied by a lepton emitted at large transverse momentum contribute in a similar way to right-sign and to wrong-sign $\Xi^{\mp} - \ell^\mp$ pairs with an excess expected in the second category.

### 6 Properties of the channel $\Xi_b \rightarrow \Xi^- \ell^- \bar{\nu}_\ell X$

Using a large sample of simulated events (Sect. 7), the distributions of several kinematic variables are plotted in Fig. 4 for $\Xi_b \rightarrow \Xi^- \ell^- \bar{\nu}_\ell X$ and for all other mechanisms in which a $\Xi^{-}$ and a lepton, each with a momentum larger than 2 GeV/c, are produced in the same hemisphere. Each hadronic event is divided into two hemispheres by the plane normal to the thrust axis which contains the beam interaction point. The accepted ranges for the variation of these variables have been displayed in Fig. 4. The simulation includes a detailed modelling of the detector behaviour and these events have been analyzed using the same reconstruction algorithms as applied to the data [8].

- A $\Xi^{-}$ produced from a $\Xi_c$ decay secondary to a $B$-baryon benefits from the large fraction of the beam energy taken by the $B$-baryon and is usually faster than baryons coming from the fragmentation of the remaining light quark-antiquark system. This is shown in Fig. 4.a, where the lack of events below 2 GeV/c comes from a cut applied at simulation. $\Xi^{-}$ with a momentum larger than 3 GeV/c have been selected.

- The transverse momentum of the lepton, relative to the jet axis, has a distribution which extends to larger values than the corresponding distributions from other lepton sources such as $B$ hadron cascade or direct charm semileptonic decays (Fig. 4.b). Events with a lepton having a transverse momentum larger than 1 GeV/c have been kept.
The analysis has been performed in two steps. Evidence for $\Xi_b$ baryon production has been obtained by evaluating the probability that a simulation which does not contain any B-baryon reproduces the data. For this purpose, it has been assumed that a simulation which does not contain any B-baryon will produce at least one genuine $\Xi$ and one genuine muon in the same hemisphere, there is no contribution from fake leptons in the quoted numbers.

This sample has been used to determine the contributions from the different production mechanisms to the $\Xi - \ell$ final state. The selection criteria described in Sect. 6 have been applied to right-sign and wrong-sign $\Xi - \ell$ pairs separately. The results are summarized in Table 2.

The Table 2 shows an excess of right-sign $\Xi^+ - \ell^+$ pairs with a lepton emitted at large transverse momentum and with a positive decay distance greater than 1 mm. The analysis outlined in Sect. 5 and including a detailed simulation of the physics, the detector and the reconstruction algorithms shows that this excess comes from B-baryon semileptonic decays.

In the second sample, equivalent to 2.8 million hadronic $Z^0$ decays, all quark flavours have been generated; this sample has been used to study the contribution to lepton candidates from misidentified hadrons.

Finally, a sample equivalent to 2.3 million hadronic $Z^0$ decays has been used to study the level of the combinatorial background under the $\Xi^+$ mass peak obtained with the "HT" algorithm.

After having normalized the simulated events to the same number of hadronic $Z^0$ decays collected from 1991 to 1993, the number of $\Xi - \ell$ candidates found in the simulation and in the data have been compared in a region where the contribution from B-baryons is expected to be negligible relative to other processes. For this purpose, wrong-sign $\Xi^+ - \ell^+$ pairs have been used which satisfy $P_\Xi > 3$ GeV/c and $M(\Xi - \ell)$ between 2 and 4.5 GeV/c. A cut was applied to the lepton transverse momentum and the $\Xi^+$ hyperon was reconstructed by either of the "HT" and "A\pi" algorithms. Figure 5.b, d gives the $A_{\pi}$ mass distributions obtained. In the simulation, because of the use of a dedicated sample of B-baryon decays, all quark flavours have been generated; this sample has been used to study the contribution to lepton candidates from misidentified hadrons.

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Fig. 5. Comparison between measured and expected numbers of right-sign and wrong-sign \( \Xi^- \rightarrow \ell^\pm \) pairs. The hatched histograms represent the Monte-Carlo events, which include only the contribution from \( \Lambda_b \) and \( \Xi_b \) semileptonic decays but not the combinatorial background. The fitted curves are the sum of a first order polynomial distribution to describe the combinatorial background and of a Gaussian distribution of fixed width and central values to account for the signal.

Table 3. Numbers of wrong-sign \( \Xi^- \rightarrow \ell^\pm \) pairs measured in data and in the simulation with the two \( \Xi^- \) reconstruction algorithms

| \( \Xi^- \rightarrow \ell^\pm \) | "\( \Lambda\pi\)" | "\( \text{HT} \)"
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>29.2 ± 7.2</td>
<td>6.2 ± 3.4</td>
</tr>
<tr>
<td>Simulation (total)</td>
<td>29.8 ± 2.9</td>
<td>7.6 ± 1.0</td>
</tr>
<tr>
<td>Detailed contributions:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non B-baryons, genuine lepton</td>
<td>14.1 ± 0.8</td>
<td>4.1 ± 0.3</td>
</tr>
<tr>
<td>Non B-baryons, fake lepton</td>
<td>12.7 ± 2.8</td>
<td>3.0 ± 1.0</td>
</tr>
<tr>
<td>B-baryons</td>
<td>3.0 ± 0.4</td>
<td>0.5 ± 0.1</td>
</tr>
</tbody>
</table>

In this comparison, the "\( \Lambda\pi\)" algorithm has been used because of its higher efficiency. The same value for the systematic uncertainty has been used for the "\( \text{HT} \)" algorithm because it was shown in Sect. 4 that the relative efficiency of the two methods was reproduced by the simulation.

Figure 5.a and c shows the \( \Lambda - \pi \) mass distribution for right-sign \( \Xi^- \rightarrow \ell^\pm \) pairs; an excess of candidates is observed in the data compared to the simulation. A comparison is given in Table 4.

To check if this excess can be attributed to B-baryon decays, selection criteria have been applied to isolate samples of events in which the expected contribution from B-baryons is not marginal but even dominates, according to the arguments developed in Sects. 5 and 6. Only \( \Xi^- \) reconstructed with the "\( \text{HT} \)" algorithm have been considered because of the reduced combinatorial background under the \( \Xi^- \) mass peak and because the \( \Xi^- \rightarrow \ell \) vertex can be accurately defined.

\( \Xi^- \) reconstructed using the "\( \text{HT} \)" algorithm and accompanied by a same sign lepton of transverse momentum larger than 1 GeV/c (Fig. 6) are in excess with respect to events from the simulation which contain no contribution from B-baryon decays. The results are summarized in Table 5 using the cuts described in Sect. 6.

The measured values for wrong-sign \( \Xi^- \rightarrow \ell^\pm \) pairs are compatible with the expectations from the simulation. In this charge configuration the effect from B-baryons decays is expected to be small. The probabilities shown in Table 5
that the observed signals in right-sign \( \Xi^+ - \ell^+ \) pairs be explained by statistical fluctuations of the expected numbers of events from all contributing mechanisms, without B-baryon decays have been evaluated using the following expression:

\[
\mathcal{P}(\geq N) = \sum_{n=N}^{\infty} \frac{e^{-\mu_0} \left( \frac{\mu_0}{n!} \right)^n}{\sqrt{2\pi\sigma_0^2}} \int_0^\infty \frac{\mu_0 e^{-\mu_0}}{n!} d\mu \quad (3)
\]

where \( N \) is the measured number of events in data, \( \mu_0 \) is the expected number of events from the Monte Carlo simulation without contribution from B-baryons, and \( \sigma_0 \) is the uncertainty on \( \mu_0 \) which corresponds to the sum of the statistical, the normalization (27\%) and the combinatorial background uncertainties added in quadrature.

To be independent of the details of the simulation and as the contribution from non-B-baryon decays is expected to be larger in wrong-sign pairs, on quite general grounds (see Sect. 5.2), \( \mu_0 \) has been evaluated by taking the greater of the estimates in right-sign and wrong-sign pairs for the signal and the combinatorial background.

Thus we find that the \( \Xi^+ \) signals observed in the right-sign sample have less than \( 5 \times 10^{-4} \) probability to be explained by a fluctuation of non-B-baryon semileptonic decays.

A display of one candidate observed in the right-sign sample is given in Fig. 7. The \( \Xi^+ \) trajectory reconstructed by the "HT" algorithm has a large offset with respect to the primary vertex and the distance between the \( \Xi^+ \) vertex and the primary vertex, in the plane transverse to the beam direction, is 3 mm which corresponds to 9 times the measurement accuracy.

8 \( \Xi_b \) baryon production rate

The contribution from B-baryon semileptonic decays to the production rate of \( \Xi - \ell \) pairs has been evaluated by subtracting the expected contribution from non-B-baryon sources from the number of \( \Xi^+ \) candidates observed in data and comparing the result with the number of events expected from the simulation for \( \Xi_b \) and \( \Lambda_b \) semileptonic decays. Systematic uncertainties are calculated by estimating the capability of the simulation to account for the different contributions to \( \Xi - \ell \) pairs of non-B-baryon origin and by evaluating the experimental acceptance for the \( \Xi^+ \) and the lepton produced in a B-baryon direct semileptonic decay. The former contribution has been measured using the data in Sect. 7. The latter is known with an accuracy of 10\%, depending mainly on the understanding of the detector acceptance for \( \Xi^+ \) decays (Sect. 4).

Results obtained with the two algorithms have been combined, keeping events reconstructed with the "HT" algorithm and adding those selected only with the "ATr" method (Fig. 8). The observed numbers of \( \Xi^+ \) hyperons and the expected contributions from the different sources are given in Table 6. Selected events have to satisfy \( P_{\Xi} > 3 \text{ GeV/c} \), \( 2 < M_{\Xi-l} < 4.5 \text{ GeV/c}^2 \) and \( P_T^\ell > 1 \text{ GeV/c} \).

Wrong-sign \( \Xi^+ - \ell^+ \) pairs have not been included in the final measurement.

The absolute production rate of B-baryons decaying to the \( \Xi^+ - \ell^+ \) final state is:

\[
\mathcal{P}(b \rightarrow B\text{-baryon}) \times BR(B\text{-baryon} \rightarrow \Xi^- \ell^- X) = (5.9 \pm 2.1 \pm 1.0) \times 10^{-4}. \quad (4)
\]

This value is significantly lower than the rate of \( \Lambda_b \) baryon production, measured by LEP experiments [14] using the \( A - l \) final state:

\[
\mathcal{P}(b \rightarrow \Lambda_b) \times BR(\Lambda_b \rightarrow A l^- X) = (3.2 \pm 0.3 \pm 0.8) \times 10^{-3}. \quad (5)
\]

Assuming that the \( \Lambda_b \) production rate in a b quark jet is equal to (10 \pm 5)\% [15], the corresponding probability for a \( \Xi_b \) baryon to be produced can be expressed using (1), (2) and (5) as a function of still unmeasured branching fractions:

\[
\mathcal{P}(b \rightarrow \Xi_b)(\%) = (3.5 \pm 1.2 \pm 0.6 - (0.6 \pm 0.3) \times BR(\Lambda_c \rightarrow \Xi^- X)(\%)) \times \frac{17.}{BR(\Xi_c \rightarrow \Xi^- X)(\%)}
\]
Table 5. Comparison between the numbers of right-sign and wrong-sign \( \Xi^- - \ell^- \) pairs measured in data and expected from the simulation. The numbers of simulated events originating from B-baryon semileptonic decays (B) and from all other sources (NB) have been quoted separately. The evaluation of the combinatorial background (Bckg) under the \( \Xi^- \) mass peak is also given.

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Data</th>
<th>M.C.</th>
<th>Data</th>
<th>M.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_\Xi &gt; 3 \text{GeV/c} )</td>
<td>10</td>
<td>NB = 1.8 ± 0.5</td>
<td>3</td>
<td>NB = 3.2 ± 1.2</td>
</tr>
<tr>
<td>( 2 &lt; M_{\Xi^- \ell^-} &lt; 4.5 \text{GeV/c}^2 )</td>
<td>5</td>
<td>Bckg. = 0.24 ± 0.14</td>
<td>(B) = 1.80 ± 0.22</td>
<td>Bckg. = 0.4 ± 0.2</td>
</tr>
<tr>
<td>( P_T \ell^+ &gt; 1 \text{GeV/c} )</td>
<td>4</td>
<td>( \sigma_{b,b}(\geq 10) = 0.24 % )</td>
<td>(B) = 0.40 ± 0.12</td>
<td></td>
</tr>
</tbody>
</table>

\[ \text{Table 6. Numbers of } \Xi^- - \ell^- \text{ candidates measured in data and expected from the Monte Carlo simulation. The values for B-baryon decays correspond to the probabilities of 7.8\% and 1\% to have, respectively, a } \Lambda_b \text{ or a } \Xi_b \text{ baryon in a } b \text{ jet. Events have been selected as described in the text} \]

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Simulation (total)</th>
<th>Simulation (components)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Xi^- - \ell^- )</td>
<td>28.4 ± 6.1</td>
<td>15.3 ± 1.5</td>
<td>Non B-baryon, genuine lepton 6.7 ± 0.5</td>
</tr>
<tr>
<td>( \Xi^- - \ell^+ )</td>
<td>15.2 ± 5.2</td>
<td>13.9 ± 1.8</td>
<td>Non B-baryon, fake lepton 2.5 ± 1.3</td>
</tr>
<tr>
<td>B-baryon</td>
<td>6.1 ± 0.5</td>
<td>2.3 ± 0.4</td>
<td>B-baryon</td>
</tr>
</tbody>
</table>

9 Measurement of the lifetime of the \( \Xi_b \) baryon

The 10 candidates containing a right-sign \( \Xi^- - \ell^- \) pair, selected by the “HT” algorithm and with the lepton transverse momentum larger than 1 GeV/c but without any cut on the \( \Xi - \ell \) flight distance, have been used to measure the lifetime of \( \Xi_b \) baryonic states.

The proper time of the parent B hadron is measured in the following way.

The \( \Xi^- \) track is reconstructed inside the VD and combined with the lepton trajectory to obtain the position of a secondary vertex. The decay distance between the primary and the secondary vertex has been measured in the plane transverse to the beam direction and computed in space using the angle of the momentum of the \( \Xi - \ell \) system relative to the beam axis. This distance is positive if the secondary vertex is found beyond the primary vertex in the direction.
of the $\Xi - \ell$ momentum. The accuracy on the flight distance of the B-baryon, as obtained from the simulation, is $280 \pm 70 \mu m$.

The $\Xi_b$ baryon momentum is obtained, with a relative accuracy of $(17 \pm 3)\%$, from the measured momentum of the $\Xi - \ell$ system and using the Monte Carlo simulation to get the parameters of the correlation between these two quantities:

$$P(\Xi_b) = \frac{P(\Xi - \ell)}{a_0 + a_1 \times P(\Xi - \ell)},$$

with $a_0 = 0.30 \pm 0.05$ and $a_1 = 0.019 \pm 0.003 \ (GeV/c)^{-1}$.

An unbinned maximum likelihood method was used to fit the proper time distribution. The proper time probability distribution for the signal is an exponential convoluted with a Gaussian to account for the smearing in the $\Xi_b$ baryon energy and decay distance measurements. The proper time probability distribution for the background has two components, a Gaussian and an exponential, whose parameters have been obtained using simulated events. In a sample of B-baryons, generated with 1.6 ps lifetime, the fitted lifetime was:

$$\tau(B - \text{baryon} \rightarrow \Xi^{-} \ell^{-} X) = 1.4 \pm 0.3 \text{ ps},$$

in agreement with the generated value.

The fitted lifetime for the data is (Fig. 9):

$$\tau(B - \text{baryon} \rightarrow \Xi^{-} \ell^{-} X) = 1.5^{+0.7}_{-0.4} (\text{stat.}) \pm 0.3 (\text{syst.}) \text{ ps},$$

where the systematic uncertainty corresponds to the statistical accuracy of the comparison between the generated and reconstructed lifetimes of the $\Xi_b$ baryon from the simulated events. The other systematic errors, coming from the uncertainties on the fraction of background events, on the modelling of the B energy reconstruction and on the mass of $\Xi_b$ baryonic states, are much smaller.

### 10 Conclusions

An algorithm which tracks charged $\Xi^+$ through the DELPHI Vertex Detector has been developed. It allows measurement of these particles to be performed with a very small combinatorial background and precise measurement of their decay vertices.

Events with a lepton with transverse momentum greater than 1 GeV/c and with a secondary $\Xi - \ell$ vertex displaced by more than 1 mm relative to the primary vertex, in the direction of the $\Xi - \ell$ system, have been selected. An excess of right-sign pairs has been measured, with a probability of $5 \times 10^{-4}$ of being explained by mechanisms other than B-baryon decays. It has been checked that the Monte Carlo simulation correctly reproduced the number of $\Xi - \ell$ pairs in kinematical regions where the expected contribution from B-baryon decays is marginal.

From the number of right-sign pairs, obtained with two algorithms described in this paper, the production rate has been measured to:

$$\mathcal{P}(b \rightarrow B - \text{baryon}) \times \text{BR}(B - \text{baryon} \rightarrow \Xi^- \ell^- X) = (5.9 \pm 2.1 \pm 1.0) \times 10^{-4},$$

per lepton species, averaged over electrons and muons and assuming that the two channels have an equal contribution.

The contribution from $A_b$ semileptonic decays followed by the $A_c \rightarrow \Xi^- K^+ \pi^+$ transition can account only for $(5 \pm 3)\%$ of the observed signal.

The lifetime has been measured using a subsample of $\Xi^+ - \ell^+$ events and found to be:

$$\tau(B - \text{baryon} \rightarrow \Xi^- \ell^- X) = 1.5^{+0.7}_{-0.4} \pm 0.3 \text{ ps}.$$
   OPAL Collaboration, contribution to the International Conference on High Energy Physics, Glasgow 1994, ref. GLS0534.
   DELPHI Collaboration, contribution to the International Conference on High Energy Physics, Glasgow 1994, ref. GLS0162.