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Lifetime and production rate of beauty baryons from Z^0 decays

Preliminary

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Abstract

A study of the production of beauty baryons in Z^0 decays is reported; the analysis is based on 1.7 Million Z^0 hadronic events collected by the DELPHI detector. Beauty baryon signals are obtained using three complementary methods :
- excess of $\Lambda\ l^-$ pairs with both particles in the same jet with respect to similarly correlated $\Lambda\ l^+$ pairs, especially when the lepton has high transverse momentum p_T,
- the presence of a fully reconstructed Λ_c baryon associated with a high p_T l^- in the same jet,
- the presence of a secondary vertex formed by a fast proton, identified by the RICH, and a muon of opposite sign.

Each signal provides an evaluation of an inclusive branching fraction and an average beauty baryon lifetime, leading to the result :

$$\tau(b - baryon) = 1.21^{+.21}_{-.18}(stat) \pm 0.04(exp.syst)^{+.02}_{-.07}(theory)\ \ ps.$$

1 Introduction

After the discovery of the Λ_b baryon, observed in the exclusive decay $\Lambda_b \rightarrow \Lambda J/\Psi$ by the UA1 experiment at the $Sp\bar{p}S$ collider [1], evidence for its production in Z^0 hadronic decays has been recently reported by the LEP experiments [2, 3]. They interpreted as due to Λ_b decays the observed excess of "right-sign" $\Lambda\ l^-$ and $\bar{\Lambda} l^-$ pairs with both particles in the same jet with respect to "wrong-sign" $\Lambda\ l^+$ and $\bar{\Lambda} l^-$ states (l is a lepton with high transverse momentum).

This paper extends the analysis of ref.[3] with significant improvements in the study of the Λ -lepton channel and studying the production of b-baryons using two new semileptonic decay channels, based on the detection of a Λ_c or a fast proton in the same jet of a high transverse momentum lepton.

The Λ-lepton channel provides an easy signature for b-baryon production; however the lifetime determination suffers from the highest error on the decay length due to the difficult Λ -lepton vertex reconstruction. The Λ_c -lepton channel, although impaired by low statistics, provides the purest b-baryon sample and its lifetime determination does not depend on any assumption on the Λ_c semi-exclusive decays. Finally, the proton-lepton channel relies on the unique particle identification capabilities of the DELPHI detector, which incorporates a Ring Imaging Cherenkov detector (RICH), to detect faster beauty baryons decaying to other modes such as $\Lambda_b \rightarrow pDl\nu$; in this case vertex reconstruction is easier.

In all the considered processes, an excess of events with *right sign* pairs, i.e. with a baryon having baryon number opposite to the lepton charge is observed with respect to events with *wrong sign* pairs i.e. with identical baryon number and lepton charge. The data used for this analysis were collected in the years 1991-93, and correspond to about 1.7 Million Z^0 hadronic decays. Reconstructed vertices from the three data samples were used to determine average b-baryon lifetimes.

The paper is organized as follows: after a short description of the detector (section 2) with some emphasis on the sub-detectors relevant to the analyses, in section 3 the lepton (muon and electron) selections, common to all methods, are briefly described. Sections 4, 5 and 6 describe the three methods in turn with subsections devoted respectively to: the expected signals and backgrounds, the baryon (Λ , Λ_c and p) reconstruction algorithms, the baryon-lepton pairs selection criteria and the final analyses which lead to the physics results on production rates and lifetimes. These results are summarised and compared in section 7, which ends with our conclusions.

2 The Delphi detector

The Delphi detector is decribed in detail elsewhere [4]. Sub-detectors particularly important for the present analysis are the central tracking devices (Vertex Detector, VD, Inner Detector, ID, Time Projection Chumber, TPC, and Outer Detector, OD), the Ring Imaging Cherenkov detector (RICH) for hadron identification, the barrel electromagnetic calorimeter (HPC) and the muon chambers for lepton identification.

Charged particles are reconstructed with 95% efficiency and with momentum resolution in the range $\sigma_p/p = (.001 - .002)p$ (GeV/c) depending on which tracking devices contribute to the reconstruction. The primary vertex of the e^+e^- interaction, reconstructed event by event with the beam spot constraint using only tracks having hits in the VD, has an r.m.s. precision of 40μ, slightly dependent on the flavour of produced quark-antiquark. Secondary vertices from beauty and charm decays are reconstructed with vertex resolution $\sigma_V = 300\mu m$ along the flight direction of the decaying particles projected into the plane transverse to the beam direction (the bending plane of the Delphi magnet) if their decay tracks have associated hits in the VD. Strange particle decays like $\Lambda \rightarrow p\pi$ can be succesfully reconstructed with good mass resolution if their decay products have at least a track segment 20 cm long in the TPC, i.e. if the projection onto the bending plane of their decay length is less than 90 cm (this must be compared with the quantity $c\tau = 8$ cm for a Λ particle).

Hadron identification relies on the specific ionization measurement performed by the TPC wires in the region of the relativistic raise (4-25 GeV/c for a proton, with a 7% resolution), and on the RICH tag. The RICH detector [5] consists of a liquid radiator which provides $p/K/\pi$ separation in the intermediate momentum region p=2–8 GeV/c, and a gas radiator which works in veto mode for proton selection in the region p=8–15 GeV/c and can separate protons from kaons up to 30 GeV/c.

The barrel electromagnetic calorimeter, covering the polar angle region $46^o < \theta < 134^o$, detects electrons with an energy resolution $\sigma_E/E = 0.25/\sqrt{E}$ and with very good position resolution due to the high granularity of the detector. Thanks to the longitudinal segmentation of the calorimeter, an independent measurement of the electron direction is also performed.

Two planes of muon chambers cover the polar angle region $20^o < \theta < 160^o$, with small holes of 2^o width around $\theta = 42^o$ and $\theta = 138^o$. The first layer is positioned inside the return yokes of the magnet, after about 90 cm Fe, while the second one is mounted on the outside of the yoke, behind a further 20 cm of iron.

3 Lepton selection in hadronic events

Hadronic events from Z^0 decays are selected requiring a charged multiplicity bigger than 5 and a total reconstructed energy greater than 0.12 $\sqrt{s}$; the overall trigger plus selection efficiency is 0.950 ± 0.011 [6].

Muon and electron candidates are considered in the analysis if their momentum is bigger than 3 GeV/c.

Candidate muon tracks are extrapolated to the muon chambers and a global χ^2 of the track is defined after the refitting procedure described in [7]. The selection corresponding to the *loose* cuts defined there has been used. The corresponding muon identification efficiency in the considered polar angular range is (90 ± 1)%, with a hadron misidentification probability of (1.2 ± 0.1)% [7]. Of the muons with transverse momentum p_T greater than 0.6 GeV/c with respect to their jets[1], 58% are estimated to come from direct b-quark decay [8].

Electron candidates are selected by requiring a match between the track extrapolation to the calorimeter and the position of a HPC shower, a match between the measured energy and the track momentum and a successful fit to the longitudinal profile of the shower in the 9 HPC layers giving a χ^2 probability for the electron hypothesis bigger than 4% [9]; in addition, the dE/dx deposition in the Time Projection Chamber (TPC) must

[1]The jet axis used to compute p_T for a track is determined including this track in the jet

have a probability bigger than 2% for the electron hypothesis and the gas RICH detector, if operational, must have at least one photoelectron associated to the electron candidate. Finally, gamma conversions are rejected by a vertex fit to the pairs of electron candidates, requiring that the e^+e^- invariant mass be less than $20MeV$. The electron identification efficiency in the HPC fiducial volume is $(62 \pm 1)\%$, with a hadron misidentification probability of $(1.5 \pm 0.4)\%$.

4 Λ -lepton channel

4.1 Signal and background characteristics

Decays of b-baryons with a Λ and a lepton in the final state originate mainly from the decay chain : $b - baryon \rightarrow \Lambda_c l \nu X, \Lambda_c \rightarrow \Lambda X$.

They have the following properties :

- the lepton has high transverse and longitudinal momentum;
- the Λ has a harder momentum spectrum than the Λ produced in light quark fragmentation;
- the Λ lepton pair has the *right sign*.

As extensively discussed in ref.[3], background events have either wrong sign correlation (the case of e.g. $\Lambda_c \rightarrow \Lambda l \nu X$ decays which, moreover, have leptons with smaller transverse momentum) or display no clear correlation between the lepton charge and the hyperon baryon number (the case of genuine Λ accompanying hadrons misidentified as leptons where also the Λ momentum and the misidentified hadron p_T spectra are softer). Semileptonic B meson decays like $B \rightarrow \Lambda_c N l^- \nu X$ (where N is an antibaryon), which can also contribute to an excess in right sign pairs, are estimated to be negligible. A quantitative analysis of the background based on detailed simulation of Z^0 hadronic events is reported in sect.4.3.

4.2 Λ selection

In the search for $\Lambda \rightarrow p\pi$ decay, oppositely charged tracks with momentum $0.1 < p < 30$ GeV/c are considered for reconstructing secondary vertex candidates; they are kept if their projections in the plane transverse to the beam intersect or if their minimum distance in this plane, Δ_{xy}, is less than 3 mm and their perigee separation in the z-direction, Δ_z, is less than 5 mm. If a track belongs to more than one vertex candidate, that with the maximum transverse decay length L_T is retained for further analysis, a choice which favours candidates occurring in detector regions where the combinatorial background is lower. Particle identification greatly improves the background rejection, with negligible loss in efficiency; dE/dx cuts in TPC and selection cuts for rejection of γ conversions and K^o decays are discussed in [3]. Moreover, the RICH 'loose' tag described in [10] is used for the proton track from the Λ candidate (defined as the Λ prong with the higher momentum) when the information from the liquid radiator is available.

To further improve the signal/noise ratio, the following cuts are applied:

- the angle in the plane transverse to the beam between the line of flight and the reconstructed Λ momentum must be smaller than 2^o;

- the probability for the decay candidate to have the observed lifetime or more if it were a Λ must be bigger than 4%;

- at least one VD hit must be associated to each track for decays inside the beam pipe;

- the Λ decay length must be less than the distance from the interaction point of the starting point of both decay tracks.

Fig.1.a shows the (pπ) invariant mass for the final selection in the data for candidates with momentum bigger than 4 GeV/c. From a fit to the data mass spectrum, the Λ mass and width are computed to be 1114.9 $\pm$ 0.5 and 3.7 $\pm$ 0.6 MeV/c^2. The background-subtracted momentum spectrum for the reconstructed Λ candidates in the mass region $1.106 < m(p\pi) < 1.126$ GeV/c^2 is shown in fig.1.b. The $\Lambda \to p\pi$ reconstruction efficiency predicted by the Monte Carlo, shown in fig.1.c as a function of the Λ momentum, is on average $(20 \pm 1)\%$ for $p > 4$ GeV/c, better than in [3] due to an improved tracking pattern recognition.

4.3 Λ - lepton correlation

To select Λ and leptons coming from the Λ_b decay chain, the following cuts have been applied (hereafter referred as 'Λ_b selection cuts') :

- $p_\Lambda > 4$ GeV/c;
- $p_l > 3$ GeV/c and $p_T > 0.5$ GeV/c ;
- $(p_l + p_\Lambda) > 9$ GeV/c;
- $1.9 < m(\Lambda l) < 5.0$ GeV/c^2 .

These cuts reduce background sources of Λ l pairs (hereafter called *accidental combinations*) by more than two orders of magnitude [3] and select Λ_b decays with an overall efficiency of $(50 \pm 3)\%$.

The (p π) invariant mass spectra in the data after the above cuts for the right and wrong sign pairs are shown by the dots in figs.2.a and 2.b, together with the result of a fit to the data using a Gaussian function superimposed on a polynomial background. The fit gives a signal of (234 ± 20) Λ in the right sign pairs and (112 ± 19) Λ in the wrong sign pairs. The histograms are the corresponding Monte Carlo distributions normalized to the total number of hadronic Z^0 events; the yield of *genuine* Λ predicted by the simulation is shown by the dashed area; the double hatched areas show the Monte Carlo prediction for the Λ coming from a b-baryon decay.

The simulation assumes a Λ_b production rate $f(b \to \Lambda_b) \times Br(\Lambda_b \to \Lambda l \nu X) = 0.3\%$ and a Ξ_b and Σ_b production rate 10 times smaller. It also predicts a small signal in the wrong sign pair combinations, due to $\Lambda_c \to \Lambda l \nu X$ decays and to associated production of $\Lambda_b - \bar{\Lambda}$ in which the $\bar{\Lambda}$ has been reconstructed and associated to the lepton.

4.4 Determination of $BR(b - baryon \to \Lambda l \nu X)$

As shown in figs.2.a,b, after all the cuts described above, the Monte Carlo predicts a sizeable signal of Λ coming from sources other than b-baryon decays, both in right and wrong sign correlations. The prediction of the simulation on the absolute number of these *background* Λ , slightly overestimated compared to the data, is not used in the following. However, the Monte Carlo value for the ratio between background Λ in the two distributions in fig.2.a and 2.b, $R = 1.0 \pm 0.1$, is assumed to be correct; its error, which includes the limited Monte Carlo statistics, is included in the systematic error on the production rate. Moreover, as noticed above, a small b-baryon signal $(15 \pm 5\%$ of

Table 1: Contributions to the total systematic error on the b-baryon production rate times its branching ratio to $\Lambda\ell\nu X$.

$Source$	$variation\ level$	$Syst.error$
$lepton\ id.\ efficiency$	$\pm 2\%$	$\pm .006$
$\Lambda\ rec.\ efficiency$	$0.20 \pm .01$	$\pm .016$
$background\ subtraction$	$-$	$\pm .032$
$< E_b >$	$0.70 \pm .03$	$\pm .006$
$BR(\Lambda_b \to \Lambda_c l\nu n\pi)/BR(\Lambda_b \to \Lambda_c l\nu)$	$0 \to 0.3$	$+.020$
$total\ syst.\ error$	$-$	$^{+.042}_{-.037}$

the signal in the right sign sample) is predicted in the wrong sign pair combinations. Accordingly, to estimate the b-baryon yield in the right sign combinations the Λ signal in wrong sign combinations is subtracted from the signal in fig.2.a and the result is scaled by the correction factor $C = 1.18 \pm 0.07$. This leads to a total signal of $144 \pm 33(stat) \pm 14(syst)$ events.

For the analysis of the Λ -μ pairs, the hadronic data sample in which the TPC and the barrel and forward muon chambers were more than 90% operational has been used; this requirement selects 1 615 000 Z^0 events. The overall efficiency for the Λ μ channel is $(4.4 \pm 0.4)\%$. The estimated number of b-baryons in this sample $(118 \pm 27 \pm 12)$ leads to a production rate :

$$f(b \to b - baryon) \times Br(b - baryon \to \Lambda\mu\nu X) = (0.38 \pm 0.08(stat) \pm 0.05(syst))\%.$$

For the analysis of the Λ -e pairs, the hadronic data sample in which the TPC and HPC were more than 90% operational has been used; this requirement selects 1 589 000 Z^0 events. The overall efficiency for the Λ e channel is $(2.0 \pm 0.3)\%$. The estimated number of b-baryons in the sample is $(26 \pm 19 \pm 3)$, giving a production rate :

$$f(b \to b - baryon) \times Br(b - baryon \to \Lambda e\nu X) = (0.19 \pm 0.13(stat) \pm 0.03(syst))\%.$$

Assuming lepton universality, these results may be averaged :

$$f(b \to b - baryon) \times Br(b - baryon \to \Lambda l\nu X) = (0.32 \pm 0.07(stat) \pm 0.04(syst))\%.$$

Table 1 shows the contributions of the different error sources to the total systematic uncertainty. The efficiency of the selection defined by the kinematical cuts discussed in sect.4.3 is slightly dependent on the assumed momentum spectrum and polarization of the b-baryon. Different assumptions on the $\Lambda_c \to \Lambda X$ branching fractions give negligible effects on the overall efficiency. A small effect can arise if the $\Lambda_b \to \Lambda_c^* l\nu$ and $\Lambda_b \to \Lambda_c n\pi l\nu$ (not resonant) decays are an important fraction of the total width. However, as can be seen from the table, the dominant contribution to the systematic error comes from the background subtraction procedure used to eliminate accidental Λ -lepton correlations. The above result can be compared with the previous determination by DELPHI [3]: $f(b \to \Lambda_b) \times Br(\Lambda_b \to \Lambda l\nu X) = (0.41 \pm 0.13(stat) \pm 0.09(syst))\%$.

Fig.3.a shows the right-sign Λ momentum spectrum after the subtraction of the wrong sign Λ sample for the data (dots); the superimposed histogram, showing the Monte Carlo prediction for the momentum of reconstructed Λ originating from a b-baryon, is in good

agreement with the observed spectrum. Similar plots for the lepton p_T spectrum, the sum of the lepton and Λ momenta and the $\Lambda - \mu$ invariant mass are shown in figs.3.b-d.

4.5 Measurement of b-baryon lifetime

The analysis follows the method used in [3] and is based on the muon sample only. Secondary vertices are reconstructed using the Λ , the correlated high p_T muon and an oppositely charged particle (supposed to be a pion) with momentum greater than 0.4 GeV/c and with at least 2 associated hits in the microvertex detector.

This procedure selects b-baryons in which the following charmed-particle in the decay chain has a decay length within the resolution of the vertex reconstruction (300 μm), but does not introduce any bias in the length distribution of the original b-baryon [3]. To reduce the combinatorial background, the $(\mu\Lambda\pi)$ invariant mass is required to be less than 5.6 GeV and the $(\Lambda\pi)$ invariant mass to be less than 2.4 GeV. Further, the contribution of the muon and pion track to the global χ^2 of the vertex must be less than 3.5; the contribution of the Λ track must be less than 5. In case of more than one reconstructed vertex, the one with the pion of highest momentum is chosen. Out of 240 right sign $\Lambda\mu$ events with $1.106 < M(p\pi) < 1.122$ GeV/c^2, 63 decay vertices were reconstructed.

In the simulation, the efficiency for reconstructing the b-baryon decay vertex is about 35%, independent of the lifetime, and in 90% of the reconstructed decays the pion attached to the vertex does originate from the b-baryon decay chain (if a b-baryon has been generated in the event).

The b-baryon purity of the sample, determined from the data by a fit to the mass plots for the right and wrong sign correlations after the b-baryon vertex reconstruction, shown in figs.4.a,b respectively, is (61$\pm$7%). It is worth noting that the additional requirement of the $\mu\Lambda\pi$ vertex fit considerably improves the b-baryon purity of the sample. Background events come from from fake vertices, whose lifetime distribution has an average value of zero and is assumed to have a Gaussian spread determined by the detector resolution, and secondary vertices originating from charm and B meson decays (*'flying background'* component). The latter component is predicted by the Monte Carlo to be 80$\pm$ 10% of the background, both in the right sign pairs and in the wrong sign ones. Its average lifetime is determined from the data using a larger sample of candidate decays reconstructed in the high p_T muon events, as described in [3].

The b-baryon momentum is estimated from the total momentum of the decaying particles using the *residual energy* technique. The residual energy is computed by subtracting the energy associated to the b-baryon candidate (the Λ , the muon and the pion energy) from the total energy associated to charged particles in the lepton hemisphere. The b-baryon energy is estimated by subtracting this residual energy from the beam energy. The energy associated to all neutral particles in the hemisphere is by definition associated to the b-baryon by this method; on the other hand, charged pions from the b-baryon decay chain may be wrongly included in the residual energy computation. As discussed in [3], the two effects nearly compensate, the correction factor computed in the Monte Carlo to reproduce the generated spectrum being on average 0.97. Sources of systematic error on this factor are the uncertainties on the b-baryon mass and polarization, its momentum spectrum and semi-leptonic decay modes. Their effect on the final lifetime result are listed in Table 2. The resolution on the b-baryon momentum predicted by the simulation is 8% [3].

A maximum likelihood fit was performed simultaneously to the lifetime distribution of the 63 events of the signal sample and to the one of the background vertices described above (300 events) with the likelihood function [3] :

$$L = -\Sigma_i log[f(t_i, \sigma_i, \tau, \tau_B)],$$

with

$$f(t_i, \sigma_i, \tau, \tau_B) = N_s e^{\,-\sigma_i^2/2\tau^2 - t_i/\tau}\, erf[(\sigma_i/\tau - t_i/\sigma_i)/\sqrt{2}]/2\tau +$$
$$(1 - N_s)[N_{fb} e^{\sigma_i^2/2\tau_B^2 - t_i/\tau_B} erf[(\sigma_i/\tau_B - t_i/\sigma_i)/\sqrt{2}]/2\tau_B + N_b e^{-t_i^2/2\sigma_i^2}]$$

where τ and τ_B are the signal and background lifetimes; σ_i is the error on the measured decay time t_i; the normalization constant N_s for the signal was fixed to the fitted value of the b-baryon purity discussed above; finally, N_{fb} is the normalization constant for the background from B, D meson decays and $N_b = 1 - N_s - N_{fb}$. A three parameters fit to the data gives the result:

$$\tau(b - baryon) = 1.13^{+0.30}_{-0.23}\ ps\ (\Lambda\mu\nu X \text{ channel, 63 decays})$$

with a background lifetime $\tau_B = 1.62^{+0.14}_{-0.10}\ ps$ and $N_{fb} = 0.79 \pm 0.03$, in agreement with the Monte Carlo prediction. The lifetime distributions for the signal events and for the background, together with the probability functions resulting from the fit, are shown in figs.4.c,d. The uncertainties on the magnitude of the flying background and on its lifetime are accounted for in the statistical error of the fit result. The signal and background lifetimes are slightly anticorrelated, the correlation factor being $C = -0.123$.

The same procedure applied to the MC sample gives: $\tau_B = 1.74^{+0.10}_{-0.08}\ ps$ and $\tau(b - baryon) = 1.52^{+0.24}_{-0.14}\ ps$, compatible with the generated average b-baryon lifetime of 1.56 ps. In the simulation, different samples of b-baryons were generated with average lifetimes varying in the range $0.75 - 2.25\ ps$ and added in turn to hadronic Z^0 events in which all the other sources of flying background were kept with constant lifetimes. The number of b-baryons in the sample was chosen to reproduce the purity observed in the data. The response of the fitting procedure was linear, without any bias over the whole time interval considered.

As can be seen in Table 2, the main contribution to the systematic error comes from the uncertainty on the relative importance of the b-baryon decay modes, which affects the estimation of the momentum. Summing the systematic errors listed in Table 2 in quadrature gives an overall systematic error of $^{+0.05}_{-0.08}\ ps$, much smaller than the statistical error from the fit.

5 Λ_c - lepton channel

5.1 Signal and background characteristics

In this section a study of Λ_b semileptonic decay with a completely reconstructed Λ_c is presented. The analysis is based on the data collected in the 1991 and 1992 runs (about

Table 2: Contributions to the systematic error on the average b-baryon lifetime measured using Λ^0-lepton correlations.

$Error\ source$	$variation\ level$	$Syst.error(ps)$
$\Lambda_c\ BR\ uncertainty$	$one\ st.deviation\ (PDG)$	± 0.02
$b - baryon\ purity$	0.61 ± 0.07	± 0.04
$< E_b >$	0.70 ± 0.03	± 0.01
$b\ baryon\ mass$	$5640 \pm 50 MeV$	± 0.01
$\Lambda_b\ polarization$	$-1 \to 0$	-0.02
$BR(\Lambda_b \to \Lambda_c l \nu n \pi)/BR(\Lambda_b \to \Lambda_c l \nu)$	$0 \to 0.3$	-0.06
$total\ syst.error$	$-$	$^{+0.05}_{-0.08}$

1 Million Z^0 hadronic events). Possible sources of Λ_c ($\bar{\Lambda}_c$) l^- (l^+) in the same jet are:
- Λ_b semileptonic decays
- B semileptonic decays
- accidental correlations of a Λ_c and a lepton.

The Λ_c l combinations from Λ_b decays are characterized by higher invariant mass and higher transverse and longitudinal momentum of the lepton than the background pairs.

5.2 Λ_c selection

The Λ_c is reconstructed via the decay $\Lambda_c \to pK\pi$. This is the most aboundant decay mode, but offers few favourable kinematical features. Taking advantage of the good particle identification capability of the Delphi detector to tag the proton and the kaon, it is possible to reduce substantially the combinatorial background.

Fig.5 shows the $pK\pi$ invariant mass distribution obtained with the following cuts :
- The χ^2 probability of the 3-prong fitted vertex exceeds 0.01.
- The flight distance in the xy plane is greater than 2 σ.
- The proton momentum is greater than the π momentum.
- The total momentum is at least 10 GeV.
- The proton and the kaon are tagged by the RICH or by the request that their dE/dx measurements in the TPC are within 2 σ of the expectation for a proton or a kaon of that momentum.

A fit to the $pK\pi$ invariant mass distribution with a gaussian superimposed on a polynomial background gives a signal of 236 ± 58 events.

5.3 Λ_c lepton correlation

To optimize the efficiency in the study of the Λ_c lepton correlation, the cut on the flight distance is relaxed requiring the Λ_c vertex position only to be on the same side of the primary vertex in the xy plane as the $pK\pi$ momentum vector.
Surviving Λ_c candidates are paired with identified leptons of momenta greater than 3 GeV, within a cone of 45^o around the Λ_c direction. The lepton must have a p_T with respect to the jet axis (computed including the lepton itself) greater than 0.6 GeV. The total momentum of the lepton and of the Λ_c was required to be greater than 18 GeV and

Table 3: Contributions to the total systematic error on the b-baryon production rate times the branching ratio to $\Lambda_c \ell \nu X$.

$Error\ source$	$variation\ level$	$Syst.error$
$\Lambda_b\ sel.\ +\ rec.\ efficiency$	$(7.2 \pm 0.6)\%$	± 0.12
$\Lambda_c\ branching\ fraction$	$(4.3 \pm 1.1)\%$	± 0.35
$Br(\Lambda_b \to \Lambda_c l \nu n \pi)/Br(\Lambda_b \to \Lambda_c l \nu)$	$0 \to 0.3$	$+0.24$
$total\ syst.error$	$-$	$^{+0.42}_{-0.35}$

the invariant mass of the Λ_c μ (Λ_c e) pair was required to exceed 3.5 GeV (3.3 GeV).

The $M(pK\pi)$ invariant mass spectrum of Λ_c^+ (Λ_c^-) candidates associated to a l^- (l^+) in the same jet is shown in fig. 6.a. A signal of 29.1 ± 7.5 events ($18.5 \pm 5.7 \Lambda_c \mu$ and $10.6 \pm 4.4 \Lambda_c e$ events) around the nominal Λ_c mass is visible; a similar cluster of events is not found in the $M(pK\pi)$ mass distribution for Λ_c candidates with a lepton of the same sign in the same jet (fig.6.b).

The signal in fig.6.a is interpreted as coming from the $b - baryon \to \Lambda_c l \nu X$ decay. The contribution to the right sign sample from accidental combinations of a Λ_c and a lepton and from pairs from B meson decay has been estimated to be negligible with a Monte Carlo simulation. It has been checked that the signal could not be attributed to a kinematical reflection of a D^+ decaying in $K\pi\pi$ or a D_s^+ decaying in $KK\pi$.

The simulation of the decay $\Lambda_b \to \Lambda_c \mu \nu$ gives an overall efficiency of selection and reconstruction of $(7.2 \pm 0.6)\%$. If one or more pions are produced in the Λ_b semileptonic decays, the efficiency becomes $(3.07 \pm 0.26)\%$ (assuming a 50% mixture of 1π and 2π modes) due to the softer spectrum of the Λ_c and of the μ. This effect is included in the systematic errors.

Using the measured rate $\mathrm{Br}(\Lambda_c \to pk\pi) = (4.3 \pm 1.1)\%$ [11], this leads to a production rate :

$$f(b \to b - baryon) \times Br(b - baryon \to \Lambda_c \mu \nu X) = (1.32 \pm 0.41(stat)^{+0.42}_{-0.35}(syst))\%.$$

The overall simulated reconstruction efficiency of $(4.6 \pm 0.6)\%$ for the decays $\Lambda_b \to \Lambda_c e \nu$ gives a production rate :

$$f(b \to b - baryon) \times Br(b - baryon \to \Lambda_c e \nu X) = (1.26 \pm 0.52(stat)^{+0.42}_{-0.35}(syst))\%.$$

Assuming lepton universality :

$$f(b \to b - baryon) \times Br(b - baryon \to \Lambda_c l \nu X) = (1.30 \pm 0.32(stat)^{+0.42}_{-0.35}(syst))\%.$$

The selection cuts have been varied up to $\pm 20\%$ of their values to check the stability of the results: the changes of the production rates are well inside the statistical errors.

Table 3 summarizes the different contributions to systematic error: the dominant one is the uncertainty in the $\Lambda_c \to pK\pi$ branching fraction.

5.4 Λ_b lifetime determination

In the $\Lambda_c \mu \nu X$ channel, b-baryon candidate vertices are reconstructed using the trajectories of the Λ_c and the μ to fit a common vertex. The Λ_b momentum is estimated with the missing energy technique:

Table 4: Contributions to the systematic error on the average b-baryon lifetime measured using Λ_c-lepton correlations.

$Error\ source$	$variation\ level$	$Syst.error(ps)$
$Monte\ Carlo\ statistics$	$-$	± 0.02
$b\ baryon\ mass$	$5640 \pm 50 MeV$	± 0.01
$b - baryon\ purity$	0.60 ± 0.20	± 0.08
$Br(\Lambda_b \rightarrow \Lambda_c l \nu n\pi)/Br(\Lambda_b \rightarrow \Lambda_c l \nu)$	$0 \rightarrow 0.3$	-0.04
$total\ syst.error$	$-$	$^{+0.08}_{-0.09}$

$$E_{\Lambda_b} = E_{beam} - E_{visible} + E_{\Lambda_c} + E_{\mu}$$

$E_{visible}$ is in this case the sum of the energies of both charged and neutral particles in the same hemisphere as the Λ_c . A Monte Carlo study shows that the estimator used must be scaled by the factor 0.950 ± 0.015, where the quoted error is due to the finite Monte Carlo statistics available.

If one or two additional pions are produced in the Λ_b decay, the estimator gives a Λ_b energy that is on average respectively 3.5 or 6 GeV too low, but this effect is depressed by the lower efficiency of the many π modes with respect to the 0 π mode.

A sample of 28 signal vertices has been constructed using right sign pairs with $2.260 < M(pK\pi) < 2.310$ GeV/c^2. The b-baryon purity of this sample is $(60 \pm 20)\%$. In a similar way, a sample of 139 background vertices has been constructed with wrong sign pairs with $2.085 < M(pK\pi) < 2.485$ GeV/c^2 and sideband right sign pairs ($2.085 < M(pK\pi) < 2.240$ GeV/c^2 and $2.330 < M(pK\pi) < 2.485$ GeV/c^2).

The proper time distribution (fig.7) has been fitted with the same technique used for the study of the Λ lepton channel. The result is:

$$\tau(b - baryon) = 1.33^{+0.71}_{-0.42}(stat)^{+0.08}_{-0.09}(syst)\ ps\ (\Lambda_c \mu \nu X \text{ channel, 28 decays}).$$

The fit procedure gives a flying background lifetime of $1.52^{+0.28}_{-0.21}$ and a correlation coefficient with the b-baryon lifetime of -0.146. The fitted flying background fraction is 0.63 ± 0.05.

The different contributions to the systematic error are shown in Table 4. The effects of the Λ_b polarization have been studied with a Monte Carlo program and found to be negligible.

The stability of the b-baryon lifetime with respect to variation of the selection cuts has been verified.

6 Muon-proton channel

In the analysis of this channel, semileptonic decays of b-baryons are selected by the presence of a muon and a proton of high momenta and opposite charges in the same jet. The analysis is based on the excellent hadron identification facilities of the DELPHI detector where most tracks cross both the TPC, which measures their dE/dx, and the RICH.

The quality of the muon-proton vertex reconstruction is the other essential ingredient of the analysis. Although some protons from beauty baryons come directly from their decay vertex, most are emitted by a secondary charm baryon. It is fortunate that the flight of the latter is, most of the time, much less than that of its parent, and that the fast proton follows its direction: detailed simulations show that 70% of such decays give rise to a reconstructed μ p vertex distributed around the simulated decay vertex with a 300 μm resolution. Backgrounds due to primary protons (from the Z^0 vertex) or tertiary protons (from a hyperon) can thus be substantially reduced[2].

6.1 Signal and background characteristics

The signal **muon-proton** pairs have the following properties :
- the muon has hard momentum (p_μ) and transverse momentum ($p_\perp$) spectra,
- the proton has a hard momentum (p_p) spectrum,
- the lepton and proton form a secondary vertex,
- the muon-proton charge correlation has the *right sign*.

A background involving genuine protons is almost completely eliminated by a proton momentum cut above 8.5 GeV/c and a muon momentum cut at 4 GeV/c. The remaining background is dominated by primary protons and has a small '$right > wrong$' muon-proton charge correlation asymmetry.

The background involving misidentified protons is dominated by charged kaons. The muon-kaon charge correlation asymmetry changes from '$right > wrong$' at low $p_\perp$ to '$wrong > right$' at high. It is caused by semileptonic b-hadron decay followed by a CKM favoured $c \to s$ transition resulting in a *wrong sign* muon-kaon combination. Because of this background, the standard procedure of cutting at a given transverse momentum of the muon and subtracting the wrong charge correlation is not relevant. The results described below have been obtained by fitting the muon transverse momentum spectra for both *right* and *wrong sign* charge correlations to a linear combination of $p_\perp$ distributions of the signal and each background source with shapes determined by the Monte Carlo simulation. A global fitting procedure is employed. For every event in a muon-hadron sample it uses also the b-baryon flight path and the dE/dx of the hadron track. It thus determines the sample composition and the b-baryon lifetime[3] simultaneously.

6.2 Hadron identification

Particle identification with the use of the DELPHI RICH detector is described in more detail elsewhere [10]. In the present analysis we have selected a momentum range where energetic kaons and protons can be separated by the gas RICH[4], namely $p \geq 8.5$ GeV/c, in which the expected mean number of Cherenkov photons detected for a kaon by the RICH is greater than 1.5. Protons up to ~ 15 GeV/c are below the Cherenkov threshold. K/p separation is effective up to 30 GeV/c and covers practically in full the high momentum part of the spectrum of the signal protons.

[2] $16 \pm 7\%$ of the signal is estimated to be due to protons from hyperons produced by chain decays of b-baryons.

[3] along with other *technical parameters*

[4] The RICH detector in DELPHI has two parts: the liquid RICH which identifies hadrons at low momenta, and the gas RICH.

Using the information provided by the RICH, four separate samples of energetic charged hadrons are defined:
- the proton sample, asking that the proton hypothesis probability exceeds 90%. This cut suppresses kaons and pions sufficiently to make the proton:kaon:pion ratio approximately 1:1:1.
- the kaon sample, asking that the kaon hypothesis probability exceeds 80%. This cut removes all protons and gives a kaon/pion ratio greater than 2.
- the pion sample, asking that the pion hypothesis probability exceeds 25% and for more than 5 Cherenkov photons compatible with the pion hypothesis. All protons and kaons from this data set are suppressed by this cut. But note that there is no discrimination against muons or electrons in this sample.
- the unresolved hadron sample taking all hadrons not accepted in the previous three samples.

The compositions of these samples can be measured using the specific ionization measurement. In the momentum range above 8.5 GeV/c pions, kaons and protons are well on the relativistic rise of dE/dx. The mean values of their energy loss stay approximately parallel to each other from $\sim$ 4 GeV/c up to $\sim$ 25 GeV/c. Requiring at least 30 hit TPC wires to analyse a track, the ratios $\frac{dE}{dx}/T_i(p)$ of the measured mean energy loss to the momentum dependent theoretical values $T_i(p)$ (i = p,K,π) have Gaussian distributions with a common resolution of 7%. The proton-pion difference is about twice the resolution, the proton-kaon difference is a bit less than the resolution. The consistency between the theoretical and observed specific ionization has been checked on the three samples described above. This ensured a very good parameterization of the specific ionization measurement, independent of the Monte Carlo simulation.

6.3 Signal selection

In the present analysis $\sim$ 500k hadronic events recorded in 1992 with the barrel gas RICH operational are used. An event is accepted if the primary vertex is successfully reconstructed. This is enforced in particular by applying the following event selection $\mathcal{E}$:
- the primary vertex is formed by at least three tracks,
- the primary vertex probability is greater then 1%.

Identified muon candidates are accepted when they pass the following additional muon track selection $\mathcal{M}$:
- the muon candidate has at least two associated hits in the silicon micro-strip vertex detector,
- the muon candidate has momentum above 4 GeV/c.

Hadrons are accepted when they pass the RICH selections described in Sec.6.2 and the following track quality selection $\mathcal{H}$:
- the hadron track has at least two associated hit in the silicon micro-strip vertex detector,
- the hadron track has more than 30 wires used for the specific ionization measurement.

Muon-hadron pairs are accepted when they pass the following additional kinematic and secondary vertex selection $\mathcal{V}$:
- the hadron has momentum above 8.5 GeV/c,
- the muon and hadron are in the same jet,
- the muon-hadron secondary vertex has a probability greater then 1%,
- the error on the distance δ_V between primary and secondary vertices is smaller than

1mm.

Using the selections described above, four samples of muon-hadron pairs were obtained: the muon-proton signal sample (μp) and the muon-kaon (μK), muon-pion ($\mu\pi$), and muon-unresolved (μX) control samples.

6.4 Determination of the number of μp pairs and average b-baryon lifetime

6.4.1 Global fit procedure

A maximum likelihood fit is used to estimate the number of muon-proton pairs from b-baryon decays and the average lifetime of b-baryons. The determination of these two physical parameters is based on the μp sample. The μK, $\mu\pi$ and μX samples are introduced (1) to control and optionally to correct the muon transverse momentum distribution resulting from the components of the background involving genuine kaons (pions) , and (2) to determine the parameterization of the background proper time distributions.

For each μ-hadron event, the dE/dx, the signed muon transverse momentum $p_\perp^{(S)} = S \cdot p_\perp$ (where $S = +1$ for the *right sign* and $S = -1$ for the *wrong sign* correlation), and $t = \delta_V/(p_{bar}/M_{bar})$ are considered as a set of three independent measurements. The last quantity estimates the b-baryon proper time assuming the event belongs to the signal. To compute it, $M_{bar} = (5641 \pm 50)$ MeV/c^2 is used and p_{bar} is evaluated using a linear relationship with respect to $\|\vec{p_\mu} + \vec{p_p}\|$ obtained in the Monte Carlo ($\sim$ 16% accuracy at 13 GeV/c and ~6% at 35 GeV/c).

There are four basic *classes* of events: the signal and the backgrounds involving genuine protons, kaons and pions respectively. Every measured quantity has a probability density function (*pdf*) appropriate for each *class*. The *pdf* for an event in sample $i = \mu\mathrm{p}, \mu\mathrm{K}, \mu\pi, \mu\mathrm{X}$ is thus given by:

$$\mathcal{P}(event|i) = \sum_{classes} \mathcal{P}_f(class|i) \cdot \mathcal{P}_\Delta(\tfrac{dE}{dx}|class) \cdot \mathcal{P}_\perp(p_\perp^{(S)}|class) \cdot \mathcal{P}_t(t|class)$$

where $\mathcal{P}_f(class|i)$ is the fraction of events of a given *class* in sample i. In particular $\mathcal{P}_f(signal|\mu\mathrm{p})$ is the number of muon proton pairs from b-baryons we are looking for.

The dE/dx *pdf* are known from the data (see section 6.2). The $p_\perp^{(S)}$*pdf* are taken from the Monte Carlo. The signal t *pdf* has been parameterized as a convolution of an exponential decay *pdf* of mean $\tau_{\mu\mathrm{p}}$ and a gaussian resolution function. The background t *pdf* have been taken as linear combinations of a flying part (fraction: $f_{\mathrm{BGD}}(K$ or $\pi)$, effective lifetime: $\tau_{\mathrm{BGD}}(K$ or $\pi)$)[5] and a non flying part (fraction: $1 - f_{\mathrm{BGD}}$). For the residual proton background two extreme parameterizations were used: the pion parameterization and a gaussian parameterization.

The fitting procedure, by which the product of the *pdf*'s of all events is maximized, determines simultaneously the sample compositions $\mathcal{P}_f(class|i)$ and the physical (lifetime) and technical parameters of the *pdf*.

The final results were obtained by averaging the results of the fits performed with two parameterizations of the proton background t *pdf* (taking half the difference as a contribution to the systematic error).

[5]We call the f_{BGD} and τ_{BGD} technical parameters

6.4.2 Evaluation of the fit systematics and test the fit reliability

The kaon and pion background compositions were fitted with one additional parameter each, reflecting the proportions of true kaons and pions arising from b decay. These parameters were kept the same for all four samples. To examine relevant systematic effects (1) three different definitions of these parameters were used (a) $\frac{\mathrm{K}\ (\pi)\ \mathrm{from\ b}}{\mathrm{all\ K}\ (\pi)}$, (b) $\frac{\mathrm{K}\ (\pi)\ \mathrm{and}\ \mu\ \mathrm{from\ b}}{\mathrm{all\ K}\ (\pi)}$, (c) $\frac{\mathrm{K}\ (\pi)\ \mathrm{and\ direct}\ \mu\ \mathrm{from\ b}}{\mathrm{all\ K}\ (\pi)}$, (2) these fractions were fixed to the Monte-Carlo prediction, (3) μK or μX samples were excluded from the fit. The contribution to the systematic error is given in Table 5 ("K, π BGD composition").

There is no control sample for genuine proton background. To evaluate possible systematics this background was divided into four groups characterized by very different $p_{\perp}^{(S)}$ spectra (1a) *right sign* muons from b-hadron decays, (1b) *wrong sign* muons from b-hadron decays, (2a) other *right sign* muon candidates (2b) other *wrong sign* muon candidates. From these four groups, 14 non-trivial subsets can be chosen (4 containing one group, 6 containing two groups and 4 containing three groups). The fit was performed 14 times with the chosen subset scaled up by a factor of 2. The maximal variation was taken as estimate of the systematic effects ("p BGD composition" in Table 5).

The results quoted in the next section were obtained with $p_{\perp}$ calculated without excluding the muon candidate from the jet. To evaluate systematic errors $p_{\perp}$ was replaced (1) by ${p_{\perp}}^{out}$ calculated excluding muon candidate from the jet and (2) by the quadratic sum $p_{\perp} \oplus p_{\mu}/10$. All three definitions were tested with several binnings. The maximal variation was taken as a contribution to the systematic error ("$p_{\perp}$ binning/definition" in Table 5).

The lifetime fit was restricted to the *right sign* muon-hadron combination, and optionally to the part above some $p_{\perp}$ cut. The result was found to be stable within 2% in the range of $p_{\perp}$ cut from 0 GeV/c (no cut) to 0.7 GeV/c. For higher cut values, the b-baryon lifetime begins to oscillate within the rapidly increasing statistical error.

The fit reliability was checked replacing the muon-proton sample by 28 simulated signal events (the estimated number of signal events in the real data, see below, randomly chosen from the available simulation statistics) mixed in the appropriate proportion with events randomly chosen from the unresolved hadron sample. This exercise was repeated 81 times. The mean values of the fit results were consistent with the known input values, their spreads were consistent with the estimated fit errors.

6.4.3 The results of the fit

The fit was performed with 125 events of the μp sample, 243 events of the μK sample, 295 events of the $\mu\pi$ sample and 369 events of the μX sample. The projections of the fit space onto $\zeta = (\frac{dE}{dx}/T_{\mathrm{p}} - 1)/\sigma_{(dE/dx)}$, $p_{\perp}^{(S)}$ and t axes are shown in the Figures 10, 11 and 12 respectively. The number of signal events present in the muon-proton sample was estimated to be

$$N(\mu\mathrm{p\ from\ b\text{-}baryon}) = 28.9^{+6.7}_{-6.2}(\mathrm{stat.})^{+6.1}_{-9.1}(\mathrm{syst.})^{+0.2}_{-0.6}(\mathrm{syst.})\ .$$

The average lifetime of b-baryons was estimated to be

$$\tau_{\mu\mathrm{p}} = \left\{1.28^{+0.35}_{-0.29}(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})^{+0.02}_{-0.03}(\mathrm{syst.})\right\}\ \mathrm{ps}\ .$$

The first systematic error is due to the measurement procedure, whereas the second represents the influence of unknown b-baryon properties (see Tab.5).

The estimates of all the variable fit parameters are given in Table 6. The fractions of protons in the μK, $\mu\pi$ and μX samples, as well as the fraction of kaons in the $\mu\pi$ sample, were found to be compatible with zero and were subsequently fixed to zero.

The correlation matrix for the variable parameters is given in Table 7. The 'composition' parameters (P1–P7) and the 'lifetime' parameters (P8–P12) are practically uncorrelated. There is no parameter correlated to the mean b-baryon lifetime (P8) by more than $\sim$12%.

Table 5: Systematic errors of the fit.

source of variation	variation level	resulting variation of	
		$N(\mu$p from b-baryon)	$\tau_{\mu\text{p}}$
height	Experimental systematics		
dE/dx normalization	one stand. dev.	±4.0 %	±2.0 %
dE/dx error normalization	one stand. dev.	±0.5 %	±0.5 %
$p_\perp$ binning/definition	see text	$^{+4.0}_{-8.0}$ %	±6.0 %
K, π BGD composition	see text	±0.8 %	±0.4 %
p BGD composition	see text	$^{+2.0}_{-1.0}$ %	$^{+0.4}_{-1.0}$ %
t pdf paramet. of p BGD	see text	±0.9 %	±2.3 %
boost estimate	one stand. dev.	—	±2.2 %
total (relative)		$^{+6.1}_{-9.1}$ %	±7.0 %
total (proper units)		$^{+1.8}_{-2.6}$ events	$\pm.09$ ps
MC systematic errors due to unknown b-baryon properties			
polarization	$-0.936 \to 0$	-2.0 %	-2.3 %
Isgur-Wise form-factor	see text	±0.5 %	±1.0 %
mean fract. of E_{beam}	0.70 ± 0.02	—	±1.0 %
$\Lambda_c\ell\nu\text{n}\pi/\Lambda_c\ell\nu$	$0 \to 0.3$	$+3$ %	—
total MC (relative)		$^{+3.0}_{-2.1}$ %	$^{+1.4}_{-2.7}$ %
total MC (proper units)		$^{+0.9}_{-0.6}$ events	$^{+0.02}_{-0.03}$ ps

6.5 Branching ratio estimate

The number of signal events found by the fit was used for the calculation of the following branching fraction

$$f(\text{b} \to \text{b-baryon}) \times \text{BR}(\text{b-baryon} \to \mu\bar{\nu}_\mu\text{pX}) = N(\mu\text{p from b-baryon}) \times \frac{C_\Lambda}{\epsilon_{\mathcal{H}\wedge\mathcal{V}}} \times \frac{\text{BR}(\text{b} \to \mu\bar{\nu}_\mu\text{X})}{N(\mu\,\text{from b}) \times C_{\mathcal{M}}}$$

where:

- $N(\mu$p from b-baryon) is the number of signal events found in the previous section.
- C_Λ is the correction due to the residual presence of protons from the decay chain b-baryon$\to$c-baryon$\to$hyperon$\to$proton.

Table 6: The result of the maximum likelihood fit of the average b-baryon lifetime and the composition of the selected samples. Only the variable parameters determined in the fit are given in the table. For each one, the first error quoted comes from the fit, the second is half the difference between the results from two different proton background t *pdf* parametrisations that were averaged to give the result quoted.

	parameter	result
P1:	fraction of signal in the 'proton' sample	$0.233^{+0.054}_{-0.050} \pm 0.002$
P2:	ratio (signal)/(all p)	$0.79 \pm 0.20 \pm 0.02$
P3:	ratio (K from b)/(all K)	$0.557^{+0.053}_{-0.051} \pm 0.001$
P4:	ratio (π from b)/(all π)	$0.453^{+0.057}_{-0.056} \pm 0.001$
P5:	fraction of kaons in the μp sample	$0.354^{+0.105}_{-0.095} \pm 0.009$
P6:	fraction of kaons in the μK sample	$0.858^{+0.039}_{-0.038} \pm 0.001$
P7:	fraction of kaons in the μX sample	$0.467^{+0.044}_{-0.042} \pm 0.001$
P8:	average lifetime of b-baryons $\tau_{\mu p}$	$1.28^{+0.35}_{-0.29} \pm 0.03$ ps
P9:	$\tau_{BGD}(K)$	$1.51^{+0.29}_{-0.25} \pm 0.002$ ps
P10:	$\tau_{BGD}(\pi)$	$1.84^{+0.19}_{-0.17} \pm 0.001$ ps
P11:	$f_{BGD}(K)$	$0.64 \pm 0.09 \pm 0.001$
P12:	$f_{BGD}(\pi)$	$0.731^{+0.047}_{-0.050} \pm 0.000$

Table 7: Correlation matrix for the fit parameters (coefficients are in % units). The definitions of the parameters are given in table 6.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
P2	40										
P3	6	5									
P4	-4	-1	-3								
P5	-19	62	0	3							
P6	-1	-1	-11	8	0						
P7	-1	-1	-13	7	0	2					
P8	-1	9	0	1	9	-0	-1				
P9	2	-1	-1	-1	-0	1	3	-12			
P10	1	1	-0	-1	2	0	1	-2	-12		
P11	-5	-3	-2	-2	4	-0	5	-4	-22	5	
P12	-1	1	0	1	0	2	-1	-0	2	-20	-22

Table 8: Contributions to the total systematic error of the b-baryon production rate times its branching ratio into $p\mu X$.

quantity	value			contribution
$N(\mu$p from b-baryon)	28.9	$^{+1.8}_{-2.6}$(syst.)	ev.	±6.4 %
$N(\mu$ from b)	7842	±166	ev.	±2.1 %
$\mathcal{H}$ efficiency	0.308	±0.009		±3.2 %
$\mathcal{V}$ efficiency	0.259	±0.014		±5.4 %
$C_{\mathcal{M}}$	1.125	±0.005		±0.4 %
RICH efficiency	1.0	−0.06		+6.0 %
BR(b $\rightarrow \mu\bar{\nu}_\mu$X)	0.105	±0.009		±8.6 %
total systematic error (measurement)				$^{+14}_{-13}$ %
MC systematic errors due to unknown b-baryon properties				
C_Λ(hyperons)	0.84	±0.07		±8.3 %
polarization		$-0.936 \rightarrow 0$		+26.0 %
Isgur-Wise form-factor		see text		±5.0 %
mean fract. of $E_{\rm beam}$	0.70	±0.02		±5.0 %
$\Lambda_c\ell\nu{\rm n}\pi/\Lambda_c\ell\nu$		$0 \rightarrow 0.3$		+27.0 %
total systematic error (MC)				$^{+39}_{-11}$ %

- $\epsilon_{\mathcal{H}\wedge\mathcal{V}}$ is the combined efficiency of the RICH proton sample selection defined in Sec.6.2 and selections $\mathcal{H}$ and $\mathcal{V}$ defined in Sec.6.3.

  The efficiency of the $\mathcal{V}$ selection was obtained from the dedicated Monte Carlo simulation of semileptonic decays of b-hadrons. The secondary vertex finding algorithm was cross-checked with the data, comparing its efficiency for all events in the data and standard Monte Carlo simulation.

  The efficiency of the $\mathcal{H}$ selection was found from the data.

  The efficiency of the RICH selection was found by fitting the proton content of muon-kaon, muon-pion, and muon-unresolved samples. No protons were found in these samples.

- $C_{\mathcal{M}}$is the correction due to the difference between the selection efficiencies $\mathcal{M}$ for an average b-hadron and a polarized b-baryon.

- BR(b $\rightarrow \mu\bar{\nu}_\mu$X) is the average semileptonic branching fraction of b-hadrons determined by the DELPHI collaboration [?].

- $N(\mu$ from b) is the number of muons from the semileptonic decays of the b-hadrons present in the data after selections $\mathcal{M}$ and $\mathcal{E}$ described in Sec.6.3. This number was obtained from the binned maximum likelihood fit to the $(p_\perp, p)$ distribution of muon candidates. The shapes of the $(p_\perp, p)$ distributions of the different muon sources were taken from the Monte Carlo simulation.

The values of the quantities described above are listed in Tab.8 together with systematic effects due to unknown b-baryon properties.

Finally the following combined branching fraction (protons from hyperons excluded) was obtained

$$f(\mathrm{b} \to \text{b-baryon}) \times \mathrm{BR}(\text{b-baryon} \to \mu\bar{\nu}_\mu \mathrm{pX}) = \left\{3.6 \pm 0.8(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})^{+1.4}_{-0.4}(\mathrm{syst.})\right\}\ 10^{-3}\ .$$

The first systematic error is due to the measurement procedure, whereas the second represents the influence of unknown b-baryon properties (see Tab.8).

7 Conclusions

The production and lifetime of the b-baryon has been studied with three different and complementary methods, relying on the detection of a fast Λ , a fast proton and a Λ_c in the same jet as a high p_T lepton. The following semi-exclusive branching ratios have been measured :

$$f(b \to b - baryon) \times Br(b - baryon \to \Lambda l \nu X) = (0.32 \pm 0.07(stat)^{+.042}_{-.037}(syst))\%,$$

$$f(b \to b - baryon) \times Br(b - baryon \to \Lambda_c l \nu X) = (1.30 \pm 0.32(stat)^{+.42}_{-.35}(syst))\%,$$

$$f(b \to b - baryon) \times Br(b - baryon \to p\mu\nu X) = (0.36 \pm 0.08(stat)^{+.15}_{-.07}(syst))\%.$$

From partially reconstructed b-baryon decay candidates in these three different semi-leptonic channels, the following values for the average b-baryon lifetime have been measured:

$$\tau(b - baryon) = 1.13^{+0.30}_{-0.23}(stat)^{+0.05}_{-0.08}(syst)\ ps\ \text{(63 decays, } \Lambda\mu\nu X \text{ channel)}$$

$$\tau(b - baryon) = 1.32^{+0.71}_{-0.42}(stat)^{+0.08}_{-0.09}(syst)\ ps\ \text{(28 decays, } \Lambda_c\mu\nu X \text{ channel)}$$

$$\tau(b - baryon) = 1.28^{+0.35}_{-0.29}(stat) \pm 0.09(syst)\ ps\ \text{(47 decays, } p\mu\nu X \text{ channel).}$$[6]

The above lifetime determinations rely on completely independent event samples. This has been checked on an event by event basis for the μ-proton and μ-Λ_c samples, where a small overlap could not be excluded a priori by the selection criteria discussed above. The common systematics, due to the modelling of the b-baryon production and decay properties, can be inferred from Tables 2, 4 and 5.

Averaging the three results, under the assumption that the different b-baryon species enter in the same proportion in the decay channels considered (all of them are expected in fact to be largely dominated by the Λ_b baryon), gives the mean b-baryon lifetime:

$$\tau(b - baryon) = 1.21^{+0.21}_{-0.18}(stat) \pm 0.04(exp.syst)^{+.02}_{-.07}(theory)\ ps.$$

[6] After a cut at $p_\perp^{(S)} > 0.7$ GeV/c.

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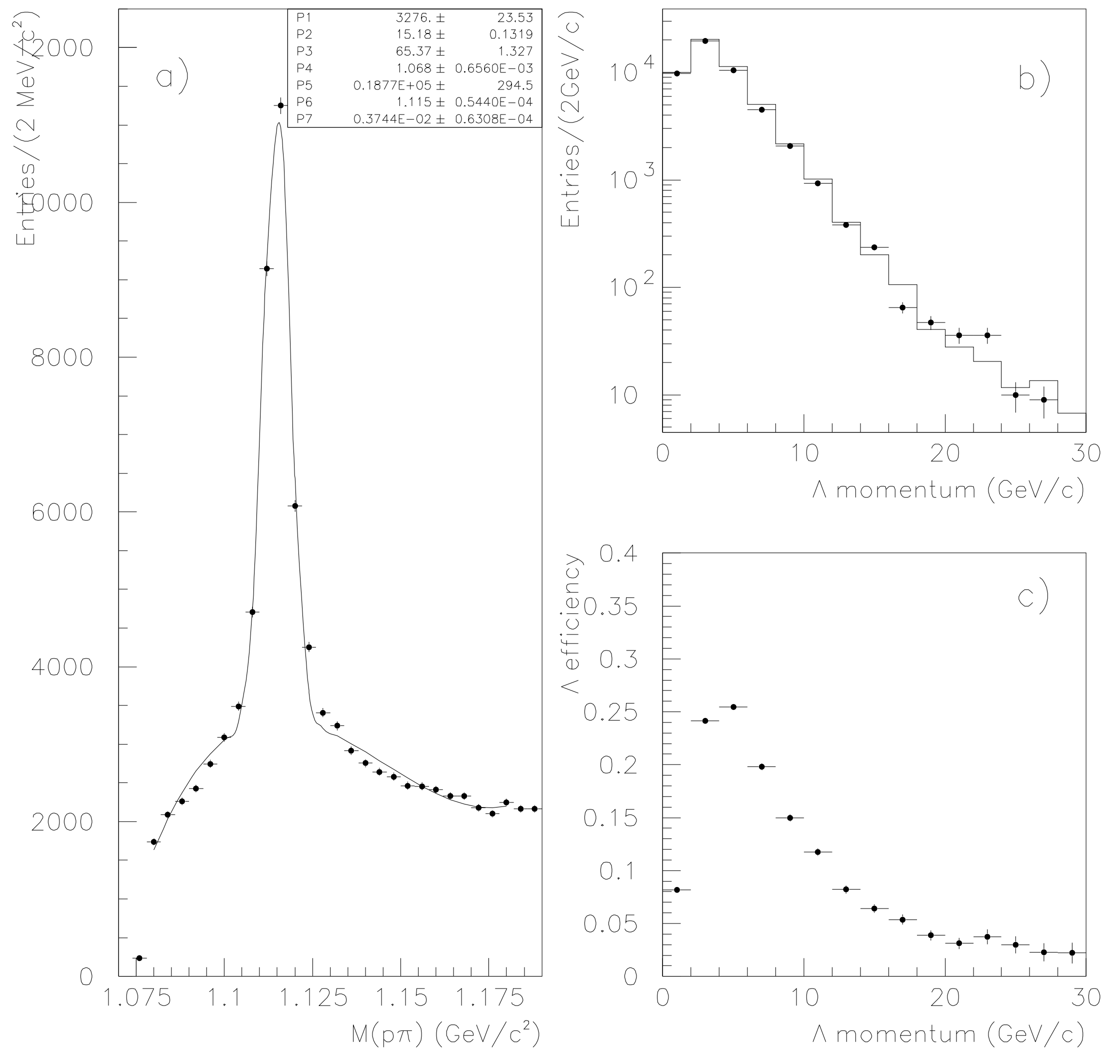


Figure 1: a) p π invariant mass distribution for decay candidates with $p > 4GeV/c$; b) background subtracted Λ momentum spectrum (dots: data; histogram: Monte Carlo simulation) ; c) $\Lambda \to p\pi$ reconstruction efficiency.

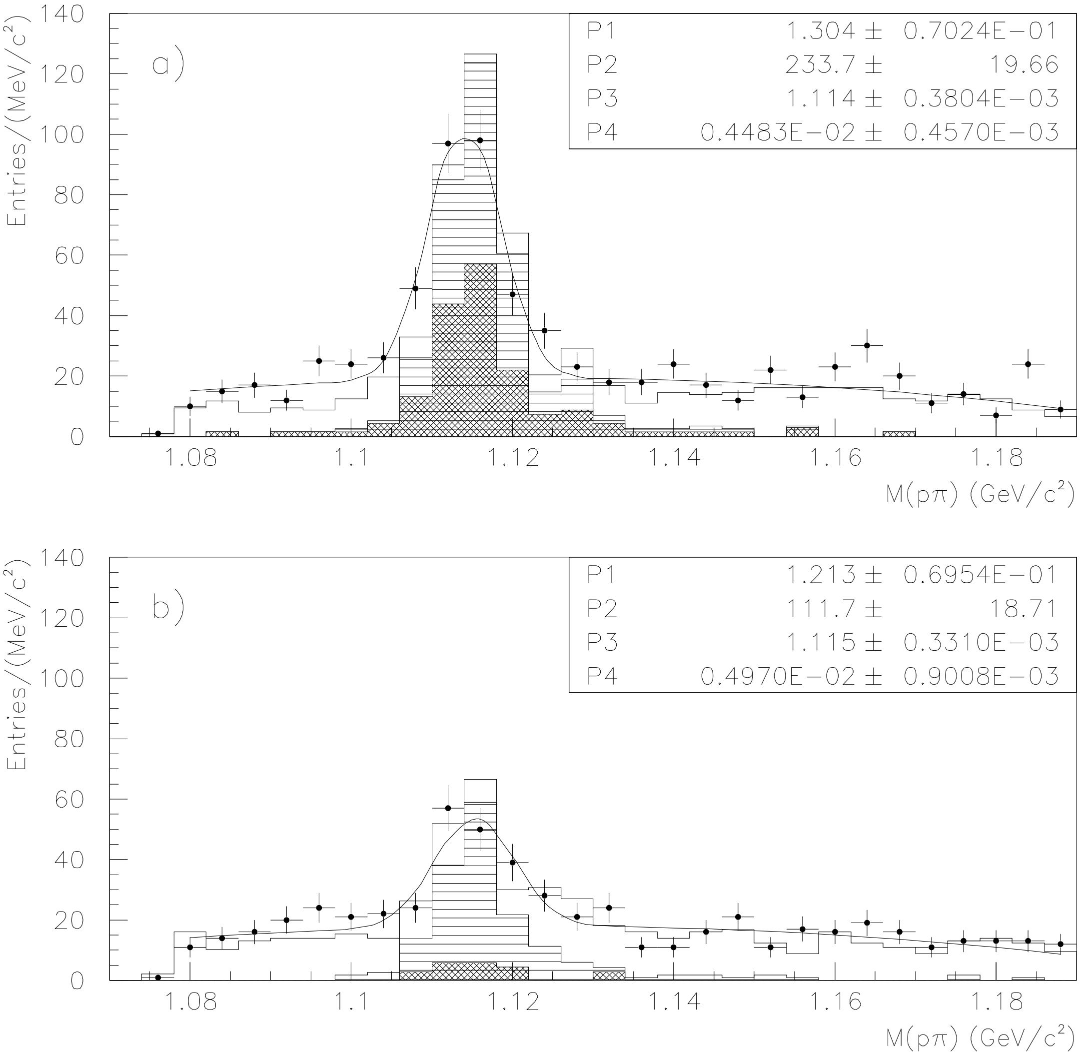


Figure 2: Distribution of p π invariant mass for Λ candidates correlated to high Pt leptons in the same jet: a) right-sign pairs; b) wrong-sign pairs. The data are shown by the points and the MC prediction, normalised to the total number of hadronic Z^0 decays, as a histogram: the contribution from b-baryon decay is shown double-hatched, while the background from fragmentation Λ's is shown single-hatched. The fitted Λ signals from the data amount to 234 ± 20 right-sign and 112 ± 19 wrong-sign events.

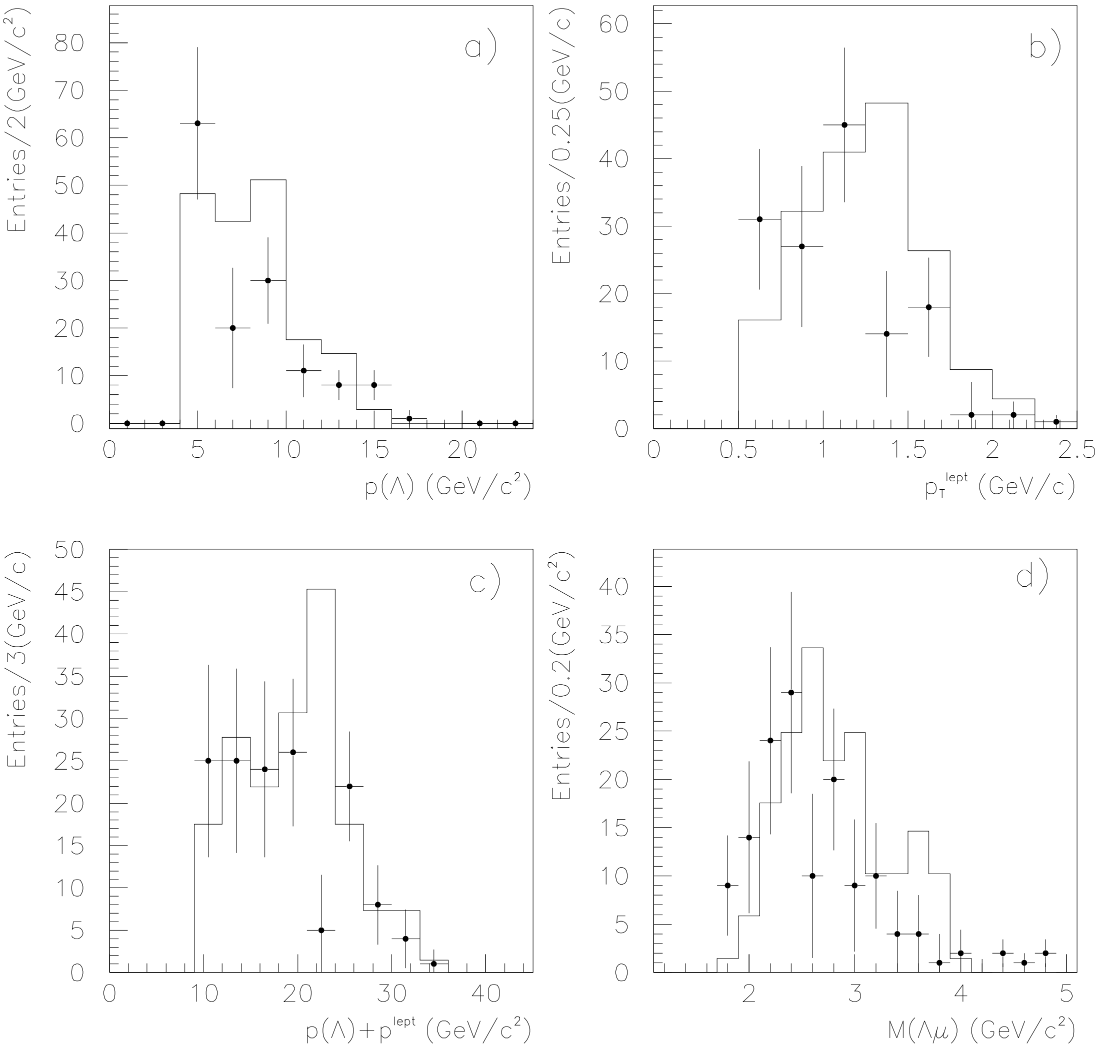


Figure 3: Subtracted spectrum (right sign - wrong sign) in the data (dots) for : a) Λ momentum, b) lepton transverse momentum, c) the sum of the Λ and lepton momenta and d) $\Lambda - \mu$ invariant mass. The histograms are the Monte Carlo expectations for the b-baryon signal.

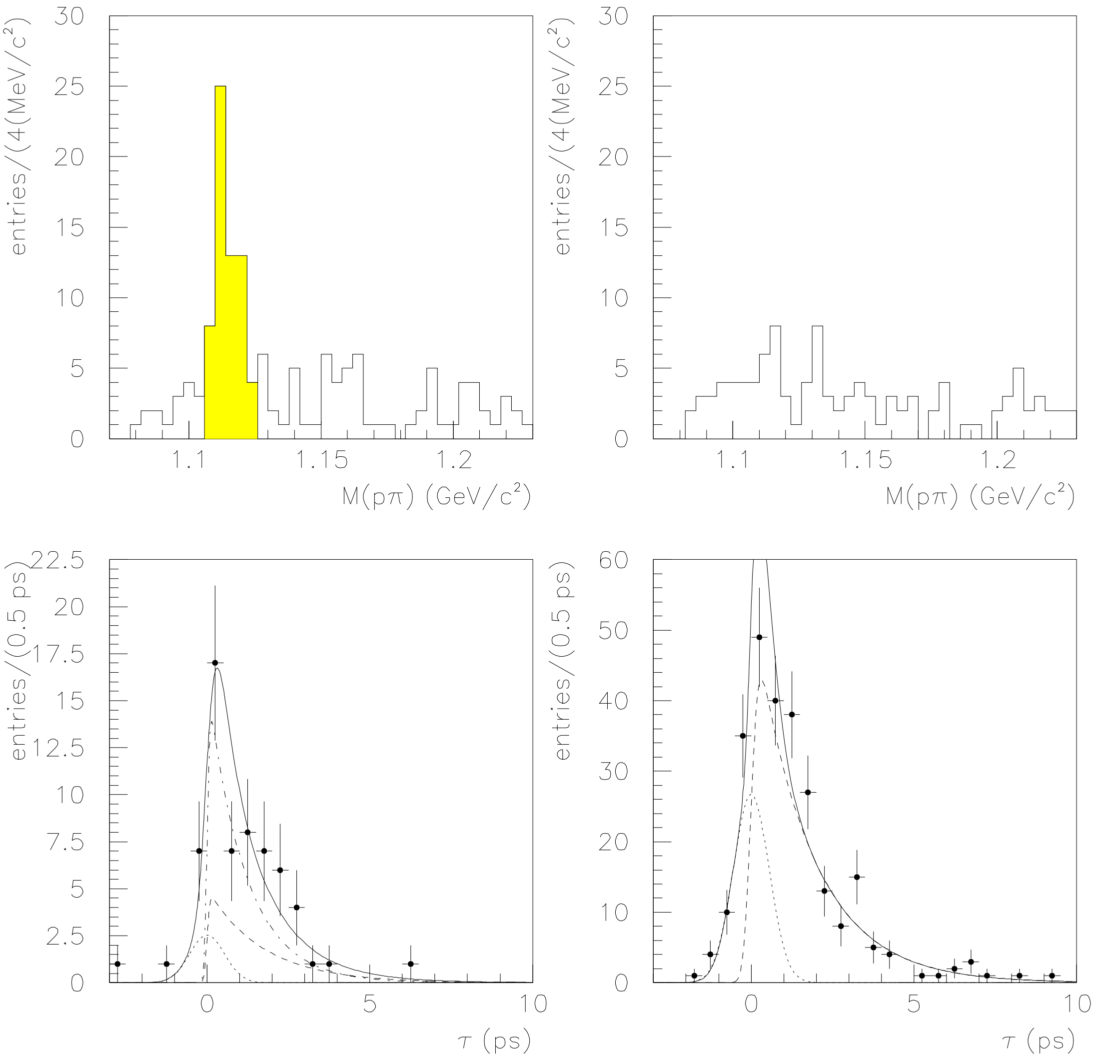


Figure 4: a,b) Λ signal for reconstructed $\Lambda\mu\pi$ vertices of right sign and wrong sign respectively; c) lifetime distribution for b-baryon candidates, 63 right-sign $\Lambda\mu\pi$ vertices with good $p\pi$ mass ($1.106 < M(p\pi) < 1.122$ GeV/c^2: hatched area in the Λ mass plot) ; the dotted-dashed line is the the estimated b-baryon contribution, the dashed and dotted lines represent the flying and not-flying background respectively, determined from d) the lifetime distribution of the background sample, $\Lambda\mu\pi$ vertices with wrong sign or $p\pi$ mass outside the above range.

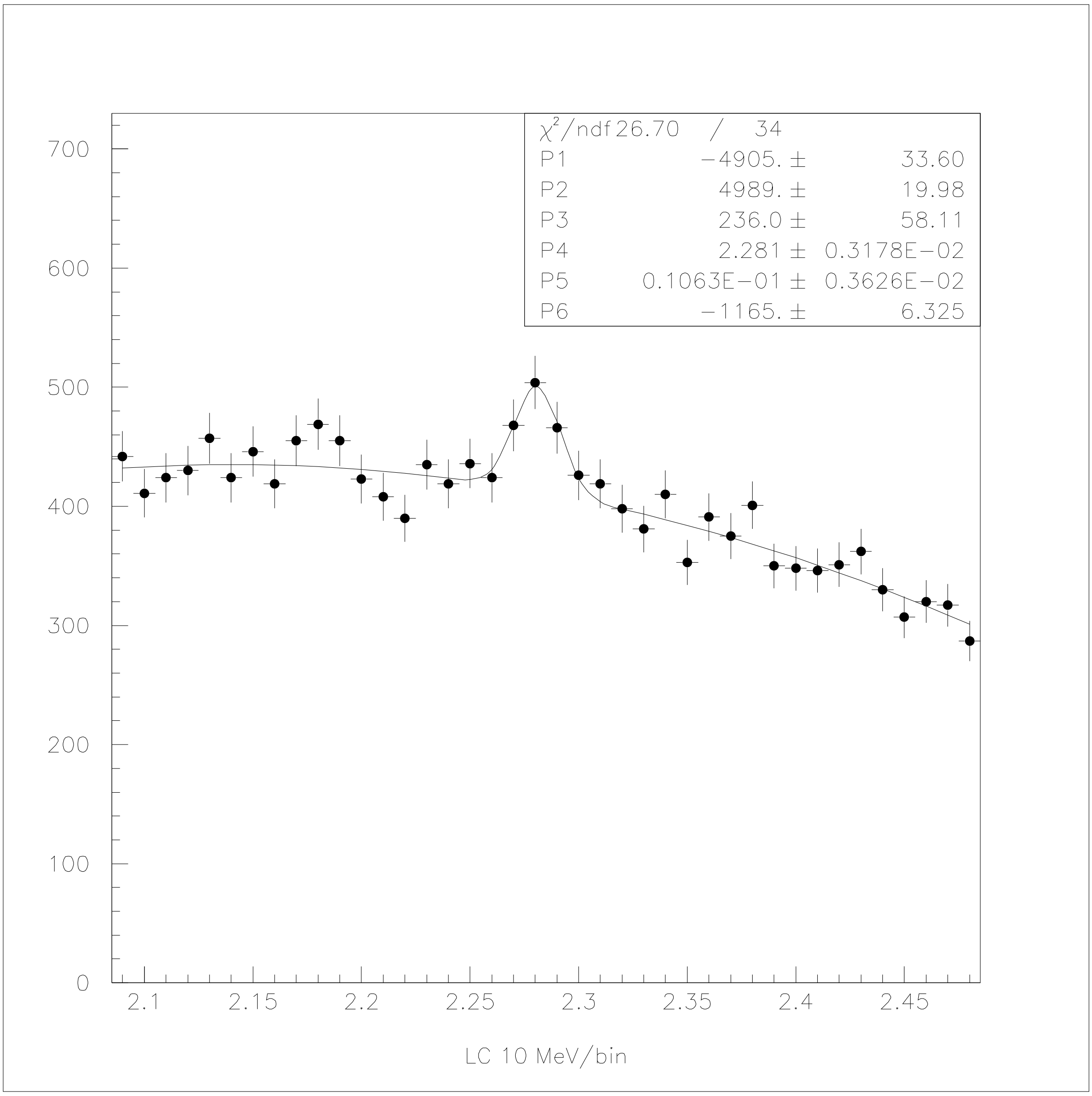


Figure 5: Λ_c inclusive signal for reconstructed $pk\pi$ vertices.

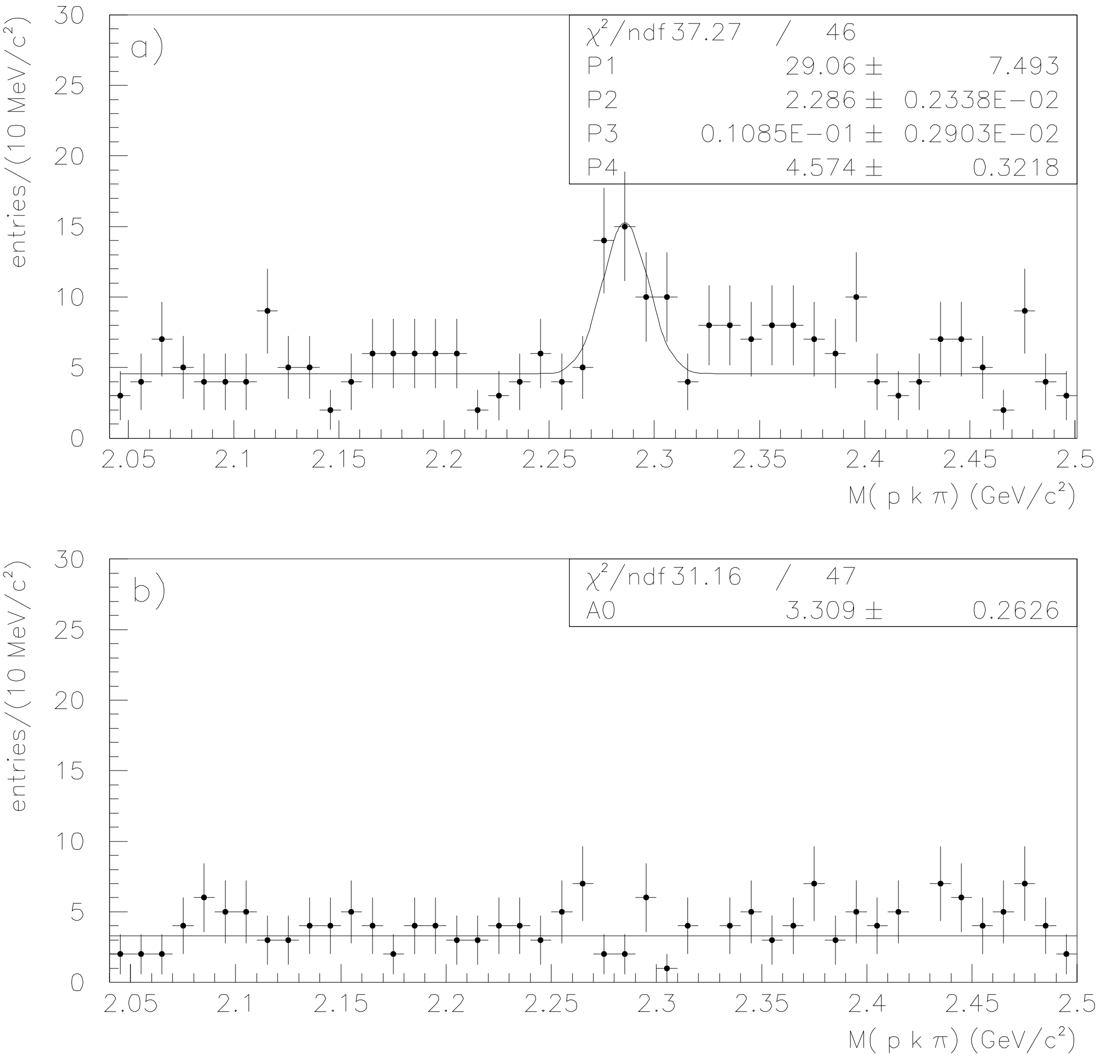


Figure 6: $pk\pi$ invariant mass distribution for $\Lambda_c l$ pairs a) of opposite sign and b) of same sign.

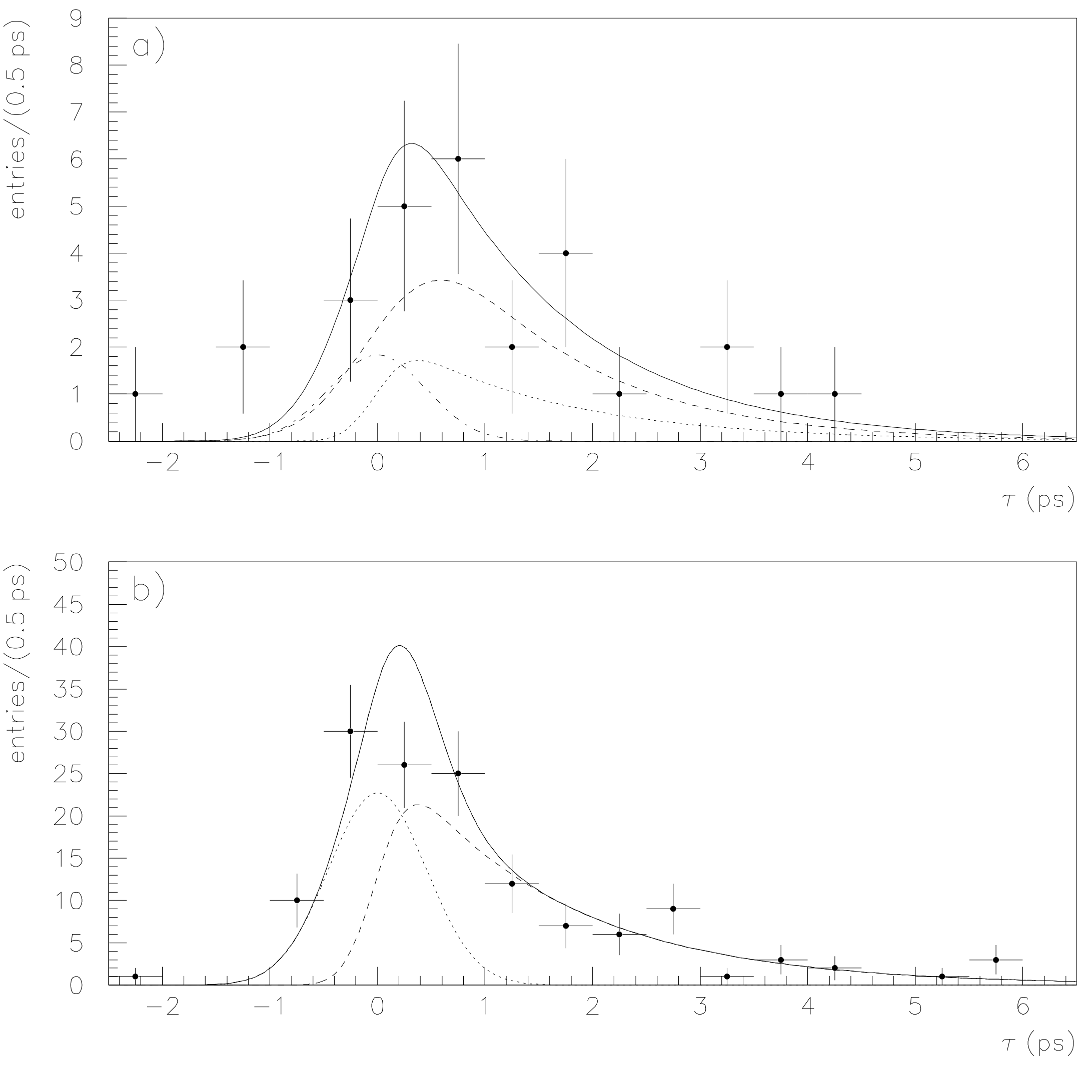


Figure 7: Proper time distribution for reconstructed $\Lambda_c\mu$ vertices: a) opposite sign pairs; b) sideband and same sign pairs.

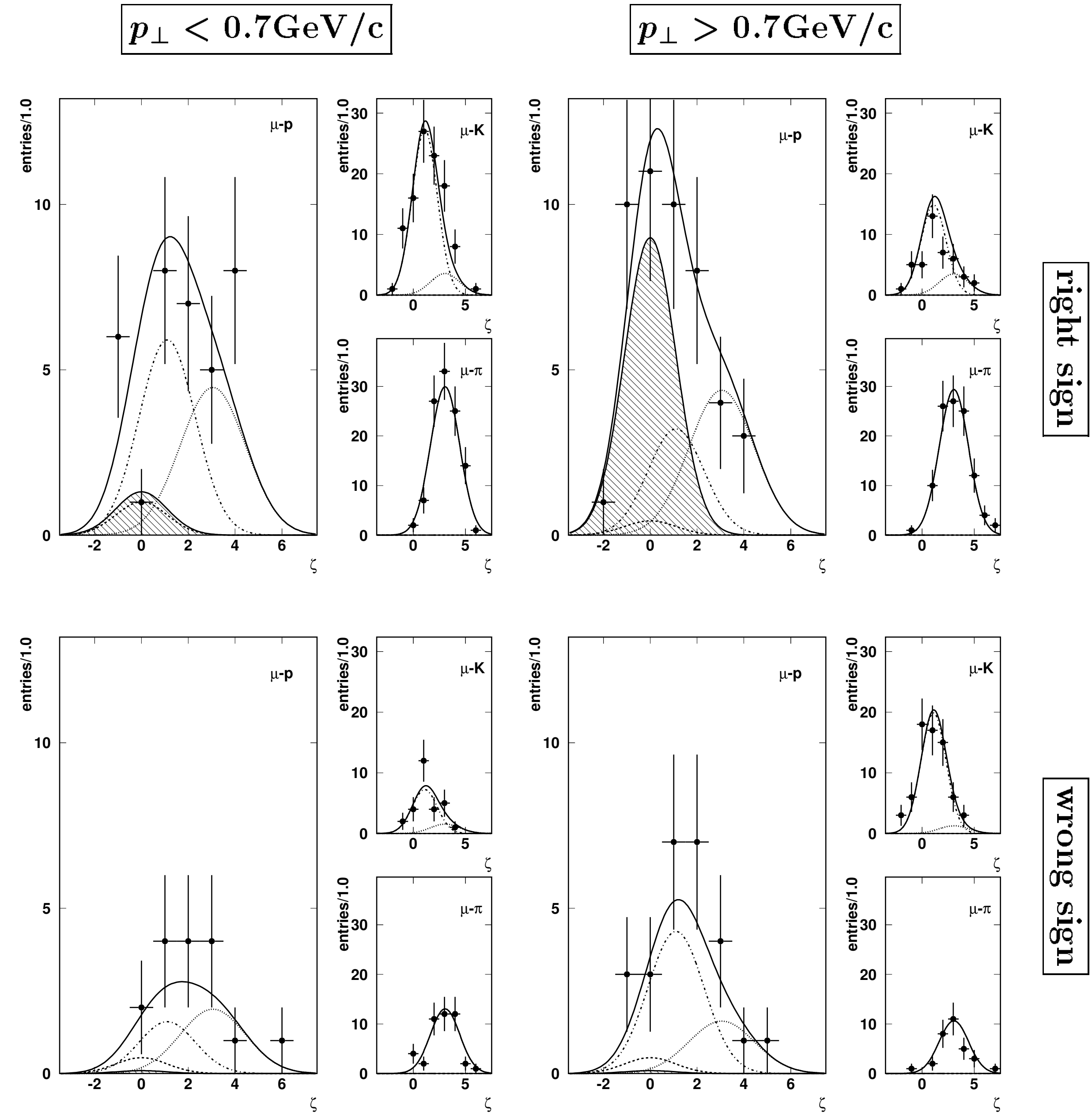


Figure 8: Projection of the data onto the $\zeta = (\frac{dE}{dx}/T_{\rm p} - 1)/\sigma_{(dE/dx)}$ axis. Four $p_\perp^{(S)}$ intervals are shown: right sign $p_\perp < 0.7$GeV/c, right sign $p_\perp > 0.7$GeV/c, wrong sign $p_\perp < 0.7$GeV/c and wrong sign $p_\perp > 0.7$GeV/c . The muon-proton sample is shown on the bigger plots. The muon-kaon and muon-pion samples are shown on the smaller plots (flushed to the right in each of the four $p_\perp^{(S)}$ group of three plots). The points with error bars represent the data. The fit is shown by the following lines: total and signal by continuous lines, proton background by dashed lines, kaons by dash-dotted and pions by dotted lines. The areas corresponding to the signal are hatched. The mean values of the Gaussians decrease with increasing hadron mass.

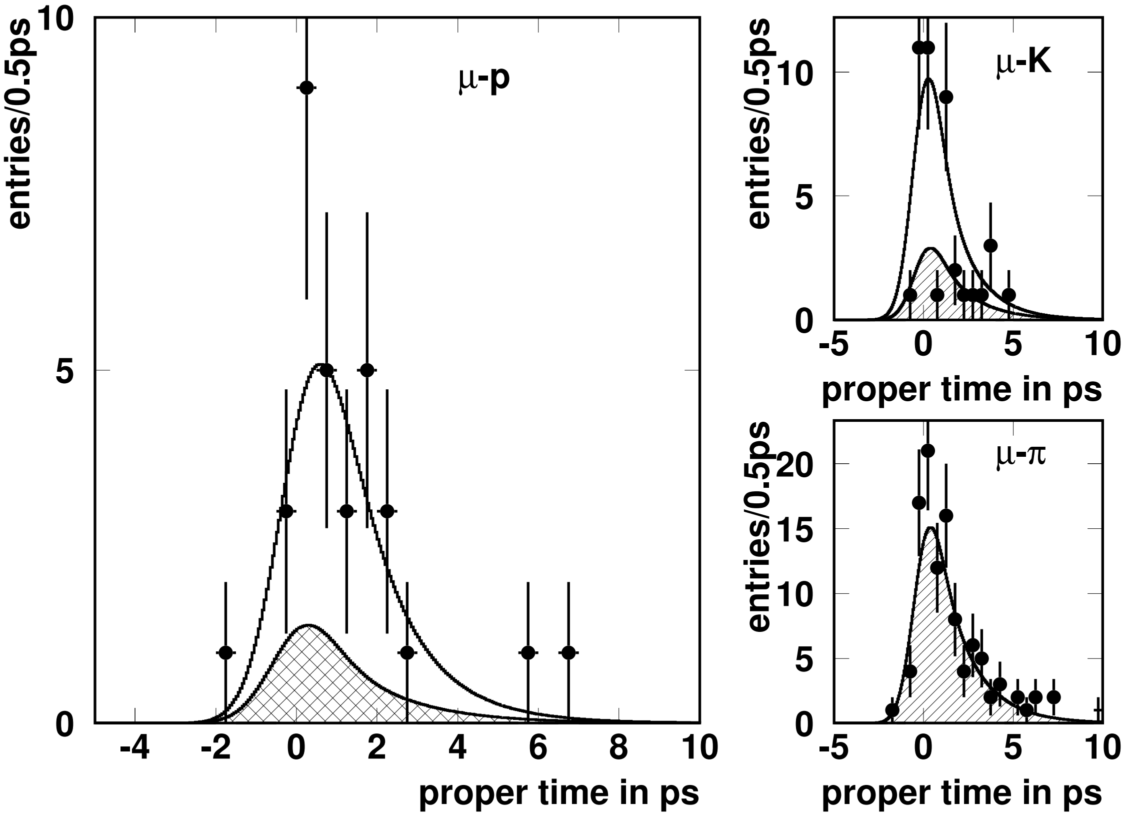
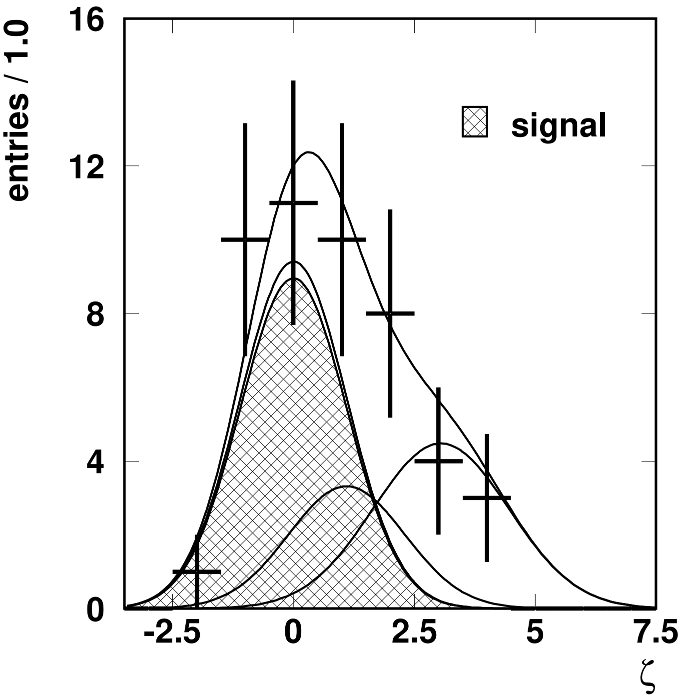


Figure 9: Projection of the data of the lifetime fit subsample onto the proper time axis. The muon-proton sample is shown on the bigger plot. The smaller plots flushed to the right show the muon-kaon (upper plot) and muon-pion (lower plot) control samples. The data are represented by points with error bars. The fit is shown by continuous lines. On the muon-proton plot the double hatched area represents the total background present in this sample. The muon-proton plot (but not the fit) was made with an additional cut $\zeta < +1.5$, to show the effective purity of the signal. There are 32 entries on this plot, of which 22 ± 5 are signal events. The single hatched areas on the smaller plots show the pion contributions.

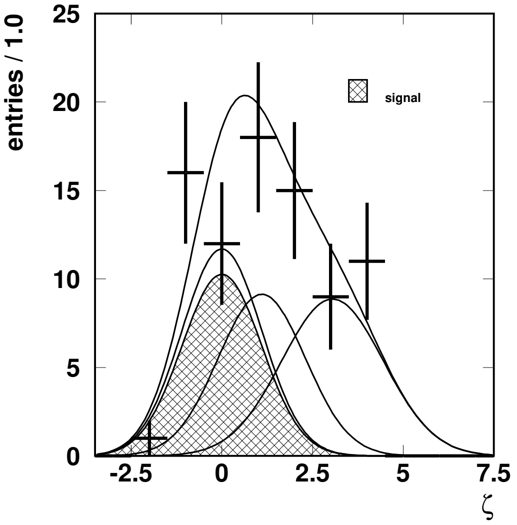
Figure 10: Projection of the data distribution onto ζ axis.



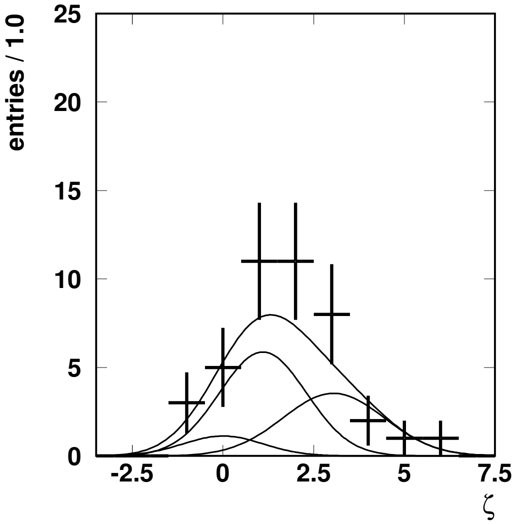
μ–p sample
right sign
$p_\perp > 0.7$ GeV/c

Points with error bars (data) are compared to the fit represented by the upmost curve. This curve is the sum of the p, K, π contributions, shown with gaussians centered at $\zeta = 0.0$, 1.1, 3.05 respectively. The signal part of p content is hatched. Shown above is the signal region: muon-proton, right sign sample with an additional cut $p_\perp > 0.7$GeV/c. Below, whole muon-proton sample is shown. Muon-kaon, muon-pion and muon-unresolved samples are shown on the next page (there is no proton contribution).

right sign μ–p



wrong sign μ–p



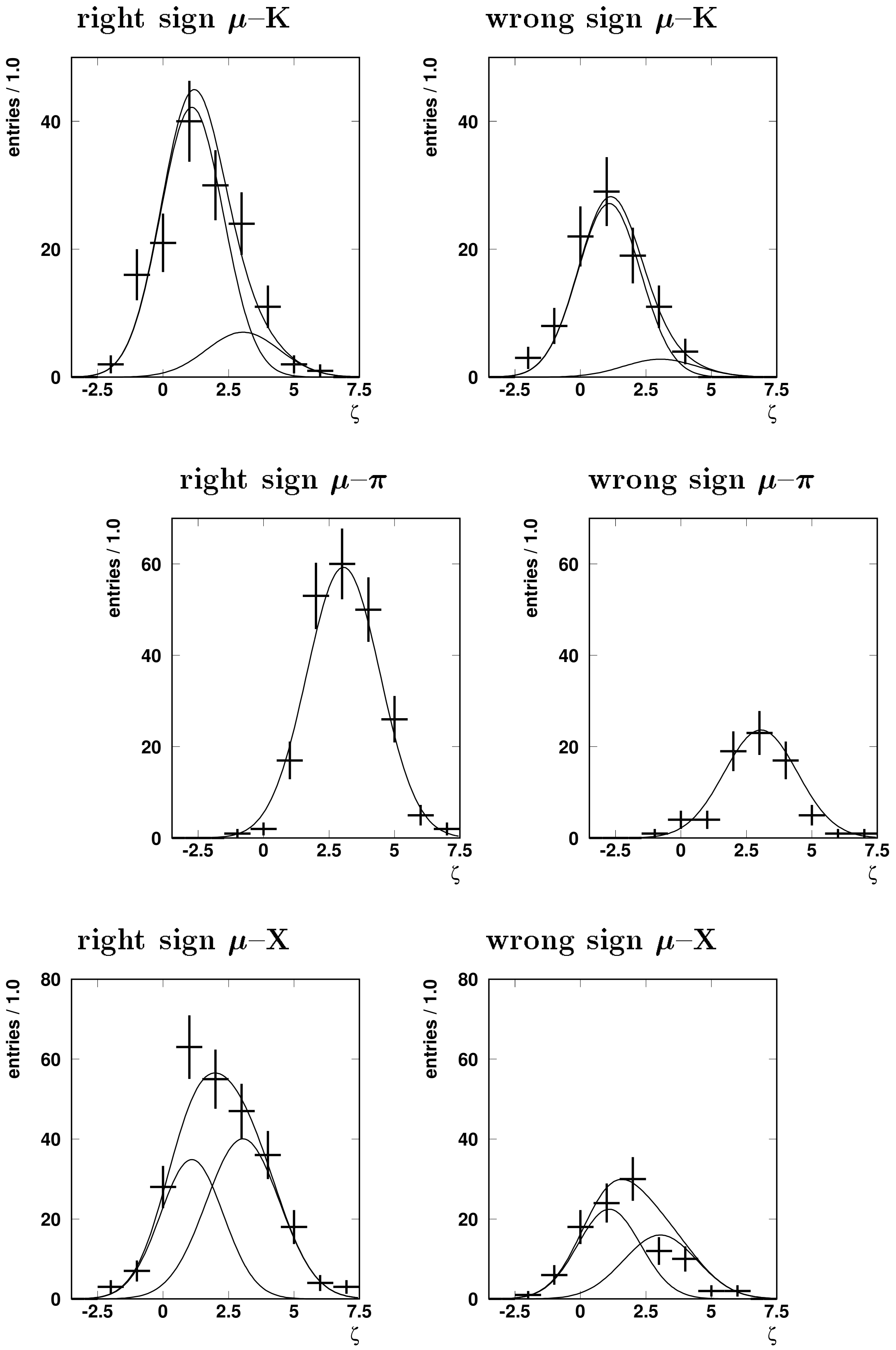
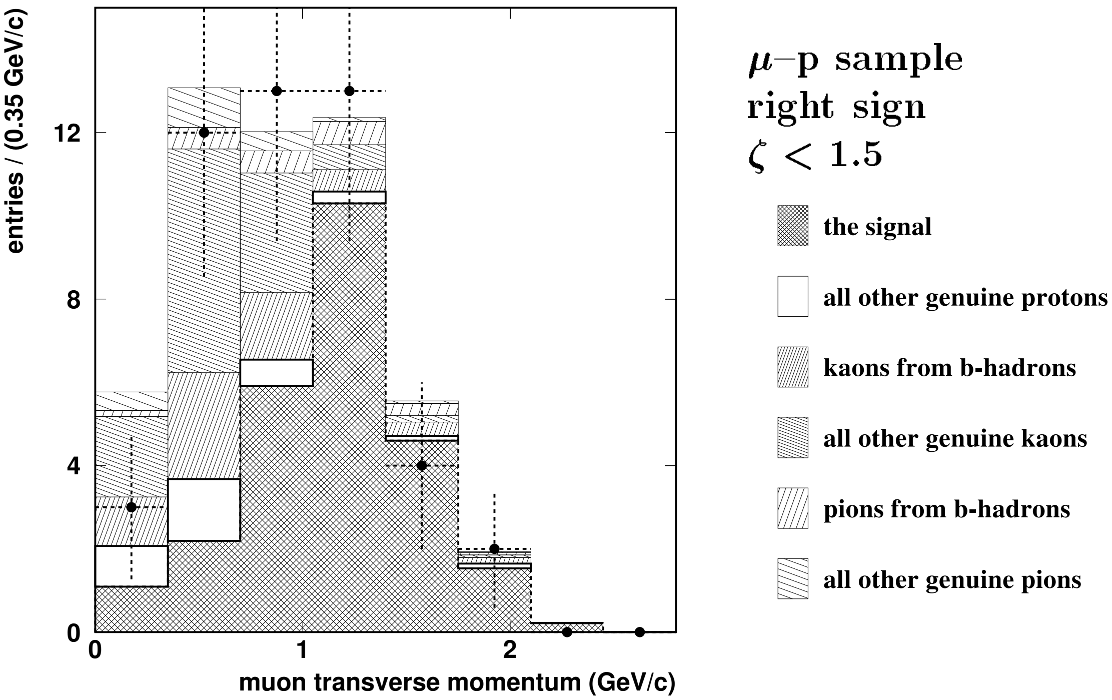
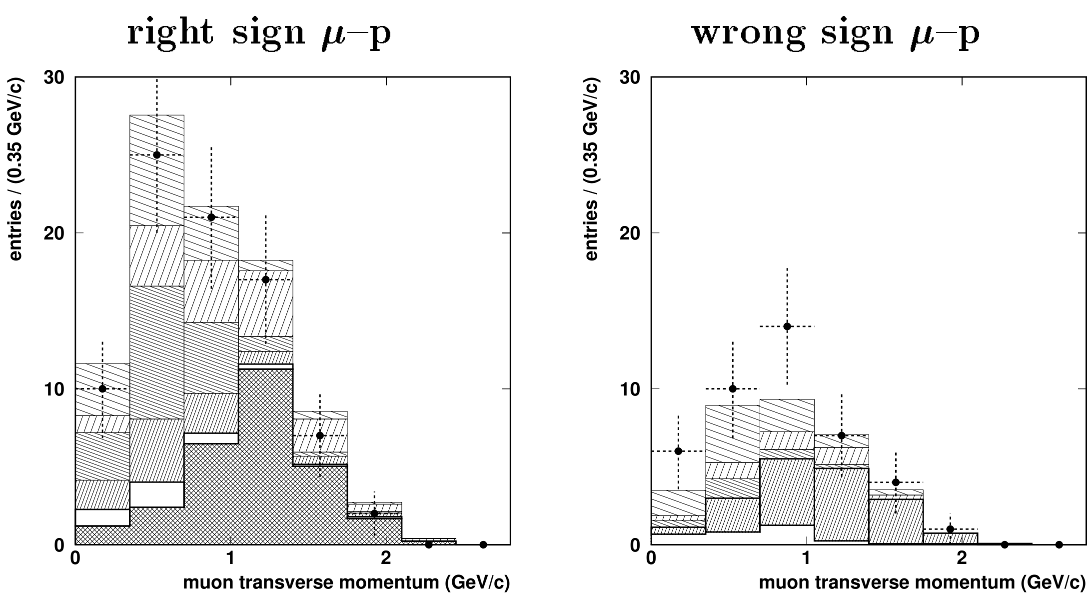

right sign μ–K
wrong sign μ–K
right sign μ–π
wrong sign μ–π
right sign μ–X
wrong sign μ–X
entries / 1.0
ζ
-2.5
0
2.5
5
7.5
0
20
40
60
80

Figure 11: Projection of the data distribution onto muon transverse momentum axis.



Points with error bars (data) are compared to the fit (histogram) decomposed into six classes.
Shown above is the signal region: muon-proton, right sign sample with an additional cut $\zeta < 1.5$. Below, whole muon-proton sample is shown. Muon-kaon, muon-pion and muon-unresolved samples are shown on the next page.



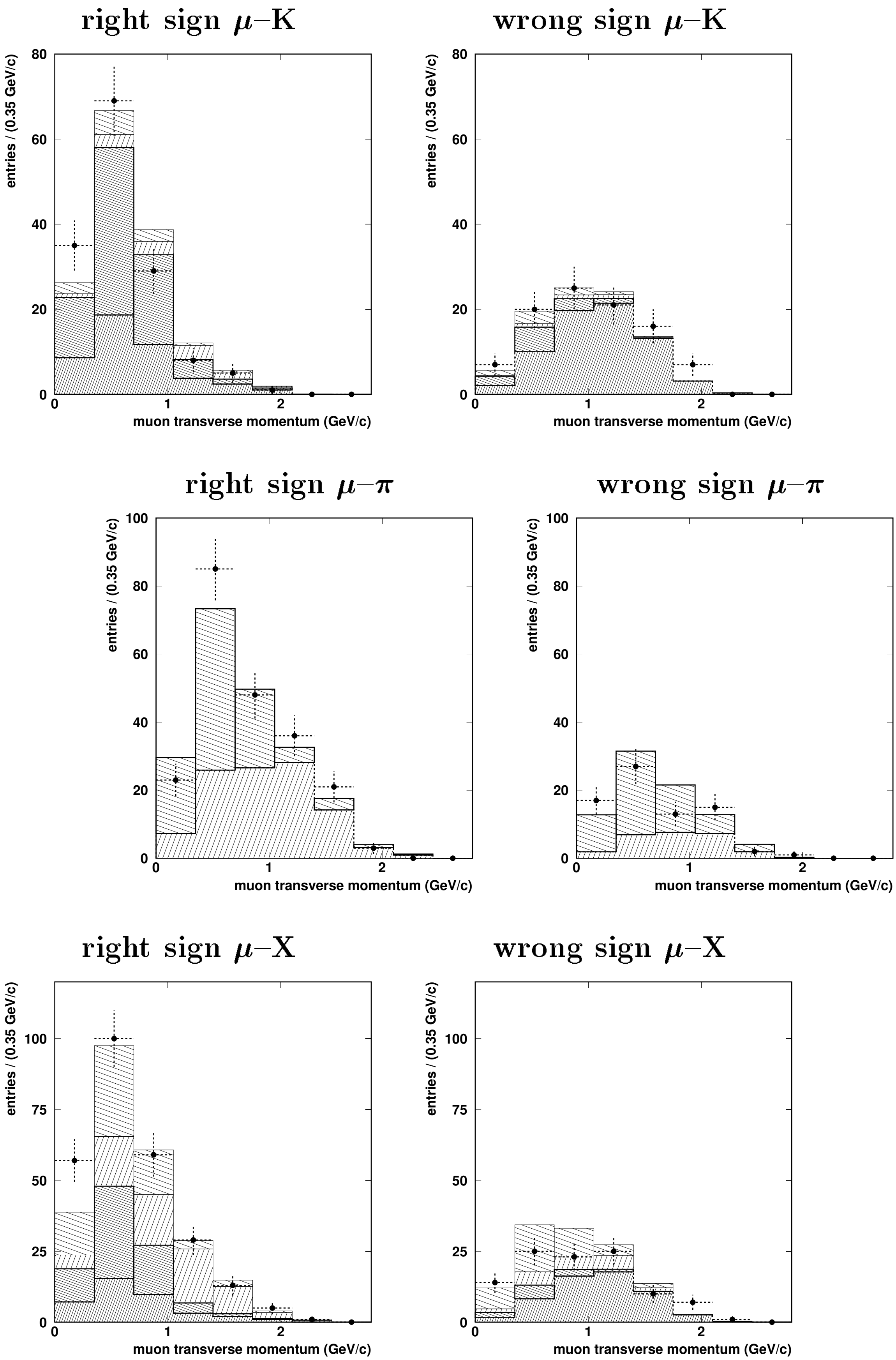
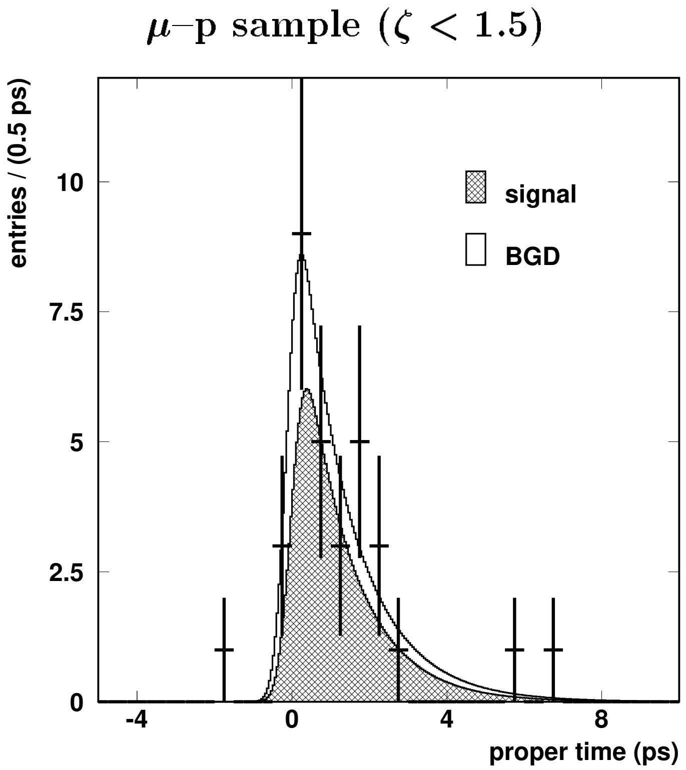
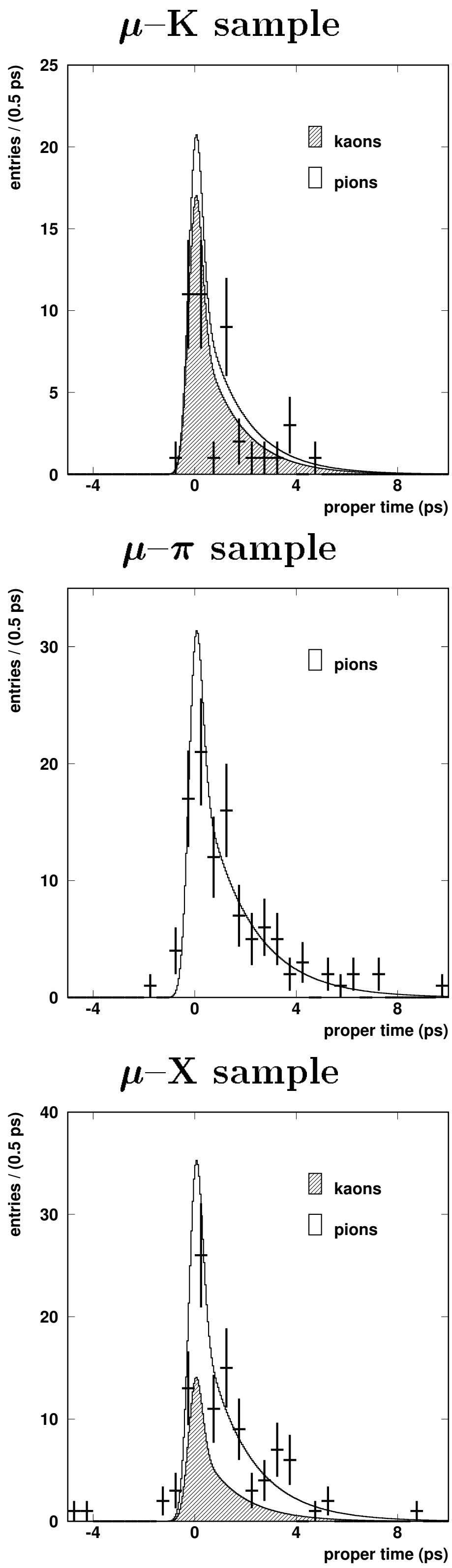

right sign μ–K
wrong sign μ–K
right sign μ–π
wrong sign μ–π
right sign μ–X
wrong sign μ–X
entries / (0.35 GeV/c)
muon transverse momentum (GeV/c)

Figure 12: Projection of the data distribution onto proper time axis. Lifetime fit subrange: right sign, $p_\perp > 0.7$ GeV/c





Projection of the data distribution of the lifetime fit subrange (right sign, $p_\perp > 0.7$ GeV/c) onto proper time axis. Muon-proton sample is shown above. To the right, muon-kaon (upper plot), muon-pion (middle plot) and muon-unresolved (bottom plot) samples are shown.
The data are represented by points with the error bars. The fit is shown with continuous lines. On the muon-proton plot the double hatched area represents the signal. This plot (but not the fit) was done with an additional cut $\zeta < 1.5$, to show the effective purity of the signal. There is 32 entries to this plot from which 22 ± 5 are signal events.
The single hatched areas on smaller plots show the kaon contents.