EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–PPE/97–27

7 March 1997

Rapidity Correlations in Λ Baryon and Proton Production in Hadronic Z^0 Decays

DELPHI Collaboration

Abstract

In an analysis of multihadronic events recorded at LEP by DELPHI in the years 1992 through 1994, rapidity correlations of Λ-Λ, proton-proton, and Λ-proton pairs are compared with each other and with the predictions of the string fragmentation model. For $\Lambda\overline{p}$ pairs, the additional correlation with respect to charged kaons is also analysed.

(Accepted by Phys. Lett. B)

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1 Introduction

Due to the small number of baryons (B) produced in hadronic Z^0 decays, their study offers the possibility of a more detailed understanding of the fragmentation processes than the study of mesons. In particular, because baryons are produced only in pairs and at a relatively low rate, studies of baryon correlations can reveal finer details of the transition of partons into hadrons, e.g. how far the interactions in a string reach. In addition, the combined study of Λs and protons allows the compensation of strangeness to be investigated.

The string model, as implemented in the Monte Carlo program JETSET [1], describes the soft hadronization process as several break-ups of a colour string which is stretched between the partons (the colour-charged particles) that were produced in the hard QCD processes. The string is a 1-dimensional object and has an energy density per unit length of $\kappa \approx 1$ GeV fm^{-1}. When the energy in the string becomes large enough, $q\overline{q}$ pairs are produced, breaking the string.

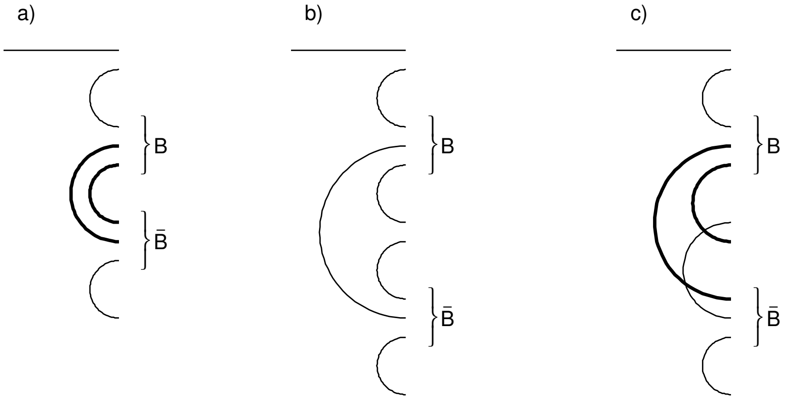

Figure 1: Schematic representation of the baryon production in the string model. The top lines indicate the primary quarks, and the semi-circles indicate quark-antiquark pairs that arise in the fragmentation.

Occasionally, the string can break up producing a diquark-antidiquark ($D\overline{D}$) pair. This process is very similar to producing a $q\overline{q}$ pair since both states, the $D\overline{D}$ and the $q\overline{q}$, are pairs of colour triplets and colour anti-triplets. With the neighbouring quark and antiquark in the string, the $D\overline{D}$ pair will form a baryon-antibaryon pair (Fig. 1 a). In addition to this *direct* process, baryons can also be formed when $q\overline{q}$ pairs overlap in other ways. This mechanism is called *popcorn* [2], and is illustrated in Figs. 1 b) and c). Figure 1 b) focuses more on the fact that in the popcorn model the quarks are in principle produced separately, while Fig. 1 c) underlines more the close relationship with, and possible transition to, the direct diquark fragmentation in Fig. 1 a).

Neighbouring baryons in the string typically differ in rapidity[†] by about 1 unit, with popcorn fragmentation leading to bigger rapidity differences than the direct process. Thus the rapidity correlation of baryon-antibaryon pairs is a tool to study the popcorn mechanism, i.e. to study to what extent baryons are locally produced.

Previous publications on baryon production stated either that the data on $\Lambda\overline{\Lambda}$ rapidity correlations [3–5] and on $p\overline{p}$ rapidity correlations [6] are in agreement with a relative probability of popcorn production of 0.5, or that the data indicate larger values. However, a difficulty in distinguishing direct baryon production from popcorn production is the fact that the massive particles produced in the fragmentation process subsequently decay.

[†]The rapidity is defined as $y = \frac{1}{2}\ln\frac{E+p_{\parallel}}{E-p_{\parallel}}$, where E is the energy of the particle and $p_{\parallel}$ the projection of the momentum onto the thrust axis.

2 Event and particle selections

A general description of the DELPHI detector and its performance can be found in [7,8]. Features of the apparatus relevant for the analysis of multi-hadronic final states (with emphasis on the detection of charged particles) are outlined in [9].

This analysis is based on $2.74 \cdot 10^6$ multihadronic events recorded in the years 1992 through 1994. Hadronic events were selected using the standard criteria as defined in [8]. The DELPHI detector contains Ring Imaging CHerenkov (RICH) detectors [11] to perform pion, kaon and proton identification. Here, this identification was performed for particles with momenta from 0.7 up to 45.6 GeV using the NEWTAG package [12]. This is based on the RIBMEAN clustering algorithm [8], which reconstructs a weighted mean Cherenkov angle. For momenta below 1.3 GeV, down to 0.3 GeV, the measurement of the specific ionisation, $\mathrm{d}E/\mathrm{d}x$, in the DELPHI Time Projection Chamber (TPC) [8] was also used. Giving equal logarithmic intervals in momentum equal weight in the average, the mean purity of the selected proton sample was 76% for a mean efficiency of 75%. The DELPHI procedure for reconstructing neutral 2-body decays (V^0) is described in [8]. After rejecting candidates in which the higher momentum particle was identified as a pion, the sample of Λ-Baryons selected had a purity of 97 %.

The biases in the analysis due to the detector acceptance and performance and to the selection criteria were studied using the full detector simulation program DELSIM [8]. Around 10^7 events were generated using the JETSET 7.3 PS model with parameters tuned as in [10]. The particles were followed through the detailed detector geometry, and simulated raw data were produced and processed by the same analysis programs as the real data.

3 Baryon Correlations

3.1 Rapidity Difference Distributions

The analysis of $\Lambda\Lambda$ pairs used the data taken from 1992 through 1994, which comprise $2.74 \cdot 10^6$ hadronic events. For proton identification over the entire momentum range, both the liquid and the gas radiator of the RICH detector need to be operational. Therefore the analysis of Λp and pp pairs was restricted to the data taken in 1994 ($1.33 \cdot 10^6$ hadronic events).

Hadronic events with

$$N_{\mathrm{B}} = N_{\mathrm{p}} + N_{\Lambda} = 2 \quad , \tag{1}$$

were selected, where N_{p}, N_{Λ} are the numbers of protons and Λs respectively (antibaryons are included). Events with more than two baryons were excluded, because already in the case of $N_{\mathrm{B}} = 3$ at least two of the three possible combinations are uncorrelated. When selecting the baryons, double counting was avoided by requiring that the Λs did not share a common outgoing track, and that the protons were not part of a reconstructed Λ. The numbers of baryon pairs selected are given in Table 1.

Figure 2 shows the differences in rapidity with respect to the thrust axis of the event for the three different types of baryon pairs. The pairs with non-zero baryon number, shown shaded, consist of different sources of background. The analysis-specific background is due to misidentifications (of one or both of the baryons) and inefficiencies (e.g. only a Λp pair of a $\Lambda\overline{\Lambda}$-$\mathrm{p}\overline{\mathrm{p}}$ event is reconstructed). But even with an ideal reconstruction and

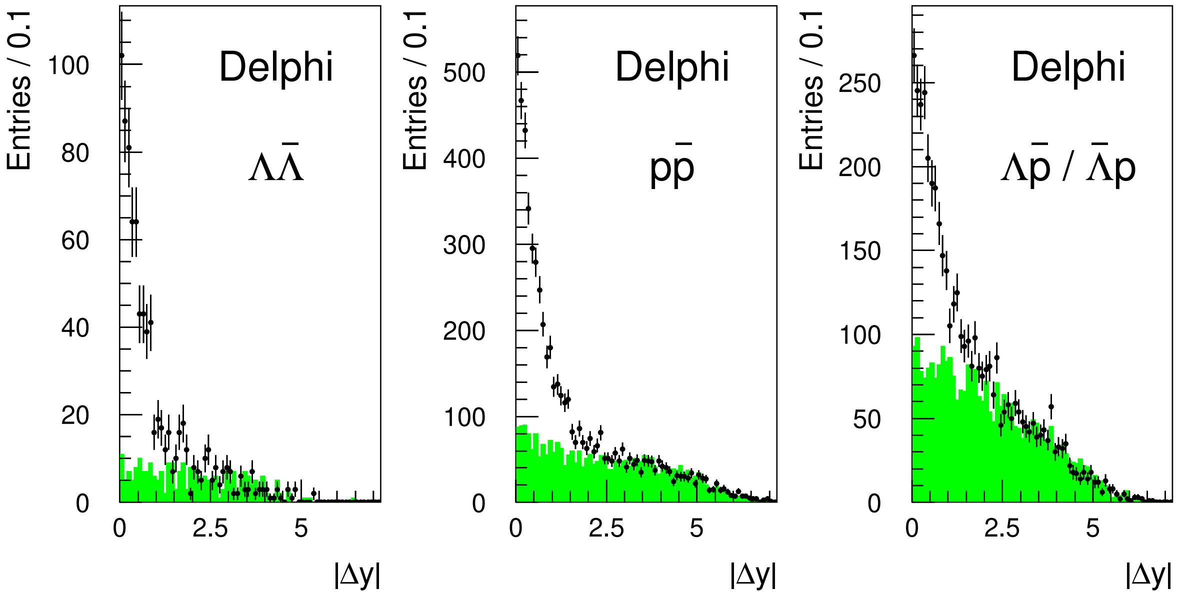

Figure 2: Rapidity differences of baryon-antibaryon pairs (points with error bars) compared to those of baryon-baryon and antibaryon-antibaryon pairs (shaded histograms) from DELPHI data.

identification, one would find uncorrelated baryon pairs from events with more than one baryon pair, because of baryons that are not included in the analysis (e.g. n and Σ).

3.2 Background Subtraction

To determine the rapidity difference distribution for correlated $B\overline{B}$ pairs, the background as estimated from the sum of the distributions of the BB and the $\overline{BB}$ pairs was subtracted. Statistical fluctuations of the background distributions were reduced by fitting a third order polynomial spline function before the subtraction.

The subtracted rapidity difference distributions have to be corrected for detector acceptance effects. These tend to strengthen the correlation observed. The correction factors were obtained from the full simulation. They were found to depend linearly on $|\Delta y|$. Consequently the corrections were made using the result of a straight line fit to the correction function. The pairs of fit parameters for the three different $B\overline{B}$ types agreed within their statistical errors. Thus a common correction factor calculated from the mean values of the three parameter pairs could be used, independently of the $B\overline{B}$ type.

Figure 3 compares the resulting rapidity difference distributions both in the data and in the full simulation, which assumed a popcorn fraction $f = 0.5$. There are only very few pairs with absolute differences greater than 2. Thus correlated baryons are always either both in a common jet or both in the inter-jet region. There is no evidence for a long range baryon correlation.

While pairs of baryons of the same type are highly correlated, and show a similar behaviour for $\Lambda\overline{\Lambda}$ and $p\overline{p}$ pairs, the mixed pairs in the data are clearly less correlated and exhibit a plateau in the range $|\Delta y| < 0.4$. This suggests that the popcorn probability might be higher for the mixed pairs. The three points with error bars on the upper right hand side of each part of Fig. 3 show the mean of the two leftmost bins ($|y(\mathrm{B}) - y(\overline{\mathrm{B}})| < 0.2$) for the three $B\overline{B}$ combinations.

Combination	$n(\mathrm{B\overline{B}})$	$n(\mathrm{BB}) + n(\mathrm{\overline{BB}})$
pp	5552	2764
$\Lambda\Lambda$	772	225
	1829	602
Λp	2922	1519

Table 1: Numbers of pairs for the different baryon combinations. The second line for $\Lambda\Lambda$ contains the numbers for all data sets from 1992 through 1994, whereas the other lines refer only to the data taken in 1994.

3.3 Systematic Effects

Several checks of the stability and significance of the observed difference in the rapidity correlation were carried out.

Both for Λs and protons, two different selections were used. Then charged particle identification was omitted in the Λ selection, which trebled the background. The influence of protons from hadronic interactions and other secondary decays was investigated by relaxing the requirements on the impact parameters of the proton tracks. By checking the stability of the signal over the data taking period between 1992 and 1994, detector dependent fluctuations were excluded. This also checked the effects of Λ reconstruction with or without the aid of the z coordinate readout of the silicon vertex detector[‡]. The shapes of the background distributions, as obtained from the BB and the $\overline{\mathrm{BB}}$ pairs, were compared with those based on a) background candidates taken from the sidebands of the Λ mass distribution and b) randomly selected charged particles instead of tagged protons. This was done for BB- and $\overline{\mathrm{BB}}$-like pairs as well as for $\mathrm{B\overline{B}}$-like pairs.

None of these changes significantly affected the rapidity correlations. This indicated that the systematic uncertainties were unimportant compared with the statistical errors.

Finally, it should perhaps be remarked that not only do $\simeq 5\%$ of the tagged protons come from Λ decays, as remarked earlier, but some others originate from $\Sigma^{\pm}$ and a similarly small fraction of the Λ are from $\Xi^{\pm,0}$ decays, etc. However, all these effects are included in the simulation, and at about the same level as in the real data, so they are not expected to explain the effect observed.

3.4 Discussion

The correlation observed between mixed pairs (Λp) is lower than that observed between unmixed pairs (p$\overline{\mathrm{p}}$,$\Lambda\overline{\Lambda}$). This difference is not reproduced in the JETSET simulation shown in Fig. 3. We were also unable to reproduce it by varying the available model parameters,

[‡]Until 1993 the vertex detector consisted of three layers of single sided silicon strip detectors at average radii R = 6.3, 9.0, and 10.9 cm providing only an R-Φ measurement in the plane transverse to the beam. In 1994, two layers were upgraded with double sided readout including also the z coordinate. At the same time the DELPHI V^0 reconstruction procedure was updated to take advantage of the higher z resolution.

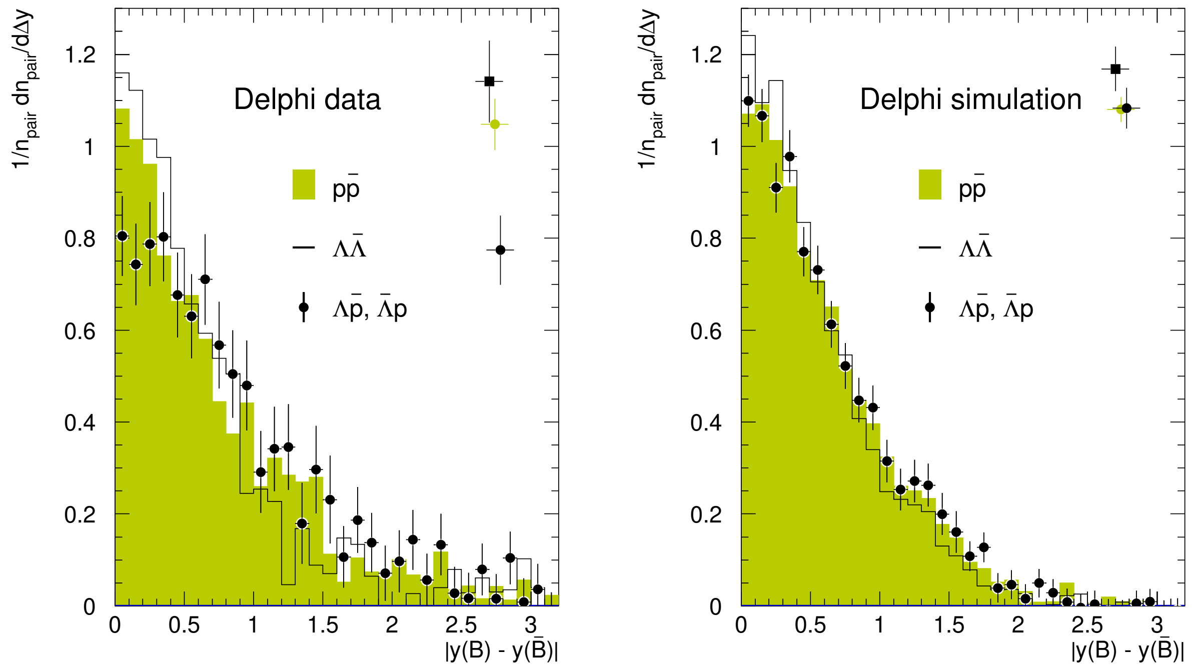

Figure 3: Rapidity differences of baryon-antibaryon pairs for real data and full JETSET 7.3 simulation with DELPHI tuning [10]. The three points with error bars on the far right of each plot show the mean values of the two leftmost bins ($|y(\mathrm{B}) - y(\overline{\mathrm{B}})| < 0.2$) for the three $\mathrm{B}\overline{\mathrm{B}}$ combinations, to show the significance of the effect.

although it seems unlikely to be in disagreement with the principles of the string model[§]. The HERWIG generator [14] was also found to predict only small differences between the peak heights of the three $\mathrm{B}\overline{\mathrm{B}}$ combinations.

3.5 Rapidity Difference with Respect to the Charged Kaons

Events with mixed pairs (Λp) in which exactly one charged kaon is also found, regardless of its rapidity, offer a possibility of investigating how far the observed rapidity correlation between baryon pairs applies also for the mesons in the vicinity.

The Λp pairs were split into three samples: correlated pairs with a small rapidity difference, $|\Delta y_{\mathrm{B}}| < 0.6$, pairs with a bigger difference, $0.6 < |\Delta y_{\mathrm{B}}| < 2$, and mostly uncorrelated pairs with $2 < |\Delta y_{\mathrm{B}}|$. Only pairs with opposite baryon numbers were taken into account: the events where strangeness was not compensated ($\Lambda\mathrm{K}^-$ and $\overline{\Lambda}\mathrm{K}^+$, $S = \pm 2$) were assumed to describe the background of misidentified and uncorrelated events with accidentally compensated strangeness ($\Lambda\mathrm{K}^+$ and $\overline{\Lambda}\mathrm{K}^-$, $S = 0$). Thus the distributions of the $S = \pm 2$ pairs were subtracted from the ones with compensated strangeness. The ratio of the number of $S = \pm 2$ pairs to the number of $S = 0$ pairs was $(72 \pm 5)\%$ in the real data and $(68 \pm 2)\%$ in the simulation. The purity of correctly identified particle trios in the simulation was about 50 % for $|\Delta y_{\mathrm{B}}| < 0.6$, and about 40 % for $0.6 < |\Delta y_{\mathrm{B}}| < 2$.

[§]It might be noted that, since the completion of this analysis, a revised version of the popcorn model has been developed [13] in which the stepwise production of the quarks is carried through more consistently and the number of free parameters is reduced.

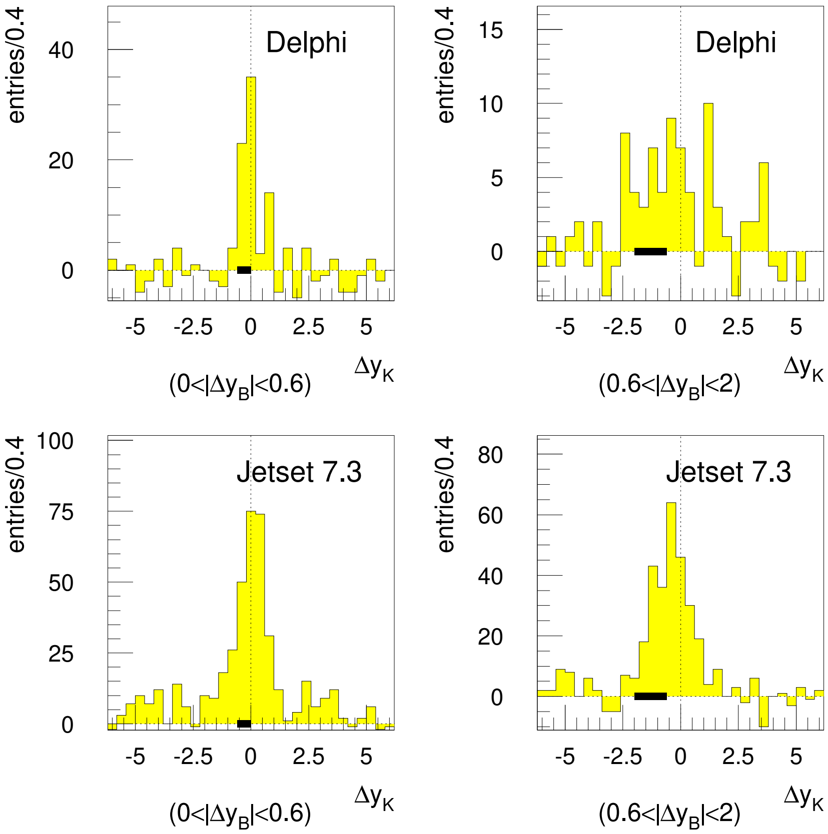

Figure 4: Rapidity difference $y_{\mathrm{K}} - y_{\Lambda}$ between the kaon and the Λ for two ranges of the rapidity difference of the Λp pair. The two upper plots are obtained from the data and the two lower ones from the DELSIM simulation, which contains 3.5 times more events than the data. The sign of y is chosen such that $\Delta y_{\mathrm{B}} = y_{\mathrm{p}} - y_{\Lambda}$ would be negative. The position range of Δy_{B} is indicated as a black bar on the abscissa.

No correlation with respect to the kaon was visible if $2 < |\Delta y_{\mathrm{B}}|$. Fig. 4 shows that for $|\Delta y_{\mathrm{B}}| < 2$ the correlation with respect to the kaon follows the correlation between the baryons. A high correlation between the baryons is associated with a high correlation between the kaon and the Λ. The link between the two correlations is also present in the JETSET simulation, but it seems to be smaller.

4 Summary

Rapidity difference distributions for protons and Λ baryons have been presented and compared with JETSET simulations. The rapidity correlations for $\Lambda\overline{\Lambda}$ and $\mathrm{p}\overline{\mathrm{p}}$ pairs agree with each other and with the JETSET model expectation. The correlation for $\Lambda\overline{\mathrm{p}}$ pairs is smaller than for $\Lambda\overline{\Lambda}$ or $\mathrm{p}\overline{\mathrm{p}}$ pairs. This effect is currently described neither by JETSET nor by HERWIG.

For $\Lambda\overline{\mathrm{p}}$ pairs, there is also clear evidence for a short range compensation of strangeness whose range depends strongly on the rapidity difference of the baryon pair. This behaviour is qualitatively described by the JETSET simulation, but there the dependence seems weaker.

Acknowledgements

We would like to thank Patrik Eden and Mike Seymour for discussing and explaining the consequences for the Monte Carlo generators. We are greatly indebted to our technical collaborators and to the funding agencies for their support in building and operating the DELPHI detector, and to the members of the CERN-SL Division for the excellent performance of the LEP collider.

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