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Study of $p\bar{p}$ and $\Lambda\bar{\Lambda}$ production in e^+e^- annihilation at 10 GeV center of mass energy

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Abstract. A study of the pp and $\Lambda\Lambda$ production in direct Υ decays and in continuum e^+e^- annihilation is reported, based on data collected using the ARGUS detector at the e^+e^- storage ring DORIS II. The production rates for events containing two protons with momenta between 0.4 and 1.2 GeV/c in the continuum and in direct Υ decays have been measured to be $n^{pp}_{\text{con}} = (4.5 \pm 0.4 \pm 0.2) \times 10^{-4}$ and $n^{pp}_{\text{dir}} = (2.00 \pm 0.07 \pm 0.10) \times 10^{-3}$, respectively. The corresponding rates for $\Lambda\Lambda$ production were found to be $(5.1 \pm 3.6 \pm 0.8) \times 10^{-4}$ and $(1.81 \pm 0.41 \pm 0.27) \times 10^{-3}$ respectively.

1 Introduction

Fragmentation of quarks and gluons into hadronic final states still does not have a satisfactory theoretical basis. However, during the last years much experimental progress has been made, particularly in the 10 GeV center-of-mass energy region where high statistics and good particle identification allow precise measurements. Results have been reported on both meson and baryon production rates [1–5], as well as baryon/antibaryon correlations [6]. In addition, differences between quark and gluon hadronization have been studied by comparing direct Υ decays with e^+e^- continuum at about the same energy. The most striking distinction is the substandial rate for baryon production on the $\Upsilon(1S)$, which is a factor of 2–3 larger than in the nearby continuum [5, 7].

Physical interpretations of these data are mainly based on a comparison with predictions of common fragmentation models. Reasonable agreement with most measurements has been obtained using the Lund model [8], but only after adjustment of parameters. A more stringent test of the physical basis of a model would be to find quantities which are not so directly connected with the model parameters. In the following a study is presented of the production of events containing two protons or lambdas*. Comparison with the Lund model, which assumes an independent production of baryon/antibaryon pairs, in this case could reveal information about the underlying string dynamics.

2 Data analysis

The data used in this analysis were collected with the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. A detailed description of the detector, its trigger and particle identification capabilities can be found in [9]. The data presented were accumulated on the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances and in the continuum, corresponding to integrated luminosities of 44.1, 35.6 and 86.2 pb^{-1}, respectively. In the analysis $\Upsilon(1S)$ and $\Upsilon(2S)$ data were combined to improve statistics for direct resonance decays, which we define as that part of data taken on a resonance after subtracting contributions from continuum and vacuum polarisation [2].

* References in this paper to a specific charged state are to be interpreted as implying the charged-conjugate state also

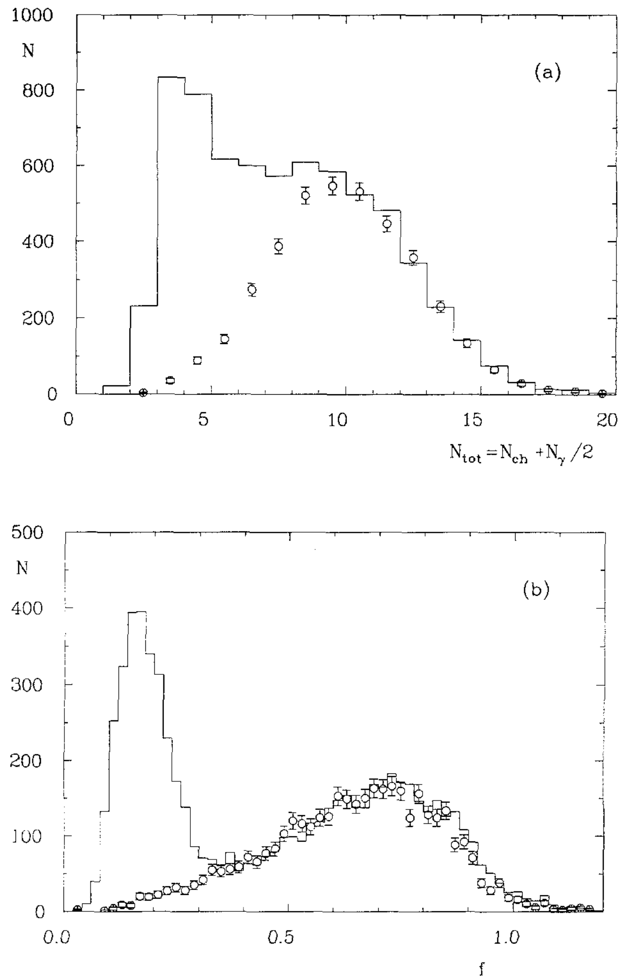

Fig. 1a, b. a Distribution of the total multiplicity $N_{\text{tot}} = N_{\text{ch}} + N_\gamma/2$, where N_{ch} and N_γ are defined in the text. The histogram shows the distribution for continuum events containing protons with momenta between 0.4 and 1.2 GeV/c. The open points with errors are plotted for events with antiprotons in the same momentum range. **b** Distribution of the variable $f = P_{\text{sum}} - 2.5 \cdot P_z^2$ defined in the text. The histogram shows the distribution for continuum events containing protons in the momentum range from 0.4 to 1.2 GeV/c. The open points with errors are plotted for events with antiprotons in the same momentum range

Multihadron candidates were selected by requiring at least 3 charged tracks from a reconstructed main vertex or 3 charged tracks, not necessarily pointing to a common vertex, in combination with a total energy of more than 1.7 GeV deposited in the shower counters.

A substantial fraction of these events are due to beam-gas and beam-wall interactions, which constitute a major source of background for events with two or more protons. Therefore, a further cut on the total multiplicity $N_{\text{tot}} = N_{\text{ch}} + N_\gamma/2 \geqq 7$ was applied, where N_{ch} is the number of charged particles pointing to the main vertex and N_γ the number of photons with energy above 50 MeV.

In Fig. 1a, the distribution of total multiplicity N_{tot} is shown for continuum events containing protons in the momentum interval from 0.4 to 1.2 GeV/c (histogram), as well as for events with antiprotons in the same momentum range (open points with errors). A comparison of the two distributions shows that the proton events still include some background.

As demonstrated in [2, 3], the contribution of beam-gas and beam-wall interactions can be substantially reduced by making use of their characteristic unbalanced longitudinal momentum. Therefore an additional cut on the quantity $f = P_{\mathrm{sum}} - 2.5 \cdot P_z^2 > 0.4$ was applied, where $P_{\mathrm{sum}} = \sum |\mathbf{P}_i| / \sqrt{s}$ is the sum of the momenta of all charged and neutral particles and $P_z = \sum p_{zi} / \sqrt{s}$ is the sum of the momentum components along the beam line, both normalized to the center-of-mass energy. The distribution of f is shown in Fig. 1b for continuum events with protons (histogram) and with antiprotons (open points with errors). The peak at low values of f in the histogram is due to beam-gas and beam-wall background.

The number of multihadron events has been calculated using the same cuts, which also reduce background from QED and two-photon events to a negligible level. The efficiency for multihadron events to satisfy these requirements is 0.92 for direct Υ decays and 0.74 for continuum events.

In our analysis proton candidates were selected in the momentum range between 0.4 and 1.2 GeV/c, where they can be identified almost uniquely. Furthermore, the protons were required to come from the main vertex and their polar angle θ was restricted to $|\cos\theta| < 0.92$. In order to remove a contamination to the two proton rate from "broken" tracks, where the drift chamber hits of a single particle have been reconstructed as two tracks, we required the cosine of the opening angle between particles with the same charge to be less than 0.98. The acceptance for the multihadron selection criteria and the cuts described in this paragraph were determined from a full detector simulation using events generated by the Lund 6.2 event generator.

Particle identification information was applied by calculating a combined likelihood ratio from $\mathrm{d}E/\mathrm{d}x$ and time-of-flight measurements [9]. A proton hypothesis was accepted if the corresponding likelihood value exceeded 0.15. The acceptance of this cut was determined using a clean proton sample obtained from Λ decays.

Corrections for particle misidentification were applied as a function of the proton momentum. The following four momentum regions were used: 0.4–0.7 GeV/c, 0.7–0.9 GeV/c, 0.9–1.1 GeV/c and 1.1–1.2 GeV/c. Probabilities for π and K misidentification as a proton were calculated for each region using π mesons from the decay $K_s^0 \to \pi^+\pi^-$ and K mesons from the decay $\phi \to K^+K^-$. The rather small background contribution in these samples was studied using the K_s^0 and ϕ mass sidebands. The misidentification probability was calculated as the ratio of the number of tracks identified as protons over the total number of π and K mesons from K_s^0 and ϕ decays. The fraction of the faked protons has been calculated from the known ratios N_π/N_p and N_K/N_p [4] and from the misidentification probability. Contributions from muons and electrons to the fake rate were estimated to be negligible.

In the case events with two protons, the main source of faked proton pairs turns out to be meson-proton pairs. Estimates of the background from misidentified $p\pi(pK)$ pairs were made by applying the experimentally determined misidentification probabilities to the $p\pi(pK)$ rates obtained from the Lund 6.2 program. Since the misidentification probabilities are small, we checked that the numbers of $p\pi$ and pK pairs per event from the event generator agree well with the experimental data.

Λ hyperons were reconstructed by a secondary vertex fit of $p\pi^-$ combinations. In this analysis p and π were identified in the full momentum region if the corresponding likelihood values exceeded 0.05. The flight direction of the Λ candidate was restricted to $|\cos\theta| < 0.85$. Only $p\pi^-$ combinations with a scaled momentum $x_p = p_\Lambda / p_{\max} > 0.1$ were considered, since the acceptance is small below this value. Data have been extrapolated to a region of low x_p and a correction has been made with the procedure described in [6]. In order to reduce the combinatorial background under the Λ signal, the radial distance of the decay vertex, R_{vx}, from the beam line was restricted to the interval $4\,\mathrm{cm} < R_{vx} < 40\,\mathrm{cm}$. Converted photons were rejected by a cut on the opening angle between the proton and pion candidate, requiring $\cos(p, \pi^-) < 0.998$. To suppress Λ particles produced in the inner detector material, the angle between the flight direction of the Λ and the vector $\mathbf{d}$, connecting the main and the secondary vertex, had to satisfy the condition $\cos(\mathbf{p}, \mathbf{d}) > 0.995$.

For the further analysis of pp production, protons from Λ decays were removed from consideration. Many protons produced in Λ decays were already rejected by the cut on the main vertex χ^2. Furthermore, all protons have been excluded which form a reconstructed secondary vertex and have an invariant mass around the Λ mass when combined with another oppositely charged track in the event. Some fraction of the protons from Λ decays cannot be identified by a secondary vertex. For this contribution, the $p\pi^-$ invariant mass spectrum was studied. The size of the observed Λ signal was determined as a function of momentum and a correction factor applied. For example, in the continuum the value of the Λ decay correction factor varied from 22% for protons in the momentum range 0.4–0.7 GeV/c to 12% for momenta between 1.1 to 1.2 GeV/c. Because of their different absorption in the inner detector material, separate correction factors were applied for protons and antiprotons.

3 Results on production rates and correlations

After applying the cuts described in the last section, we found 11995 events with protons and 10871 with antiprotons in the continuum sample in the momentum range between 0.4 and 1.2 GeV/c, while the combined $\Upsilon(1S)$ and $\Upsilon(2S)$ data consisted of 47805 events with protons and 43687 with antiprotons. The number of detected antiprotons is less than the number of protons because of the stronger $\bar{p}$ absorption in the inner detector material.

In these data samples we find 83 events with two proton and 60 events with two antiproton candidates

Table 1. Rates per multihadron event for two proton and two Λ hyperon production for continuum data. For a comparison the rate for one (anti)proton production n_p is given. The proton rates were determined for the momentum interval 0.4–1.2 GeV/c, while the Λ rate is given for the full momentum region. The first error quoted is statistical, and the second reflects the systematic uncertainties

	ARGUS	Popcorn model	Diquark model
$n_p+n_{\bar{p}}$	$(9.65\pm0.08\pm0.24)\times10^{-2}$	$(10.6\pm0.1)\times10^{-2}$	$(13.1\pm0.1)^{-2}$
$n_{pp}+n_{\bar{p}\bar{\pi}}$	$(4.5\pm0.4\pm0.2)\times10^{-4}$	$(5.6\pm0.2)\times10^{-4}$	$(18.6\pm0.4)\times10^{-4}$
$n_{\Lambda\Lambda}+n_{\bar{\Lambda}\bar{\Lambda}}$	$(5.1\pm3.6\pm0.8)\times10^{-4}$	$(1.8\pm0.2)\times10^{-4}$	$(12.2\pm0.5)\times10^{-4}$

Table 2. Rates per multihadron event for two proton and two Λ hyperon production for direct Υ decays. For a comparison the rate for one (anti)proton production n_p is given. The proton rates were determined for the momentum interval 0.4–1.2 GeV/c whereas the Λ rate is given for the full momentum region. The ratio r reflects the ratio of rates from direct Υ decays compared with continuum. The thirst error quoted is statistical and the second reflects the systematic uncertainties

	ARGUS	Popcorn model	Diquark model
$n_p+n_{\bar{p}}$	$(22.4\pm0.2\pm0.6)\times10^{-2}$	$(33.1\pm0.1)\times10^{-2}$	$(33.3\pm0.1)\times10^{-2}$
$n_{pp}+n_{\bar{p}\bar{p}}$	$(2.00\pm0.07\pm0.10)\times10^{-3}$	$(10.3\pm0.12)\times10^{-3}$	$(16.6\pm0.15)\times10^{-3}$
$r_{p+\bar{p}}$	$2.32\pm0.02\pm0.09$	3.12 ± 0.03	2.54 ± 0.02
$r_{pp+\bar{p}\bar{p}}$	$4.45\pm0.42\pm0.29$	18.7 ± 0.7	8.9 ± 0.2
$n_{\Lambda\Lambda}+n_{\bar{\Lambda}\bar{\Lambda}}$	$(1.81\pm0.41\pm0.27)\times10^{-3}$	$(1.7\pm0.1)\times10^{-3}$	$(5.3\pm0.1)\times10^{-3}$

for continuum data, while there are 631 (252) pp pairs and 458 (183) $\bar{p}\bar{p}$ pairs on the $\Upsilon(1S)$ ($\Upsilon(2S)$) resonance. After applying corrections for background and acceptance we obtain the combined rates per multihadron event for pp and $\bar{p}\bar{p}$ production presented in Tables 1 and 2. These rates have not been extrapolated to the full momentum range, since there is no suitable means available. For example, use of the measured inclusive spectrum for protons seems unreliable because the distribution in events with two baryon/antibaryon pairs can be expected to be much softer than in events with a single pair. Instead, a comparison is made with the production rate of protons and antiprotons in the same momentum interval. As in the analysis of pp pairs the contribution from lambda decays has been removed from the inclusive proton rate. It appears that the production rate for events with two baryon/antibaryon pairs is suppressed by about 2 orders of magnitude in comparison with those with a single pair.

Our results have been compared with the predictions of the Lund model (version 6.2), where the influence of several free model parameters was tested. The production rate for events with two protons was found to have a strong dependence on the popcorn parameter $\rho=BM\bar{B}/(B\bar{B}+BM\bar{B})$, which determines the number of mesons produced simultaneously with a baryon/antibaryon pair. Using $\rho=0$ one obtains the prediction of a pure diquark model, while we refer to the model prediction with $\rho=0.9$ as the popcorn model.

As shown in Tables 1 and 2, the pp rate decreases with increasing values of ρ, due to the larger meson multiplicity brought about by the popcorn mechanism. The sensitivity to this parameter is much stronger for pp pairs than for single proton production, because the production of two baryon pairs at $\sqrt{s}=10$ GeV is close to the kinematical bound in the hadronization process. While the continuum data are well described by the popcorn model, the rate in direct Υ decays is smaller than the prediction of even the popcorn mechanism by more than a factor 5.

A similar comparison was made for production of events containing $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ pairs. After subtraction of background, we observe only 7 such pairs in the continuum, while we find a signal of 41 pairs in the combined $\Upsilon(1S)$ and $\Upsilon(2S)$ data. Correcting for acceptance using the procedure described in [6] we obtained the combined $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ production rates presented in Tables 1 and 2. Since Λ's can be identified even at the highest momenta, the production rate corresponds to the whole momentum range. The model predictions give a better description of the data than for pp pairs, although the data have large statistical errors. The dependence of the $\Lambda\Lambda$ rate on the model parameter ρ turns out to be even stronger than for events with protons, probably due to the higher mass of the Λ particles.

Correlations between two protons or antiprotons were studied using the distribution of the opening angle between the two particles. For continuum the observed spectrum as a function of the cosine of the opening angle is shown in Fig. 2a, while Fig. 2b shows the corresponding distribution for direct Υ decays. The errors in both plots represent the combined statistical and systematic uncertainties added in quadrature.

Background from misidentification of πp and Kp pairs was subtracted using the a procedure analogous to that described in the previous section. The distribution of the opening angle between the $\pi(K)$ meson and the proton was determined from the Lund 6.2 event generator, normalized to the number of misidentified $\pi p(Kp)$ pairs in different momentum intervals. Based on Monte Carlo simulation, the efficiency was found to be independent of the opening angle for the momentum region used for this analysis.

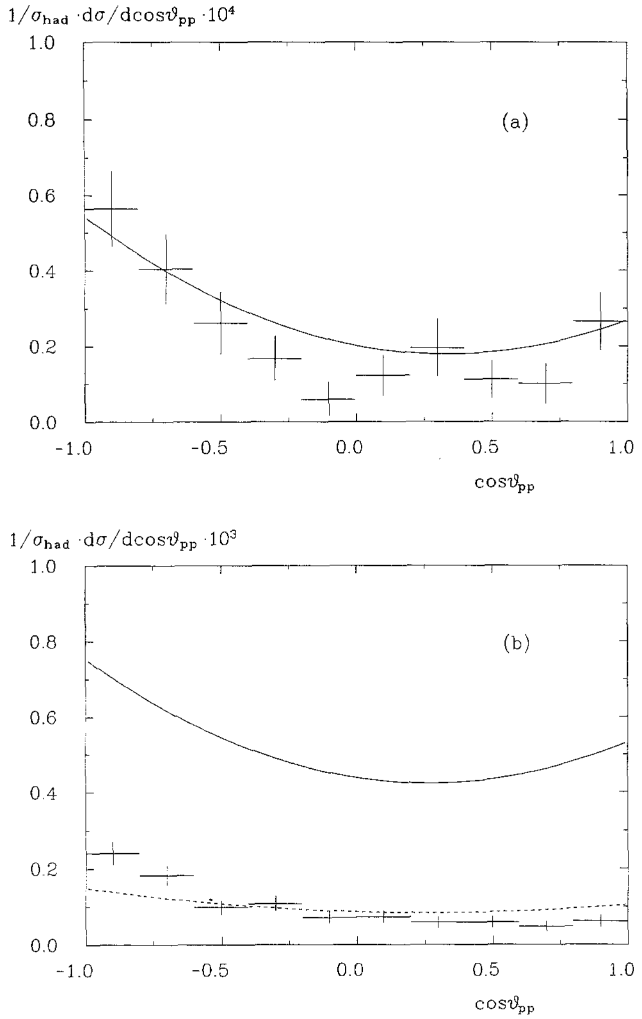

Fig. 2a, b. Distribution of the opening angle between two protons (antiprotons) for continuum data **a** and direct Υ decays **b**. The errors shown include both statistical and systematic uncertainties. The solid line represents the prediction of the Lund model with a popcorn fraction of 0.9. In **b** the dashed line corresponds to the Lund prediction, where the integral of the curve has been normalized to the experimental data

The solid curves in the Figs. 2a and 2b show the distribution predicted by the Lund model. The predicted spectra differ only marginally for the diquark and popcorn mechanisms. Since the popcorn mechanism is generally in better agreement with the absolute pp production rate, it has been used here. Again there is very good agreement between the model and the data for the continuum events, while for direct Υ decays the model predicts a flatter distribution of the opening angle.

A possible explanation for the experimentally observed back-to-back correlation of the two protons could be that two baryons cannot be produced close to each other in rank of rapidity. In contrast the Lund model assumes a uniform baryon production probability along the string, hence softening the back-to-back correlation especially in case of Υ decays into three gluons. The assumption that a second baryon/antibaryon pair will be produced only in a rapidity interval distant from the first pair would also reduce the absolute pp rate in the Lund model, since fewer "places in rank" are available for such a second pair.

4 Conclusions

The production rates of events containing two (anti)protons in the momentum range from 0.4 to 1.2 GeV/c and of events with two $\Lambda(\bar{\Lambda})$ particles have been measured. The experimental data have been compared with the predictions of the Lund model. It appears that for continuum data the best agreement is obtained using a large popcorn contribution to baryon production. For direct Υ decays the Lund model overestimates the two baryon production rate by more than a factor of 5.

Moreover we observe in direct Υ decays a discrepancy between model and data for the distribution of the opening angle between the two protons, which hints to different string dynamics as assumed in the model.

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