Study of inclusive Λ production in e^+e^- annihilations at 29 GeV

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Cross sections are presented for the inclusive production of Λ hyperons in electron-positron annihilations at $\sqrt{s}=29$ GeV based on the full 291-pb^{-1} sample of data taken in the High Resolution Spectrometer experiment at the SLAC e^+e^- storage ring PEP. These results, and the associated correlation analyses, are consistent with the Lund model predictions with the strange diquark suppression ratio δ fixed at $0.59\pm0.10\pm0.18$, as compared to the standard Lund value of 0.32. The Λ multiplicity has been found to be 0.182 ± 0.020 per event. The opposite-strangeness multiplicity $\langle n_{\Lambda\bar{\Lambda}}\rangle$ has been measured to be 0.046 ± 0.020, whereas the like-strangeness multiplicity $\langle n_{\Lambda\Lambda+\bar{\Lambda}\bar{\Lambda}}\rangle$ is 0.009 ± 0.028. A strong correlation is found between Λ's and $\bar{\Lambda}$'s; when one is found in an event, the other is found in the same event with a probability that exceeds 50%.

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INTRODUCTION

We report herein the results of an analysis of the inclusive production of Λ hyperons in e^+e^- annihilations at 29 GeV based on data from the High Resolution Spectrometer (HRS) experiment conducted at the SLAC e^+e^- storage ring PEP. The Λ cross sections presented are the first based on the final sample of HRS data, corresponding to an integrated luminosity of 291 ± 7 pb^{-1}.

Details of the experimental apparatus have been previously published in Ref. [1], the techniques used to select Λ's have been summarized in Ref. [2] and previous results, based on an integrated luminosity of 256 ± 8 pb^{-1}, have been reported in Ref. [3]. The present analysis, in addition to benefiting from the increased luminosity, is based on the standard HRS version of the Lund Monte Carlo program [4,5] (version 5.3), which is a more advanced version than previously used in any HRS inclusive Λ analysis. The previous analyses were based on detector acceptances calculated using Lund version 4.3 as the event generator. The new Monte Carlo sample also had twice as many Λ's as in the previous sample. In addition, the reconstruction techniques used previously varied from the "standard" HRS cuts summarized in

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Ref. [2]. The present analysis uses a more direct approach in determining the background in the single and dual particle spectra. The particular techniques employed in refining the data samples utilized are described below.

Studies of the inclusive production of neutral kaons and lambda hyperons are relevant to the general question of how strange particles are produced in e^+e^- collisions. The cross sections for these processes, when compared with those from other reactions, provide an insight into strange-quark fragmentation. Further, events containing multiple strange particles can be used to determine what knowledge one strange particle has about the production of the others in the same event. Whether or not strange particles with opposite strangeness are more likely to be in the same jet than in opposite jets is an example of a question whose answer relates directly to the production process.

The problem under study, however, extends well beyond the tracking of strangeness quantum numbers. There is considerable interest in the question of how baryons in general are produced in the fragmentation process. Though the subject has been explored by several experiments in recent years, numerous central issues remain unresolved. The baryons most accessible for study are the proton and lambda hyperon. Complicating the analysis of the production of these particles, however, is the fact that they arise as products of e^+e^- annihilations both as a result of fragmentation processes and as a result of the decays of other baryonic states.

In present fragmentation models baryons are produced via the creation of diquark pairs which then combine with a neighboring quark to produce the baryon. The Lund model parameter that governs the ratio of the baryonic to mesonic production rates is (qq/q), specifying how much more difficult it is to produce a diquark pair than a quark pair. In the inclusive production of Λ's the strangeness quanta can come either from the quark or the diquark. To describe both the K^0 and Λ inclusive production data, two additional parameters are required: (s/d) and $\delta=(us/ud)/(s/d)$. The first parameter specifies the relative rate of the production of strange quarks and light quarks. The second specifies the extra suppression associated with the production of a strange diquark in contrast with the production of a diquark composed of light quarks—over and beyond what would be expected on the basis of the suppression due to (s/d) alone.

A variant of this simple parametrization for producing baryons is the "popcorn model," in which the remnant quarks left over after the quark pair and diquark pair produce a baryon contribute to the production of intermediate mesons and other baryons, rather than directly forming the counterpart antibaryon. This effect is illustrated in Fig. 1 [6]. The simple Lund model implies a rather strong correlation between $\Lambda\bar{\Lambda}$ pairs, while the popcorn model implies a much weaker correlation between the two. Recent work by a UCLA group [7] attempts to avoid the heavy parametrization of the Lund model by relying on two minimal assumptions: the Wilson area law and the principle of hadronic phase space.

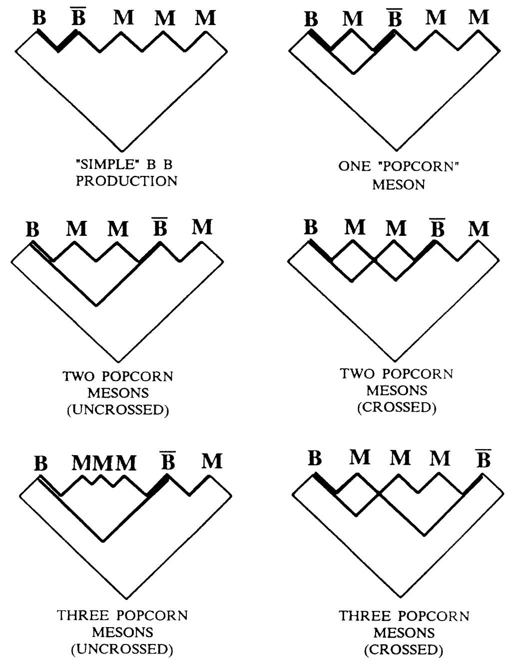

FIG. 1. Comparison of possible production mechanisms.

Their general overall agreement with available data is impressive and their Λ^0 multiplicity prediction of 0.18 compares well with the value to be presented here.

In this paper we utilize the large sample of Λ and $\bar{\Lambda}$ events to extract the δ parameter and to examine the dominance of the simple Lund fragmentation mechanism through an analysis of the production rates of like-strangeness and opposite-strangeness Λ ($\bar{\Lambda}$) pairs.

The HRS consisted of an inner and outer drift-chamber system which permitted charged-particle track positions to be determined to 200 μm over a radial distance of 1.89 m, and a barrel shower system which had an energy resolution of $\pm 0.16/\sqrt{E}$ GeV, all contained within a 16-kG longitudinal magnetic field. Because of the signature of vee events within the large volume of the HRS detector, it was possible to identify Λ hyperons with a high level of confidence. In the 123 000 hadronic events observed in the experiment, there were 8698 neutral kaons, 1259 Λ's and 1124 $\bar{\Lambda}$'s. The Λ ($\bar{\Lambda}$) events represent the single largest sample of any experiment conducted in this energy region. An analysis of the neutral kaon events has been reported in a separate publication [8].

We summarize below the selection steps used to extract the final set of data utilized in this analysis, and describe the selection criteria used in the identification of lambdas. Also, the approach used to determine the background for each mass bin is discussed. Then a summary of the cross sections for lambda production is given as a function of z the fractional energy, and y the rapidity. Comparisons are made with previously published results and a summary is provided of the Lund model parameters resulting from fits to the cross section.

Correlations between Λ's and $\bar{\Lambda}$'s in the same event are also reviewed in an effort to determine the extent to which the production of multiple strange particles might be enhanced or retarded beyond that one would expect on the basis of the random single-particle production probabilities.

EVENT SELECTION

A typical event in the HRS has 13 charged-particle tracks. To pick out a true vee in the midst of these tracks requires a rather sophisticated reconstruction process. The selection of the actual data sample was based on a set of conditions placed both upon the individual charged-particle tracks and upon the track pairs [2]. The individual track conditions were the χ^2 per degree of freedom from the fit of each track to the drift-chamber hits had to be less than 10; the polar angle was constrained by the relation $\cos(\theta)<0.9$, where θ is the track angle with respect to the beam; the transverse momentum was restricted by the condition $p_t > 120$ MeV/c; the track had to pass within 0.4 m of the intersection point in the z direction (along the beam line), and within 0.3 m in the x-y plane; at least 50% of the drift chamber layers traversed by the track must have been used in the fit; and, reconstructed track segments from looping charged tracks are removed.

The potential vees were identified by systematic pairing of oppositely charged tracks. Intersection points were then calculated as secondary vertices and subjected to the following criteria: the distance in the x-y plane from the primary to secondary vertex was greater than 5 mm; the distance in z between the two tracks at the intersection point was less than 30 mm; the impact parameter of the neutral particle momentum at the primary vertex was less than 5 mm; the tangent of the angle between the vee's momentum direction and the line connecting the primary and secondary vertices was less than 0.05; the sum of distances of closest approach to the primary vertex of the two tracks in the x-y plane was greater than 2 mm; the tracks had to have no drift chamber hits between the primary and secondary vertices; each event had to have a charged track multiplicity greater than 5; and, in order to remove nonhadronic (e.g., two-photon or beam gas) events, the total energy was required to be greater than 10 GeV/c.

CROSS SECTIONS

To determine the inclusive cross section for the production of Λ's (where Λ refers to both Λ and $\overline{\Lambda}$) it is necessary to extract the real number of Λ's above background in each z or y bin and the detector acceptance for each z or y bin.

The HRS Lund Monte Carlo simulation (version 5.3) was used to calculate the acceptance of the detector. Particles generated by the Monte Carlo simulation were passed through a detector simulation program and the particles that emerged from the simulated detector were then subjected to the same cuts as the real particles. An error on the efficiency was calculated using a binomial distribution of the number of reconstructed particles and a contribution due to systematic uncertainties in background fit, which dominated the error.

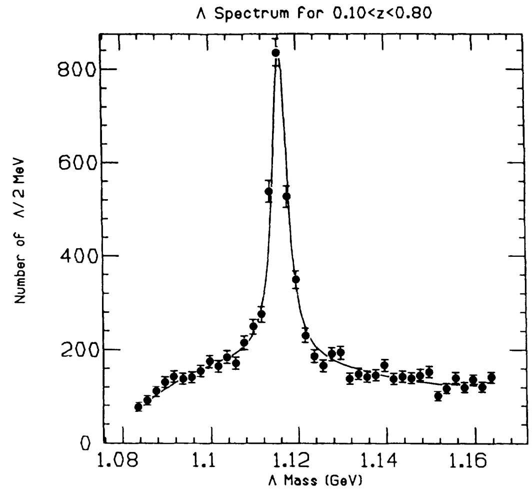

FIG. 2. Pion-proton mass distribution.

Figure 2 presents the pion-proton mass distribution, and a fit consisting of a Breit-Wigner (BW) and a third-degree polynomial background. We find a Λ central mass value of 1.1157±0.0001 GeV, and a Γ of 0.0042±0.0002 GeV. In order to avoid the problem of having signal events in the tail of the Λ Breit-Wigner be interpreted as background in a joint polynomial-BW forced fit, we made a separate determination of the background, removing all bins within ±15 MeV of the Λ mass peak. The signal was then determined through a bin-by-bin subtraction of this background from the total bin populations.

The inclusive differential cross section for particle production is

$$\frac{d\sigma}{dz}=\frac{N}{\Delta z\ AL} ,$$

where N is the number of particles, Δz is the width of the z interval, A is the acceptance of the detector in that z interval, and $L=291\pm7$ pb^{-1} is the integrated luminosity. The cross section $s/\beta(d\sigma/dz)$ was calculated, using an adjusted value of $\sqrt{s}=28.3$ GeV to take into account radiative corrections.

The Λ inclusive cross section is shown in Fig. 3, with the bin-by-bin values in Table I. The errors in the luminosity, the efficiency, the background fit, and the statistical error in the number of particles were added in quad-

TABLE I. Inclusive Λ cross sections as a function of fractional energy.

z	No. of Λ	$(s/\beta)d\sigma/dz$ (nb GeV^2)
0.125	585.9	539.4±66.4
0.175	411.4	193.8±24.6
0.225	329.1	142.4±19.2
0.275	223.4	85.7±12.3
0.350	223.8	56.9±8.1
0.450	99.3	26.9±4.8
0.650	51.2	5.6±1.2

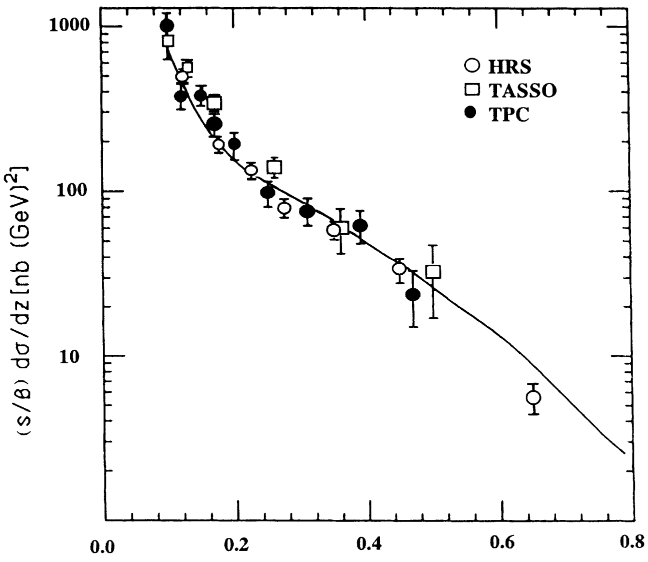

FIG. 3. Lambda-inclusive cross section at 29 GeV.

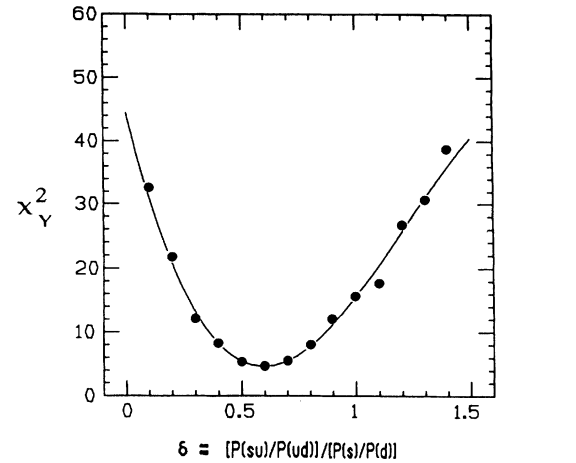

FIG. 4. χ^2 vs δ. χ^2 is calculated by comparing the Lund-generated $[(1/\sigma)d\sigma/dz]$ distribution to the experimentally determined distribution.

rature to get the final error quoted. Included for comparison are the results from other experiments in this energy range. As indicated, the agreement with the experiments of TASSO (at 34 GeV) [9] and TPC [10] is good.

The curve shown in Fig. 3 is a Lund fit, which is discussed later. Using these data we calculate total cross sections of $\sigma_\Lambda = 62.8 \pm 6.0$ pb for the interval $0.10 \le z \le 0.80$. Extrapolating the Lund fit to the Λ data to cover the unmeasured extremes gives a total cross section of 76.9 ± 7.5 pb for the interval $0.0 \le z \le 1.0$. These measurements lead to a single-particle multiplicity of $\langle n_\Lambda \rangle = 0.182 \pm 0.020$.

As a check on the method we used to extract the Λ signal above background, a similar analysis was made for the neutral kaon data. This analysis yielded $\sigma_{K^0} = 472.5 \pm 9.7 \pm 11.4$ pb for the interval $0.06 < z < 0.70$. This value was then compared to the recently reported HRS value $\sigma_{K^0} = 480.6 \pm 6.1 \pm 14.5$ pb for the same interval, determined independently using an analysis procedure designed to optimize the K signal-to-noise ratio [8].

LUND PARAMETERS

The rate of production of inclusive lambdas in e^+e^- annihilations can be parametrized in terms of the strengths of a small number of basic processes involved in the production of the strange quarks that end up in the final lambdas. In particular, the parameters that describe the rates for producing $s\bar{s}$ pairs $\{s/u\}$ and strange diquarks $\{us/ud\}$ form the keys for specifying lambda production in the Lund model. From earlier analyses of the HRS data, the ratio of K meson and pion inclusive cross sections yields a s/d value of 0.34 ± 0.03 [11]. The diquark ratio, $qq/q = 0.078 \pm 0.005$, is from the TPC measurement of proton and pion inclusive cross sections [12]. We measure the final major parameter, $\delta = (us/ud)/(s/d)$. There are other processes which can contribute to lambda inclusive production, including the decays of higher-mass strange particles, and the production of baryon-antibaryon systems with mesonic intermediate states, such as in the popcorn model. All known higher-mass strange baryon decays have been explicitly taken into account in our subsequent analysis. In particular, the charmed lambda hyperon decay $\Lambda_c \to \Lambda + X$ is explicitly taken into account with a branching ratio of $23\% \pm 10\%$ [13].

The sensitivity of the rapidity cross section to δ is illustrated in Fig. 4. At each point on the curve in Fig. 4, a χ^2 was calculated by comparing the experimentally determined rapidity distribution (shown in Fig. 5) with the rapidity distribution predicted using the Lund Monte Carlo

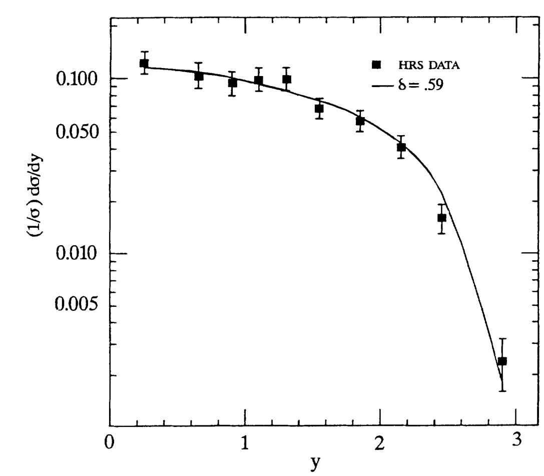

FIG. 5. Lambda-inclusive cross section as a function of rapidity.

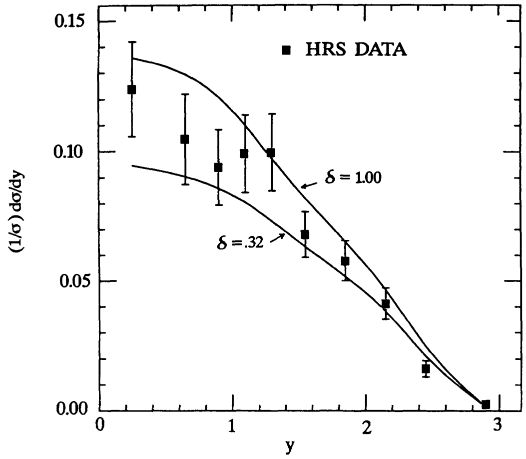

FIG. 6. Comparison of the rapidity distribution to predicted distributions for $\delta=0.32$ and 1.00.

simulation (with δ varying between 0.1 and 1.4) to generate a new set of Λ's. The δ value corresponding to the best fit is $0.59\pm0.10\pm0.18$. (The deep minimum found in χ^2 vs δ is a much stronger minimum than found in previous HRS publications [14].) The first error is statistical while the second is a systematic error based on the errors in qq/q, s/d, and $B(\Lambda_c\to\Lambda+X)$. The systematic error is consistent with Monte Carlo results obtained by varying each of these parameters independently. We note that $d\sigma/dy$ is much more sensitive than $d\sigma/dz$ to δ, due at least in part to the additional information of the thrust axis contained in y. The curves shown in Figs. 3 and 5 are the inclusive cross sections with $\delta=0.59$, superimposed on the experimental cross sections. Figures 6 and 7 show, respectively, a comparison of various δ values to the rapidity distribution and the contribution from Λ_c decay. This value of δ is significantly larger than the default value of 0.32 in the standard Lund model [4,5]. The implication is that a larger fraction of the lambdas produced in inclusive electron-positron annihilations derive from the production of strange-diquark pairs than is postulated in the basic Lund model.

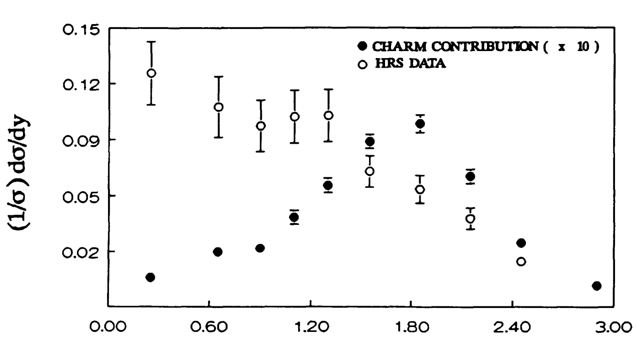

FIG. 7. Contribution to Λ production from Λ_c decay. (Charm contribution has been multiplied by a factor of 10.)

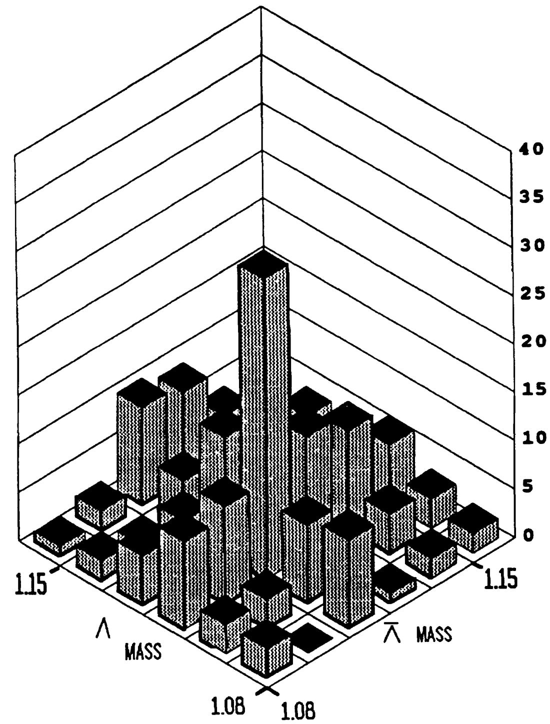

FIG. 8. Mass distribution of opposite-strangeness pairs.

CORRELATIONS

Additional insight into strange-baryon production processes can be gained by examining the rate at which Λ-$\bar{\Lambda}$ pairs are produced, compared to the rate for the generation of single lambdas. This comparison provides a measure of local strangeness conservation and a test of the reasonableness of the proposed production processes.

We observed 212 candidates for Λ-$\bar{\Lambda}$. A three-dimensional view of the Λ-$\bar{\Lambda}$ distribution is shown in Fig. 8. We estimate that 68.2 ± 27.5 of these pairs are true signal events. The background subtraction is made using a detailed analysis of Monte Carlo events, with cross checks to ensure that the single-particle background spectra are well reproduced. We calculate a corresponding value of $\langle n_{\Lambda\bar{\Lambda}}\rangle=0.046\pm0.020$, in agreement with previous experiments. The single-lambda inclusive production rate $\langle n_\Lambda\rangle$ and the opposite-strangeness production rate $\langle n_{\Lambda\bar{\Lambda}}\rangle$ indicate a λ value of 0.51 ± 0.23, where

$$\lambda=2\frac{\langle n_{\Lambda\bar{\Lambda}}\rangle}{\langle n_\Lambda\rangle+\langle n_{\bar{\Lambda}}\rangle}$$

indicating that half the time a Λ or $\bar{\Lambda}$ is produced, it is accompanied by its antiparticle. We have also examined our data for lambda pairs of the same strangeness and, employing the same background subtraction technique as above, find $\langle n_{\Lambda\Lambda+\bar{\Lambda}\bar{\Lambda}}\rangle=0.009\pm0.028$. It is thus improbable that when a lambda of one strangeness is observed in an event another lambda of the same strangeness will also be present in that event.

TABLE II. Comparison of Λ parameters.

Experiment	Energy (GeV)	n_Λ	$n_{\Lambda\bar{\Lambda}}$	$n_{\Lambda\Lambda+\bar{\Lambda}\bar{\Lambda}}$	δ
TPC [10]	29	0.211 ± 0.017	0.053 ± 0.013		
TASSO [9]	35	0.218 ± 0.023	0.052 ± 0.016		
JADE [15]	35	0.234 ± 0.064		0.0052 ± 0.0088	0.48[a]
Mark II [16]	29	0.213 ± 0.022			
HRS-86 [3]	29	0.220 ± 0.023	0.054 ± 0.018		$0.89\pm0.10^{+0.56}_{-0.16}$
HRS	29	0.182 ± 0.020	0.046 ± 0.020	0.009 ± 0.028	$0.59\pm0.10\pm0.18$

[a]Value set.

CONCLUSIONS

We have reported the cross sections for inclusive lambda production in e^+e^- annihilations at 29 GeV, and have extracted the single-particle and pair-production rates. We have found $\langle n_\Lambda \rangle=0.182\pm0.020$, $\langle n_{\Lambda\bar{\Lambda}} \rangle=0.046\pm0.020$, and $\langle n_{\Lambda\Lambda+\bar{\Lambda}\bar{\Lambda}} \rangle=0.009\pm0.028$. Our cross-section measurements are consistent with the Lund model predictions, with $\delta=0.59\pm0.10\pm0.18$.

A comparison of the principal parameters extracted from recent lambda inclusive measurements is presented in Table II.

ACKNOWLEDGMENTS

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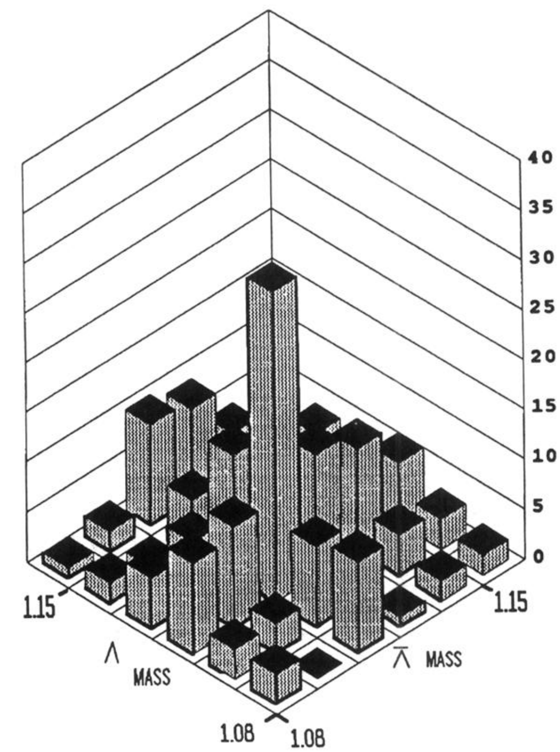

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