EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/82-181
16 November 1982

THE PRODUCTION OF HIGH-MOMENTUM PARTICLES AND
RESONANCES IN pp COLLISIONS AT THE CERN INTERSECTING STORAGE RINGS

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ABSTRACT

Data are reported on the momentum distributions of Λ , $\Lambda(1520)$, $\phi(1020)$, $\bar{\Lambda}$, and $\bar{p}$, inclusively produced between 1° and 2° with respect to one of the primary proton beams at the CERN Intersecting Storage Rings. In addition, the decay angular distribution of the $\Lambda(1520)$, the ratio of the cross-sections for the production of $\Sigma^-(1385)$ and $\Sigma^+(1385)$ and the ratios among different charge states of the pairs $\Lambda\pi$, ΛK , $\Delta^{++}(1232)\pi$ and $\pi\pi$ have been measured. These data are confronted with current ideas on fragmentation.

(Submitted to Nuclear Physics B)

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1. INTRODUCTION

This paper is a continuation of earlier work on the fragmentation of protons into low- p_T , high $x = 2p_L/\sqrt{s}$ secondaries at the CERN Intersecting Storage Rings (ISR). In such collisions the proton fragments presumably contain one or more of the original constituents carrying a large fraction of the incident momentum. The momentum distribution of the secondaries can be calculated by folding the quark content of the incident protons, as derived, for example, from lepton-nucleon scattering data, with a mechanism for the hadronization of the final-state quarks. Different models have been proposed for the hadronization mechanism. For example, in the recombination and fusion models the momentum of the produced particle is calculated by adding the momenta of the relevant quarks and gluons, the distributions of the latter being derived from deep inelastic scattering experiments. In other models the final-state particles result instead from the decay of high- x quarks or of diquarks. In view of the number of free parameters it is not clear which, if any, of the different models is correct.

In this paper we present new data on the x -dependence of the inclusive production of Λ , $\Lambda(1520)$, $\phi(1020)$, $\bar{\Lambda}$, and $\bar{p}$, on the decay angular distribution of the $\Lambda(1520)$, on the ratio of the cross-sections for the production of $\Sigma^-(1385)$ and $\Sigma^+(1385)$, and on the ratios among different charge states of the pairs $\Lambda\pi$, ΛK , $\Delta^{++}(1232)\pi$ and $\pi\pi$, in pp collisions at $\sqrt{s} = 45, 53$, and 62 GeV, and we briefly confront these with current ideas on fragmentation.

2. APPARATUS AND DATA REDUCTION

The data were taken with one of two identical small-angle spectrometers built primarily to conduct correlation studies between high-momentum particles produced in the fragmentation regions of the colliding protons at the CERN ISR. The spectrometers, one of which is shown in fig. 1, have been described elsewhere [1,2]. Each spectrometer had an acceptance of about 1 msr and covered vertical angles between 18 and 39 mrad with respect to one of the ISR beams. It consisted of a septum magnet with $\int B dl = 2.1$ T·m, 24 planes of drift chambers in five modules (DC1-DC5), three atmospheric Čerenkov counters ($\check{C}1, \check{C}2, \check{C}3$), and scintillation

counters (A, B, D, E, F, H1, H2). Both Čerenkov counters Č2 and Č3 were equipped with split mirrors and two RCA8854 Quantacon photomultipliers. The Čerenkov counters were operated with various gas fillings. The scintillation counters A-F were viewed by two photomultipliers. The hodoscopes H1 and H2 had ten 25 mm wide elements and sixteen 40 mm wide elements, respectively. For luminosity monitoring two sets of scintillation counters were mounted below the beam pipes at about 5 m from the interaction region. For part of the data taking an additional 6-plane drift-chamber module was placed behind DC1 in one of the arms*).

The basic trigger consisted of a coincidence A-F and an appropriate pattern of Čerenkov bits. For single-particle triggers high momenta were selected by means of a matrix pattern in H1 and H2. For multiparticle triggers, the multiplicities in H1 and H2 were required to be greater than or equal to two, and pulse-height cuts were imposed on the scintillators A-F. Figure 2 shows the pulse-height distribution in one scintillator for triggers with multiplicity greater than or equal to two. The additional pulse-height cut resulted in a 40% reduction in the trigger rate, at the expense of a 2% loss of two-track events.

Momenta and angles were determined using standard tracking methods. Accurate momentum measurements were possible because the magnetic field was nearly uniform and could be described by an average field value and an effective length (2 m). The combined effects of errors in the magnetic field and the positioning of the drift chambers resulted in a ratio of 1.0034 ± 0.0010 between the momentum of the circulating beam scaled to the appropriate machine radius and the momentum of the elastically scattered protons measured in the spectrometer. All momenta were scaled with this factor. For the detection of single particles the magnet was excited to its maximum field strength. In this case the momentum resolution was 1.3% (standard deviation) at 30 GeV. For detection of two or more particles, optimization of the acceptance was achieved by lowering the magnetic field to 20%, 30%, and 50% of its maximum value, with a corresponding deterioration of the momentum resolution.

*) A more extensive report on Λ production from data taken in this configuration will be given in a future publication.

In the off-line analysis, particles were identified by comparing pulse heights in the Čerenkov counters with the expected values for a single- or two-particle hypothesis. For the two-track $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ events, a minimum decay distance of 50 cm from the collision point was required. The Λ events needed no further identification. For the $\Lambda(1520) \rightarrow pK^-$ the K^- and the p were both required to have momenta greater than 7 GeV; for the K^- this eliminates confusion with Λ decays for which the π^- momentum is kinematically constrained to be below 7.5 GeV, while the protons from $\Lambda(1520)$, with momentum above 15 GeV, are constrained to have momenta above 7.1 GeV. A $\Lambda(1520)$ mass peak could then easily be seen without Čerenkov identification. Subsequent use of the Čerenkov counters made the signal stand out clearly.

The identification of the $\phi(1020) \rightarrow K^+K^-$ was hampered by small cross-sections and therefore by continuum contamination from various sources. In this case Č1 and Č3 were filled with FC114, with a kaon threshold of 9.5 GeV; and Č2 with CO₂, with a kaon threshold of 16.3 GeV. The identification essentially required one decay particle to count in the heavy gas if above its kaon threshold, and none in the light gas if below its kaon threshold. This criterion selected $\phi(1020)$ momenta smaller than 27 GeV, but left a considerable contamination from pK^- pairs. For part of the data, in which one Čerenkov cell failed, this contamination was reduced by selecting decays with a forward K^- . Another contamination came from abundant e^+e^- production from converted photons. This was rejected in part by a Č2 veto, in part by rejecting events with c.m. opening angles $|\cos \theta^*| < 0.31$ in the decay angular distribution.

For $\bar{p}$ production measurements the Čerenkov counters of one arm were filled with SF₆ and those of the other arm with a SF₆/CO₂ mixture, corresponding to $\pi/K/p$ threshold momenta of 3.7/13.1/25.0 GeV and 4.1/14.6/27.8 GeV in arm 1 and arm 2, respectively. In each arm the trigger consisted of a coincidence between the trigger counters, a pattern of the two hodoscopes H1 and H2 defining a high-momentum negatively charged particle, and an anticoincidence of one of the Čerenkov counters. Events for which no Čerenkov light was detected were identified as anti-protons in the range $15 < p < 24$ GeV (arm 1) and $17 < p < 27$ GeV (arm 2). This

resulted in a sample of 449 antiprotons. The π^- (K^-) contamination in this sample was calculated to be less than 10^{-5} (10^{-2}).

The spectrometer acceptance for single particles has been computed analytically by assigning a weight to each event according to the range in azimuthal angle ϕ covered by the spectrometer at a given polar angle θ . The procedure was checked with π^- and π^+ data, which were found to agree with published results [2,3] to within 10%. For the two-particle events this weight was multiplied by a weight assigned according to an assumed isotropic decay spectrum and the probability of capturing both decay products [4]. The known branching ratios and decay and absorption of the decay products were taken into account. To simplify the calculation and enhance its reliability, events were rejected which traversed regions in the spectrometer which could not be covered equally by particles produced anywhere in the interaction region, thus restricting the polar angle to be between 23 and 34 mrad. This enabled us to use the integrated luminosity for normalization of the data. The cross-section of the background under the resonance signal was subtracted using a linear interpolation of the continuum outside the resonance region. For the non-resonant two-particle and the three-particle events (e.g. $\Lambda\pi$) the results are presented as ratios and no acceptance calculation has been attempted.

The luminosity monitor was calibrated at regular intervals with the standard van der Meer method [5]. The r.m.s. spread of these calibrations at $\sqrt{s} = 63$ GeV was 3%.

The data fill a narrow band in the x, p_T plane. In this band a parametrization of the invariant cross-section $\sigma^{\text{inv}} = E(d^3\sigma/dp^3) = A(x) \exp(-bp_T^2)$ yielded values of b independent of x in the cases where the data were sufficiently accurate statistically to verify this relation. Such a factorization of the x - and p_T^2 -dependence has been found earlier in the case of pion production [3]. We have subsequently used this empirical fact to present the data at one value of transverse momentum, using the mean value of b found in the fits.

The errors quoted reflect both statistical errors and variations in different sets of data. The absolute normalization of the presented cross-sections is estimated to have a systematic error of less than 15%.

The results obtained can be divided into two categories: i) differential invariant cross-sections for the inclusive production of Λ , $\Lambda(1520)$, $\phi(1020)$, $\bar{\Lambda}$, and $\bar{p}$, and ii) ratios of the inclusive production cross-sections of $\Sigma^-(1385)/\Sigma^+(1385)$ and of the different charge states among the pairs $\Lambda\pi$, ΛK , $\Delta^{++}(1232)\pi$, and $\pi\pi$.

3. DIFFERENTIAL CROSS-SECTIONS FOR THE INCLUSIVE PRODUCTION OF Λ , $\Lambda(1520)$, $\phi(1020)$, $\bar{\Lambda}$, and $\bar{p}$

3.1 Production of Λ and $\Lambda(1520)$

The mass spectra for $\Lambda \rightarrow p\pi^-$ and $\Lambda(1520) \rightarrow pK^-$ are shown in fig. 3. The pK^- mass spectrum has been corrected for the variation of the acceptance with mass; this leaves the average number of events unchanged. The masses and widths for various ground states and resonances are given in columns 3 and 4 of table 1. The mass of the $\Lambda(1520)$ is somewhat lower than the present world average of 1519.5 MeV [6], but is in excellent agreement with two other measurements [7,8]. The width (FWHM) agrees with the world average. For the Λ and the $\Lambda(1520)$ the results from the fits to the slope parameter b , which governs the transverse momentum dependence, are shown in fig. 4. No x -dependence can be seen. The average value of b for the $\Lambda(1520)$ is not significantly different from the value for the Λ .

The x -dependence of the cross-sections is shown in fig. 5 and in table 2. The data points at the two highest x -values have undergone momentum smearing corrections, computed from the known spectrometer resolution and the fitted x -dependence. The Λ cross-sections agree to within 20% with recent data at $\sqrt{s} = 27.4$ GeV [9] and to within a factor of two with cruder data from Erhan et al. at $\sqrt{s} = 62.3$ GeV [10].

The Λ and $\Lambda(1520)$ behave as "leading" proton fragments with a relatively flat x -distribution. This can be parametrized well with the function $\sigma^{\text{inv}} = E(d^3\sigma/dp^3) = A(2E/\sqrt{s})(1-x)^n$, see fig. 5. From integration over the complete x - and p_T -range we then find: $\sigma(\Lambda) = 3.6 \pm 0.6$ mb, $\sigma[\Lambda(1520)] = 0.76 \pm 0.11$ mb, and $\sigma(\Lambda)/\sigma[\Lambda(1520)] = 4.8 \pm 0.4$. The parametrization $\sigma^{\text{inv}} \approx (1-x)^m$ fits only the very high- x part of

the Λ and $\Lambda(1520)$ spectra, but seems to fit over a larger x -range for the $\bar{\Lambda}$, $\bar{p}$, and $\phi(1020)$, which do not contain any valence quarks of the initial protons. The fitted values for b , n , and m are given in columns 6, 7, and 8 of table 1.

The x -distribution of the heavier $\Lambda(1520)$ is flatter than the one for the Λ . This result is unexpected if the x -distributions are determined by quark dynamics only, as the Λ and $\Lambda(1520)$ are just two different arrangements of u , d , and s quarks. A calculation by Fisjak and Kistenev [11], in the framework of a quark-diquark fusion model, ascribes the difference to feed-down from heavier hyperons into the Λ spectrum. These authors consider direct production of members of $SU(6)$, $L(\pi) = 56, 0(+)$ and $70, 1(-)$ multiplets and contend that less than 5% of the Λ 's are produced directly. Their computed x -distributions are also shown in fig. 5. At high x they do not agree well with the data. Generally, any picture that takes into account the Lorentz boost from excited protons should generate higher mean x -values for heavier particles. We conclude that particle masses and feed-down contributions are bound to have important effects on the x -distributions.

Further information on the production mechanism can be obtained from the decay angular distributions. In the case of Λ and $\Lambda(1520)$ the data are sufficiently accurate statistically. Figure 6 shows the decay angular distribution of the $\Lambda(1520)$ with respect to the flight direction in the particle centre-of-momentum frame; it is compatible with being isotropic. The $\Lambda(1520)$ $J^\pi = \frac{3}{2}^-$ state decays via a D-wave into pK^- . If the $\frac{3}{2}$ state were aligned with only the $m = \pm\frac{1}{2}$ substates populated, the angular distribution would follow the dashed line in fig. 6, $dN/d \cos \theta^* \approx (\frac{1}{2} + \frac{3}{2} \cos^2 \theta^*)$. In a quark-recombination approach one would expect to see some alignment if, for example, an $S = 0$ ud -quark system combines with an s -quark via a D-wave.

Fialkowski [12] has emphasized that the resonance to non-resonance ratio can be a sensitive discriminant between quark-production models. Figures 7a-e show pK^- mass spectra near the $\Lambda(1520)$ mass peak. We expect the contamination of $\bar{p}$ in the K^- sample and K^+ in the p sample to be small, as for both particles the minimum

momentum is required to be 7 GeV. One observes (fig. 7f) a non-resonant background that progressively diminishes towards higher values of x . Such an effect is expected from combinatorics if the K^- and p are decay products, together with one or more pions, of high-mass hyperons. In terms of quark-fragmentation models and spectator-quark counting rules one would expect the pK^- continuum to behave in a way similar to the $\Lambda(1520)$. On the other hand, in the quark-recombination model the pK^- continuum can contain all three valence quarks of the incident proton, whereas the $\Lambda(1520)$ can have at most two. In this model one thus expects the non-resonance to resonance ratio to increase with increasing x . The data of fig. 7 clearly point in the opposite direction.

3.2 Production of $\phi(1020)$

The mass spectra for $\phi(1020) \rightarrow K^+K^-$ are shown in fig. 3 (all x) and fig. 8 (four x intervals). The data have been corrected for the variation of the acceptance with mass. The lines in fig. 8 represent a fit with a resonance on a linear background. In spite of the relatively high background at $x \gtrsim 0.7$, the statistical significance of the $\phi(1020)$ signal remains in excess of three standard deviations. The $\phi(1020)$ cross-section has been calculated assuming an isotropic decay angular distribution. From the present data we obtain $N^{-1} dN/d \cos \theta^* = 1 + (0.64 \pm 0.74) \times \cos^2 \theta^*$, in accordance with this assumption.

The invariant cross-sections at $p_T = 0.65$ GeV are shown in table 2 and are compared with other data, mostly at lower energies, in fig. 9. In each case an interpolation or extrapolation in p_T is necessary for this comparison, and in each case we use the p_T parametrization given by the authors.

The data of Daum et al. at $\sqrt{s} = 13.7$ GeV [13] and Akerlof et al. at $\sqrt{s} = 27.4$ GeV [14] agree quite well with an extrapolation from our measurements to lower x -values, and are thus compatible with scaling for $|x| > 0.05$. The data from Antipov et al. at $\sqrt{s} = 11.5$ GeV [15] cover the same x -range as the present experiment and further confirm scaling.

The data from Drijard et al. at $\sqrt{s} = 52.5$ GeV [16] and Åkesson et al. at $\sqrt{s} = 63$ GeV [17] lie a factor of two above our data and those of refs. [13, 14, 15]. In the case of ref. [16], the extrapolation from the p_T -value of the measurement, $p_T = 1.2$ GeV, is rather sensitive to the p_T parametrization.

In fig. 9 the data are compared with a prediction from a parton-fusion model, described by Donnachie and Landshoff [18], as parametrized by Daum et al. [13]. The model predicts scaling of the invariant cross-section and accounts well for most of the data. In this parametrization the x -dependence is determined by a nearly equal mixture of $q\bar{q}$ and gluon-gluon fusion.

A fit of our data to the form $A(1-x)^m$ yields $A = 26 \pm 5 \mu\text{b/GeV}^2$ and $m = 3.56 \pm 0.29$. This value for m is comparable to the value $m = 3.44 \pm 0.14$ obtained by Branson et al. [19] for $J/\psi(3100)$ production in $p\bar{p}$ collisions at $\sqrt{s} = 20.5$ GeV.

3.3 Production of $\bar{\Lambda}$ and $\bar{p}$

The $\bar{\Lambda}$ cross-sections have been derived from $\bar{\Lambda}/\Lambda$ ratios and the Λ cross-sections, as the ratios could be derived from a larger sample of data than that used for the determination of cross-sections. Implicitly we thus assume that $\bar{\Lambda}$ and Λ production have the same p_T -dependence. Particle identification by the Čerenkov counters was valuable for enhancing the $\bar{\Lambda}$ signal and was used for the $\bar{\Lambda}/\Lambda$ ratio determination. The $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ mass spectrum is shown in fig. 3.

The $\bar{\Lambda}$ and $\bar{p}$ x -distributions are displayed in table 2 and compared with other published data [20-25] in the ISR energy range in fig. 10. The $\bar{p}$ cross-section is known to rise with s in this energy range, and, where necessary, we have applied the parametrization of Guettler et al. [20]: $\sigma^{\text{inv}} \approx s^{0.306}$. All such corrections remain below 25%. For the p_T -dependence of the $\bar{p}$ data we used a p_T^2 slope $b = 3.04 \text{ GeV}^{-2}$, which is an average of data from various authors [20, 22, 23].

The $\bar{\Lambda}$ and $\bar{p}$ cross-sections can be parametrized in the form $\sigma^{\text{inv}} \approx (1-x)^m$, with similar values for m (see table 1). Both fall more steeply with x than the $\phi(1020)$ cross-section. The origin for this may be kinematics, as by baryon number conservation the antibaryons have to be produced in baryon-antibaryon pairs, with the antibaryon acquiring on the average only half of the kinetic energy of the pair.

4. INCLUSIVE PRODUCTION OF PARTICLE PAIRS

In this section we consider the inclusive production of pairs of particles, both fragments of the same proton, i.e. both produced at small angles ($< 2.5^\circ$) with respect to one of the circulating beams. Such data place further constraints on the different fragmentation models which have been advanced to explain inclusive single-particle data at high energies. The pairs considered are $\Lambda\pi$, ΛK , $\Delta^{++}(1232)\pi$, and $\pi\pi$.

The invariant masses accepted in the spectrometer aperture are small. The mass of the $\pi\pi$ -pairs, for example, remains below the ρ -mass. The data presented here have been evaluated in the form of particle-pair ratios only and generally are statistically inferior to the single-particle and resonance-production data. The transverse momentum of the particles detected in the spectrometer on the average increases with x and ISR energy. Since particle ratios are relatively insensitive to variations in p_T , we have ignored this variable.

For the continuum particle-pair data unique identification is required. Unambiguous π/K separation was obtained for meson momenta above 3-5 GeV, depending on the Čerenkov gases (FC114 or CO_2), for the particle pairs: $\Lambda\pi^\pm$, $\Lambda K^\pm$, $\Delta^{++}(1232)\pi^\pm$, $\pi^\pm\pi^\pm$, $\pi^+\pi^-$. In the case of kaon identification a possible contamination by protons or antiprotons was neglected. This contamination was expected to be small as one baryon is already present in the Λ . The Λ and $\Delta^{++}(1232)$ were identified by their mass peaks in $p\pi$ spectra. A subtraction of background is necessary. It is a minor problem for the Λ and introduces a larger uncertainty in the $\Delta\pi$ spectra. In total 2700 Λ -meson pairs, 1300 $\Delta\pi$ pairs, and 4000 $\pi\pi$ pairs have been analysed.

The $\pi\pi$ data have been taken at the highest ISR energy, $\sqrt{s} = 62.3$ GeV; the other data were also collected at two lower energies, $\sqrt{s} = 53$ and $\sqrt{s} = 45$ GeV. The x -dependence of the various ratios has been parametrized as $A(1-x)^m$. The results of these fits are summarized in table 3.

4.1 Production of $\Lambda\pi^\pm$, $\Lambda K^\pm$, and $\Delta^{++}(1232)\pi^\pm$ pairs

The $\Delta^{++}(1232)\pi$ and ΛK invariant-mass spectra reveal no outstanding features. The $\Lambda\pi^\pm$ mass spectra, uncorrected for spectrometer mass acceptance, are shown in fig. 11. The $\Lambda\pi^+$ spectrum is dominated by $\Sigma^+(1385)$ production. The $\Lambda\pi^-$ spectrum contains at most a weak $\Sigma^-(1385)$ signal. After a background subtraction with events around the Σ -peaks, one arrives at $R[\Sigma^-(1385)/\Sigma^+(1385)] = 0.07 \pm 0.05$ at $x = 0.73$. This value is compatible with earlier measurements [10, 26, 27] and is compared with those in fig. 12. A fit to the expression $(1-x)^m$ gives a value $m = 1.59 \pm 0.06$.

As in the production of the $\Lambda(1520)$ discussed above, the clarity with which the $\Sigma^+(1385)$ resonance peak stands out may be attributed to a reduction of the combinatorial background at high x and thus seems unrelated to quark-recombination arguments [12].

Figure 13 shows the x -distribution of the ratios $\Lambda K^+/\Lambda\pi^+$ and $\Lambda K^-/\Lambda\pi^-$. They are nearly equal at medium x . At high x the $\Lambda K^-/\Lambda\pi^-$ ratio decreases, whereas the $\Lambda K^+/\Lambda\pi^+$ ratio rises. Figure 14 shows the ratios $\Lambda\pi^-/\Lambda\pi^+$, $\Lambda K^-/\Lambda K^+$, and $\Delta^{++}(1232)\pi^+/\Delta^{++}(1232)\pi^-$. All these ratios drop to a small value near $x = 1$. Fits to the x -dependence with $(1-x)^m$ (which assumes that the ratios are equal at small x) yield values of m of the order of 1. These ratios thus indicate a preference for a net charge equal to +1 at high x .

Qualitatively, the x -dependence of these ratios may be interpreted in terms of either a single trajectory exchange model or a quark-recombination model. A single trajectory exchange model has been shown [3] to account well for $pp \rightarrow \pi^+X$, $pp \rightarrow \pi^-X$, and $pp \rightarrow K^+X$, and may thus apply to two-particle production in the same region of phase space ($x > \approx 0.7$, $\theta < 2.5^\circ$ with respect to the beam proton) as well. In the language of the recombination model, the production is determined by the number of quark pairs that must be produced minimally to account for the final-state particles (see table 4). In the exchange model, the x -dependence at low p_T is $\approx (1-x)^{1-2\alpha(0)}$. Either model is in qualitative agreement with the data in figs. 12, 13, and 14. For example, the x -dependence of both the $\Sigma^-(1385)/\Sigma^+(1385)$

ratio and of the $\Lambda\pi^-/\Lambda\pi^+$ continuum ratio reflects the effect of the 3 versus 2 $q\bar{q}$ pairs that must be produced. The $\Lambda K^+/\Lambda\pi^+$ ratio of fig. 13 also reflects the effect of an extra $q\bar{q}$ pair, while the $\Lambda K^-/\Lambda\pi^-$ is determined by the apparent difference in producing an $s\bar{s}$ versus a $d\bar{d}$ pair.

4.2 Production of $\pi\pi$ pairs

The data to be presented below are complementary to earlier results. Lockman et al. [28] have investigated pion pairs with higher invariant masses, whereas Suzuki et al. [29] have explored a complete mass spectrum, but with incomplete identification of the pions.

Figure 15 shows that the $\pi^-\pi^-/\pi^+\pi^+$ and $\pi^-\pi^-/\pi^+\pi^-$ ratios decrease approximately linearly with $x_{\pi\pi}$ while the $\pi^+\pi^-/\pi^+\pi^+$ ratio remains constant. This difference in x -dependence is consistent with the observation that in $\pi^+\pi^-$, as well as in $\pi^+\pi^+$, both pions can carry a valence quark, leaving one spectator valence quark, while in $\pi^-\pi^-$ there are ≥ 2 such spectators. Hence, the $\pi^+\pi^-/\pi^+\pi^+$ is expected to be independent of x , while the $\pi^-\pi^-/\pi^+\pi^+$ and $\pi^-\pi^-/\pi^+\pi^-$ ratios are expected to decrease in an identical manner as $x \rightarrow 1$, in agreement with the data of fig. 15. To investigate whether a connection with single-pion data can be made, we suppose that on average all pion momenta in the multipion event are equal. If $\pi^+\pi^+/\pi^+\pi^-/\pi^-\pi^- = 1/a/b$ we can then form a π^+/π^- ratio in two-pion events related to a and b by $R^{(2)}(\pi^+/\pi^-) = (2 + a)/(2b + a)$. A comparison between $R^{(2)}(\pi^+/\pi^-)$ and inclusive π^+/π^- ratio is shown in fig. 16, where $R^{(2)}(\pi^+/\pi^-)$ is plotted at the average value $x_{\pi} = x_{\pi\pi}/2$. One observes that both sets of data show a rise with x_{π} , the single-particle data being significantly higher. We tentatively conclude that there is substantial π^+ production not accompanied by π^- production in the same hemisphere.

5. CONCLUSIONS

The main results of this investigation are:

- i) The Λ and $\Lambda(1520)$ behave as "leading" proton fragments with a relatively flat x -distribution; the x -dependence for baryons with the same quark content depends on the particle mass and/or feed-down from higher mass states.

- ii) The production of $\Lambda(1520)$ at high x shows no spin alignment.
- iii) The ratio of the $\Lambda(1520)$ resonance to the continuum pK^- pairs around the $\Lambda(1520)$ mass increases with x , corresponding to a reduction of the combinatorial background and contrary to expectations from quark-production models.
- iv) The $\phi(1020)$ production cross-section agrees well with a parton-fusion model prediction fitting the data at lower energy. The data agree with scaling for $|x| > 0.05$ in the energy range $\sqrt{s} = 11.5-62.3$ GeV.
- v) Antilambda and antiproton production have a very similar x -dependence.
- vi) Data on $\Lambda\pi$, ΛK , $\Delta^{++}(1232)\pi$, and $\pi\pi$ production in the proton fragmentation region can be understood qualitatively in terms of single exchange models, or, equivalently, in terms of minimal $q\bar{q}$ production.

Acknowledgements

We would like to express our appreciation to the Physics Department of the University of Utrecht, where most of the equipment was constructed. We are grateful to the ISR Experimental Support, Vacuum, Operations, Power, and Survey Groups for extensive assistance. We thank P. Kooijman, J. Timmer and D. van Wezep for contributions to the early stages of the experiment. We have greatly appreciated the technical assistance of R. Bouhot. This work was supported by the Foundation for Fundamental Research on Matter, the Netherlands, the National Foundation for Scientific Research, Belgium, and a US Department of Energy grant.

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Table 1

Particle parameters

Particle	Decay mode	Mass (MeV)	Width FWHM (MeV)	Spectrometer resolution (MeV)	b (GeV ⁻²)	n	m
Λ	$\pi^- p$	1115.70 ± 0.10	-	2.0	3.13 ± 0.12	1.32 ± 0.05	0.93 ± 0.05
$\bar{\Lambda}$	$\pi^+ \bar{p}$	1114.9 ± 1.0	-	1.8	3.13 a)		7.50 ± 0.30
$\Lambda(1520)$	$K^- p$	1517.8 ± 1.0	16 ± 2	6.2	2.90 ± 0.27	0.92 ± 0.05	0.73 ± 0.05
$\phi(1020)$	$K^- K^+$	1019.8 ± 0.2	4.1 a)	4.8	3.2 a)		3.56 ± 0.29
$\bar{p}$					3.04 a)		7.78 ± 0.30

a) Input

Table 2

Invariant cross-sections $E(d^3\sigma/dp^3)$ in units of $\mu\text{b}\cdot\text{GeV}^{-2}$ for inclusive production in pp collisions at $\sqrt{s} = 62.3$ GeV, $p_T = 0.65$ GeV

P_L (GeV/c)	x	Λ	$\Lambda(1520)$	$\bar{\Lambda}$	$\bar{P}$	$\phi(1020)$
9.5	0.305	212.9 ± 20.5		10.88 ± 0.94		10.5 ± 2.3
10.5	0.337	224.7 ± 11.6		7.44 ± 0.67		
11.5	0.369	224.4 ± 8.8		5.52 ± 0.47		4.80 ± 0.47
12.5	0.401	210.7 ± 8.1		2.76 ± 0.29		
13.5	0.433	213.1 ± 6.4		2.02 ± 0.21		3.61 ± 0.70
14.5	0.465	229.3 ± 5.4		1.33 ± 0.17		
15.5	0.498	218.7 ± 5.1	58.0 ± 11.9	0.66 ± 0.12	1.24 ± 0.13	2.55 ± 0.49
16.5	0.530	211.4 ± 4.8	50.1 ± 8.6	0.43 ± 0.08	0.774 ± 0.091	
17.5	0.562	203.4 ± 4.9	43.4 ± 7.9	0.284 ± 0.059	0.554 ± 0.060	1.39 ± 0.23
18.5	0.594	201.3 ± 5.2	36.2 ± 6.8	0.140 ± 0.055	0.304 ± 0.060	
19.5	0.626	192.9 ± 4.7	40.3 ± 5.1	0.007 ± 0.034	0.188 ± 0.041	0.88 ± 0.17
20.5	0.658	188.7 ± 4.4	45.1 ± 4.9	0.019 ± 0.025	0.103 ± 0.033	
21.5	0.690	182.6 ± 4.9	50.6 ± 4.4		0.033 ± 0.020	0.19 ± 0.15
22.5	0.722	164.3 ± 4.7	49.2 ± 4.1	0.002 ± 0.010	0.011 ± 0.011	
23.5	0.754	139.4 ± 5.1	41.9 ± 3.7			0.33 ± 0.15
24.5	0.786	124.9 ± 4.4	38.4 ± 3.3	0.004 ± 0.025		
25.5	0.819	96.9 ± 4.4	35.8 ± 3.0			0.08 ± 0.11
26.5	0.851	76.7 ± 3.8	33.0 ± 2.5			
27.5	0.883	52.9 ± 3.5	28.8 ± 2.3			0.05 ± 0.07
28.5	0.915	32.5 ± 2.8	20.6 ± 2.0			
29.5	0.947	18.1 ± 2.0	14.3 ± 1.7			
30.5	0.979	4.5 ± 0.7	3.5 ± 0.7			

Table 3

Production ratios parametrized as $A(1-x)^m$

Ratio	A	m
$\Sigma^-(1385)/\Sigma^+(1385)$	1 a)	1.59 ± 0.06
$\Lambda\pi^-/\Lambda\pi^+$	1 a)	0.88 ± 0.13
$\Lambda K^-/\Lambda K^+$	1 a)	1.55 ± 0.18
$\Delta^{++}(1232)\pi^+/\Delta^{++}(1232)\pi^-$	1 a)	1.00 ± 0.16
$\pi^+\pi^-/\pi^+\pi^+$	3.05 ± 0.28	0.18 ± 0.09
$\pi^-\pi^-/\pi^+\pi^+$	0.47 ± 0.11	1.11 ± 0.25
$\pi^-\pi^-/\pi^+\pi^-$	0.155 ± 0.037	0.98 ± 0.26

a) Input

Table 4

Exchange and minimal $\bar{q}q$ production parameters

	Exchange	Trajectory intercept $\alpha(0)$	Minimal $\bar{q}q$ production
$p \rightarrow \Lambda K^+$	$P, f, \dots$	1	$(s\bar{s})$
$p \rightarrow \Lambda K^-$	Exotic	≤ -0.5	$(s\bar{s}) \times (s\bar{s}) \times (u\bar{u})$
$p \rightarrow \Lambda \pi^+$	K^0, K^{0*}	0.3	$(s\bar{s}) \times (d\bar{d})$
$\rightarrow \Sigma^+(1385)$	K^{0*}	0.3	
$p \rightarrow \Lambda \pi^-$	Exotic	≤ -0.5	$(s\bar{s}) \times (d\bar{d}) \times (u\bar{u})$
$\rightarrow \Sigma^-(1385)$	Exotic	≤ -0.5	
$p \rightarrow \Delta^{++} \pi^+$	Exotic	≤ -0.5	$(u\bar{u}) \times (u\bar{u}) \times (d\bar{d})$
$\rightarrow \Delta^{++} \pi^-$	$P, f, \dots$	1	$(u\bar{u})$

Figure captions

- Fig. 1 : Top and side views of one of the spectrometers. The two spectrometers are identical and are mounted above the downstream ISR vacuum pipes. A, B, D, E, and F are trigger scintillator counters; H1 and H2 are scintillator counter hodoscopes with 10 and 16 vertical strips, respectively; Č1, Č2, Č3 are atmospheric Čerenkov counters; and DC1-DC5 are modules of drift chambers with 24 planes in total. For part of the data taking an additional module with 6 planes was placed behind DC1. LUM indicates one of the luminosity counter telescopes.
- Fig. 2 : Pulse-height distribution in a typical trigger scintillator with the trigger hodoscopes H1 and H2 set to require two or more hits. The once and twice minimum ionizing peaks are clearly visible. The dashed line shows the pulse-height distribution (arbitrarily normalized) for off-line reconstructed two-track events. The lower peak, corresponding to a single particle traversing the counter, is removed from the trigger by applying pulse-height cuts on all trigger counters.
- Fig. 3 : Invariant mass spectra for $p\pi^-$, $\bar{p}\pi^+$, pK^- and K^+K^- at $\sqrt{s} = 62.3$ GeV. The pK^- and K^+K^- events are weighted by the relative acceptance, leaving the average number of events unchanged. The $\Lambda \rightarrow p\pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+$, $\Lambda(1520) \rightarrow pK^-$, and $\phi(1020) \rightarrow K^+K^-$ peaks are clearly visible.
- Fig. 4 : The slope parameter b , obtained from fitting σ^{inv} to the expression $A(x) \exp(-bp_T^2)$, versus x for the Λ and $\Lambda(1520)$ data.
- Fig. 5 : Invariant cross-sections of Λ and $\Lambda(1520)$ production at $\sqrt{s} = 62.3$ GeV and $p_T = 0.65$ GeV. The full lines represent fits to the expression $\sigma^{\text{inv}} = A(2E/\sqrt{s})(1-x)^n$. The dashed lines correspond to a calculation by Fisjak and Kistenev [11].
- Fig. 6 : $\Lambda(1520)$ decay angular distribution in c.m. frame with $\cos \theta^*$ measured with respect to the flight direction, at $\sqrt{s} = 62.3$ GeV. The curve $(- \cdot -)$ indicates an isotropic distribution and the curve $(- - -)$ the distribution $\frac{1}{2} + \frac{3}{2} \cos^2 \theta^*$.

- Fig. 7 : a)-e) Weighted mass distribution of pK^- events at various intervals of x . f) The non-resonant background diminishes with increasing x .
- Fig. 8 : Weighted mass distribution of K^+K^- events at four intervals of x . The line indicates the fitted resonance shape on a linear background.
- Fig. 9 : The invariant differential cross-section for $p + p \rightarrow \phi(1020) + X(O)$, at $\sqrt{s} = 62.3$ GeV and $p_T = 0.65$ GeV, compared with other data; (●) ref. [13] at $\sqrt{s} = 13.7$ GeV, (▼) ref. [14] at $\sqrt{s} = 27.4$ GeV, (x) ref. [16] at $\sqrt{s} = 52.5$ GeV, (□) ref. [17] at $\sqrt{s} = 63$ GeV, and (▽) ref. [15] at $\sqrt{s} = 11.5$ GeV. The data shown for comparison have been interpolated or extrapolated to $p_T = 0.65$ GeV with the p_T parametrization given by the authors. The data from refs. [14] and [15], taken with a Be target, have been converted to pp data via an $A^{2/3}$ factor. The line represents a parton-fusion model calculation [18, 13]. It coincides with the empirical fit $A(1-x)^m$ with $A = 26 \pm 5 \mu\text{b/GeV}^2$, $m = 3.56 \pm 0.29$.
- Fig. 10 : The invariant differential cross-section for $\bar{p}$ (○) and Λ (●) production at $\sqrt{s} = 62.3$ GeV and $p_T = 0.65$ GeV. The $\bar{p}$ data are compared with data from ref. [20] (▽), ref. [21] (Δ), ref. [22] (x), ref. [23] (+), and ref. [24] (□), and the $\bar{\Lambda}$ data with data from ref. [25] (■). The lines represent fits of the form $A(1-x)^m$.
- Fig. 11 : Mass spectra of $\Lambda\pi^+$ (—) and $\Lambda\pi^-$ (- - -) production at $\sqrt{s} = 45, 53, \text{ and } 62$ GeV, uncorrected for acceptance. The mean values of x are indicated.
- Fig. 12 : The ratio of the $\Sigma^-(1385)$ and $\Sigma^+(1385)$ production cross-sections. The data are from: ref. [26] at $\sqrt{s} = 6.9$ GeV (x), ref. 10 at $\sqrt{s} = 53$ and 62 GeV (Δ), ref. [27] at $\sqrt{s} = 19.5$ GeV (+), and this experiment at $\sqrt{s} = 45, 53, \text{ and } 62$ GeV (○). The line represents a fit of the form $(1-x)^m$.

- Fig. 13 : The x-distribution of the production ratios $\Lambda K^+/\Lambda \pi^+$ and $\Lambda K^-/\Lambda \pi^-$. The data at $\sqrt{s} = 45, 53$, and 62 GeV have been combined.
- Fig. 14 : The x-distributions of the production ratios $\Lambda \pi^-/\Lambda \pi^+$, $\Lambda K^-/\Lambda K^+$, $\Delta^{++}(1232)\pi^+/\Delta^{++}(1232)\pi^-$, at $\sqrt{s} = 45, 53$, and 62 GeV. The dashed lines represent fits of the form $(1-x)^m$.
- Fig. 15 : Ratios of two-pion production at low invariant mass at $\sqrt{s} = 62.3$ GeV versus x. The lines represent fits of the form $A(1-x)$.
- Fig. 16 : Ratios of single-pion production R in $pp \rightarrow \pi X$ at $\sqrt{s} = 44.7$ and 62.3 GeV compared with $R^{(2)}(\pi^+/\pi^-)$, deduced from $pp \rightarrow \pi\pi X$ at $\sqrt{s} = 62.3$ GeV as discussed in the text.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Two-pion ratios in $pp \rightarrow \pi\pi X$ at $\sqrt{s}=62.3$ GeV

Fig. 15

Fig. 16

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