Comparing fragmentation of strange quark in Z^0 decays and K^+p reactions

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The ratios of the production rates K^{*0}(892)/K, ϕ/K, ρ^0/π, ω/π, Δ^{++}(1232)/p, Σ^{*+}(1385)/Λ, Ξ^-/Λ and their x_p-dependence obtained from results of the LEP and SLD experiments in Z^0 hadronic decays are analyzed. The corresponding ratios for promptly produced mesons are estimated at $x_p \to 1$. A comparison of the LEP results with those from the Mirabelle and BEBC K^+p experiments at 32 and 70 GeV/c shows striking similarity in fragmentation of the $\bar{s}$ valence quark of the incident K$^+$ and strange quarks produced in Z^0 decays. The JETSET model describes the LEP, Mirabelle and BEBC results. The model of Pei is consistent with the data for mesons, but presumably underestimates the fractions of primary octet baryons. The quark combinatorics model of Anisovich et al. is incompatible with the data.

The vector and pseudoscalar mesons, or decuplet and octet baryons, differ in the relative orientation of the quark spins. Therefore the ratios of their production rates, V/P and D/O, provide us with important information on spin dependence in fragmentation. Hadronization models predict V/P and D/O for promptly produced particles, not resulting from decays of other particles or resonances. Therefore apart from the models based on Monte-Carlo generators, such as the JETSET model [1], these predictions are difficult to test experimentally.

In the nonrelativistic quark model, the mass difference of the vector and pseudoscalar mesons, decuplet and octet baryons is explained by the hyperfine mass splitting. The production rates exhibit a strong mass dependence. Therefore the vector-to-pseudoscalar and decuplet-to-octet suppressions could also be explained, at least qualitatively, by the hyperfine mass splitting [2,3] provided that the rates of promptly produced particles were reliably estimated.

The simplest spin model of fragmentation, such as the model suggested in [4] and subsequently developed by Anisovich and his collaborators in many other papers, is a random combination of quark spin states giving $V/P = 3$ and $D/O = 2$. Recently Anisovich et al. [5] compared these predictions with

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the LEP data. They analyzed the V/P ratios obtained from the ALEPH data [6] at large $x_p = p/p_{beam} \to 1$, where a contribution of the resonance decays is supposed to be strongly suppressed, and concluded that the experimental results are consistent with $V/P = 3$. This conclusion is in contradiction with the results obtained in [2,3]. Besides, the LEP results on hadron production, in general, and ALEPH results [6], in particular, agree well with the JETSET model [1]. In JETSET, the probability to produce a vector meson is controlled by the parameter $V/(V + P)$. This parameter pertaining to mesons directly produced in hadronization is much smaller than 0.75, the value expected from the quark-combinatorics prediction.

In order to resolve these problems and to get better insight into the nature of the vector-to-pseudoscalar and decuplet-to-octet suppressions we investigate in this paper the ratios of the production rates [2] $\mathrm{K}^*(892)/\mathrm{K}$, ϕ/K, ρ^0/π, ω/π, $\Delta^{++}(1232)/\mathrm{p}$, $\Sigma^*(1385)/\Lambda$ and Ξ^-/Λ obtained from results of the LEP [6-17] and SLD [18] experiments. We estimate the values of these ratios for promptly produced hadrons by studying their x_p-dependence and comparing the fragmentation of strange quark in Z^0 decays and K^+p reactions. Indeed, a relatively strong suppression of multi-strange final states in kaon induced reactions at moderate energies offers good possibilities to trace the flow of the incident strange valence flavour among the reaction debris. The K^0, $\mathrm{K}^{*0}(892)$, ϕ, $\bar{\Lambda}$, $\overline{\Sigma^*}(1385)$ and $\overline{\Xi^-}$ in the Mirabelle [19-24] and BEBC [25-27] K^+p experiments at 32 and 70 GeV/c are dominantly produced on the $\bar{s}$ valence quark of the incident K^+. This is clearly seen from their Feynman-x_F spectra exhibiting a prominent leading particle effect and, consequently, from a relatively small production of these particles in the central region. This allows to obtain the reliable estimates of V/P and D/O ratios for promptly produced hadrons. Therefore an interesting and sensible test of the LEP results, as well as model predictions, on V/P and D/O ratios for promptly produced hadrons is feasible with kaon beams.

In studying the ratios $\mathrm{K}^*(892)/\mathrm{K}$, ϕ/K, ρ^0/π, ω/π, $\Delta^{++}(1232)/\mathrm{p}$, $\Sigma^*(1385)/\Lambda$ and Ξ^-/Λ, the differential cross-sections, $1/\sigma_h \cdot d\sigma/dx_p$, for the resonances and Ξ^- were taken from the LEP experiments [6-17]. In some of them, the inclusive spectra have been presented as a function of $x_E = E/E_{beam}$. The difference between x_p and x_E, important only at very small values of x_p and x_E, was ignored. The differential cross-sections for the K, π, p or Λ in the same x_p-intervals were taken either from the same experiments or from combined x_p-spectra of corresponding particles measured by ALEPH [6], DELPHI [10], OPAL [12] and SLD [18] and compiled in [28]. These spectra were fitted by a sum of two exponentials, and cross-sections in the corresponding x_p-intervals were calculated using the results of these fits. Such combined x_p-spectra for

[2] Apart from Fig. 1, the charge conjugates and antiparticles are not included into definition of the rates in this paper.

the K$^{\pm}$ and $\pi^{\pm}$ with the results of their fits by exponentials are illustrated, for example, in Fig. 1.

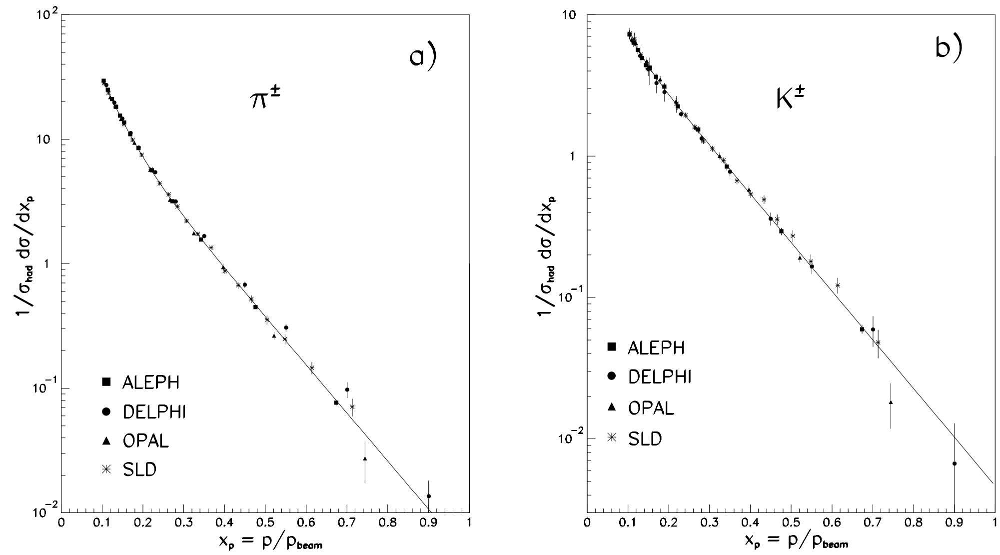

Fig. 1. The $\pi^{\pm}$ (a) and K$^{\pm}$ (b) differential cross-sections, $1/\sigma_h \cdot d\sigma/dx_p$, for $x_p > 0.1$ measured by ALEPH, DELPHI, OPAL and SLD. The *curves* are the results of the fit by a sum of two exponentials.

The K^{*0}(892)/(3K$^+$) ratios as a function of x_p are presented in Fig. 2a. The K^{*0}(892) differential cross-sections were taken from the ALEPH [6], DELPHI [9] and OPAL [14] experiments. The results of three LEP experiments are well consistent. The K^{*0}(892)/(3K$^+$) ratio increases with x_p, presumably approaching the value for the promptly produced mesons at $x_p \to 1$. The ratios K$^{*0}(892)_{prompt}/(3K^0_{prompt}) = 0.33 \pm 0.06$ and 0.28 ± 0.04 for the promptly produced mesons measured in the Mirabelle [19] and BEBC [25] K^+p bubble chamber experiments at 32 and respectively 70 GeV/c are also shown in Fig. 2a [3]. They are in excellent agreement with a trend of the LEP data for $x_p \to 1$. They are also well consistent with the predictions of the JETSET [1] [4] and Pei [29] models for the promptly produced mesons at LEP also shown in Fig. 2a. On the other hand, and contrary to conclusion of ref. [5] based on the same analysis of the ALEPH data, the quark-combinatorics prediction, K*(892)/(3K) = 1, for the promptly produced mesons is ruled out by the LEP, Mirabelle and BEBC data. The experimental values at the largest x_p are a factor of 3 lower than the prediction and deviate from it by at least 11 standard deviations.

[3] The BEBC value was corrected for the $\bar{K}^0$ production cross-section [26] not accounted for in [25].

[4] Here and below the JETSET 7.4 predictions for the total rates given in [6] were used. The fractions of the directly produced particles in JETSET were taken from [29].

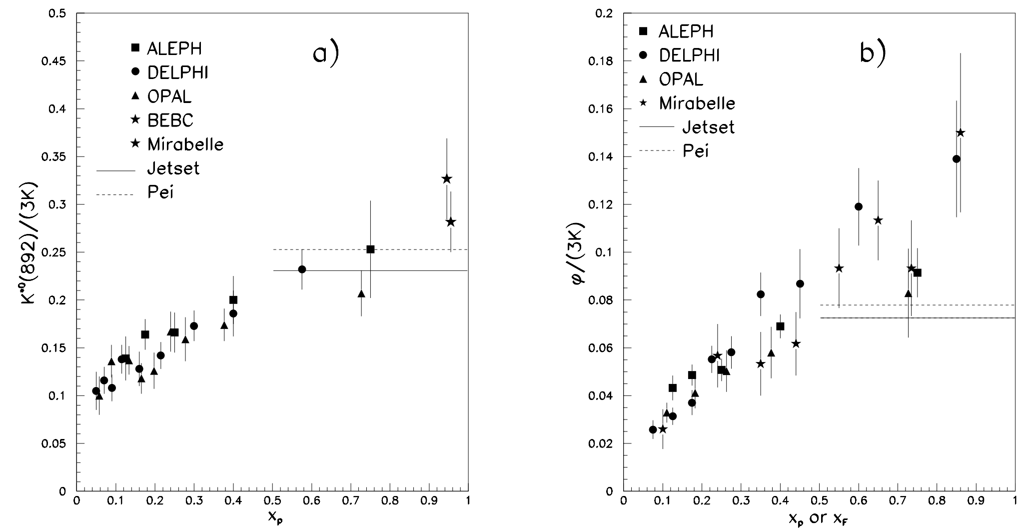

Fig. 2. The $K^{*0}(892)/(3K^+)$ (a) and $\phi/(3K^+)$ (b) ratios obtained from the LEP experiments as a function of x_p ; the $K^{*0}(892)/(3K^0)$ ratios for the promptly produced particles from the Mirabelle and BEBC K^+p experiments at 32 and 70 GeV/c (a); the $\phi/(3K^0_s)$ ratio as a function of Feynman-x_F from Mirabelle (b). The JETSET and Pei model predictions for the promptly produced particles at LEP are also shown. The quark-combinatorics model predicts $K^*(892)/(3K) = 1$ and $\phi/(3K) = \lambda$. Here and in the subsequent figures, some data points were slightly shifted to avoid overlap.

The $\phi/(3K^+)$ ratios, with the ϕ differential cross-sections measured by ALEPH [6], DELPHI [9] and OPAL [16], are presented as a function of x_p in Fig. 2b. The data from three LEP experiments are consistent within errors and exhibit a clear rise with increasing x_p, very similar to the behaviour seen in Fig. 2a. The ϕ/K^0_s ratio as a function of Feynman variable $x_F = p_L/(\sqrt{s}/2)$, where p_L is the longitudinal momentum in the centre-of-mass system, from Mirabelle [20] is also presented in Fig. 2b for $x_F > 0$. It is strikingly similar to the behaviour of the LEP data. The JETSET and Pei model predictions are somewhat lower than the experimental data at large x_p, but consistent with them within one-two errors. The quark-combinatorics model [4,5] predicts $\phi/(3K) = \lambda$, where λ is the strangeness suppression parameter. For usually accepted value $\lambda \approx 0.3$, this prediction is a factor of more than two higher than the experimental values at large x_p. It deviates from the DELPHI value of 0.14 ± 0.02 at $x_p = 0.85$ by 7 standard deviations or even more for $\lambda \approx 0.5$ suggested in [5].

The $\rho^0/(3\pi^+)$ ratios, with the ρ^0 differential cross-sections measured by ALEPH [6] and DELPHI [11], are presented as a function of x_p in Fig. 3. The results of these experiments are consistent within errors for $x_p < 0.5$. For $x_p > 0.5$, the ALEPH data point is significantly higher than the DELPHI data points. The $\omega/(3\pi)$ ratios measured by ALEPH [6] and OPAL [17] are also presented in Fig. 3. They are consistent with the $\rho^0/(3\pi^+)$ ratios for $x_p < 0.5$. For $x_p > 0.5$, the ratio $\omega/(3\pi^0)$ measured by ALEPH is close to the $\rho^0/(3\pi^+)$ ratio measured by DELPHI. The $\rho^0/(3\pi^-)$ ratio as a function of Feynman-x_F taken from the

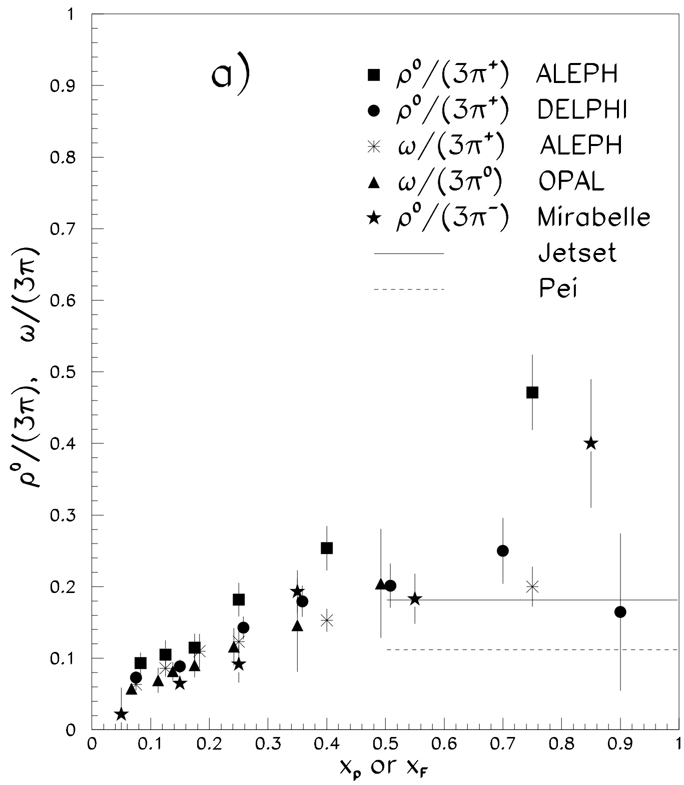

Fig. 3. The $\rho^0/(3\pi^+)$, $\omega/(3\pi^+)$ and $\omega/(3\pi^0)$ ratios obtained from the LEP experiments as a function of x_p, together with the $\rho^0/(3\pi^-)$ ratio from the Mirabelle K^+p experiment at 32 GeV/c as a function of Feynman-x_F. The $\rho^0/(3\pi^+)$ ratios for the promptly mesons at LEP predicted by the JETSET and Pei models are also shown. The quark-combinatorics model predicts $\rho^0/(3\pi) = 1$.

Mirabelle experiment [20] (and convoluted around $x_F = 0$) is also presented in Fig. 3. It is well consistent with the LEP results for $x_p < 0.7$ and lies between the ALEPH and DELPHI data points at $x_p = 0.7$-1.0. Thus, in spite of some inconsistency of the LEP results at the largest x_p, the general tendency of the LEP and Mirabelle data in Fig. 3 is quite similar to the one observed in Fig. 2. However, in this case the JETSET and especially Pei model predictions for the ratios of promptly produced mesons at LEP appear to be underestimated. The quark-combinatorics prediction, $\rho^0/(3\pi) = 1$, is not consistent with the data, contrary to conclusion of ref. [5] based on the same analysis of the ALEPH data. It is again a factor of 2 to 5 higher than the experimental values at large x_p. The values $\rho^0/(3\pi^+) = 0.250 \pm 0.046$ at $x_p = 0.6$-0.8 [11] and 0.47 ± 0.05 at $x_p = 0.5$-1.0 [6] deviate from this prediction by 16 and respectively 11 standard deviations.

In principle, the experimental values of the vector-to-pseudoscalar ratios in the fragmentation region at $x_p \to 1$ could be reconciled with the quark combinatorics predictions in case of strong spin alignment of vector mesons, since in this case the expected value would be $V/P = 1$. The spin density matrix elements for the ρ^0, $\rho^\pm$, ω, ϕ and K^{*0}(892) have been measured by DELPHI [30] and OPAL [31-33] (a summary of the results can be found in [33]). The helicity density matrix elements ρ_{00} of the ρ^0, $\rho^\pm$ and ω are found compatible, over the entire x_p range, with 1/3 corresponding to a statistical mix of helicity -1, 0 and +1 states, with no evidence for spin alignment. For the K^{*0}(892) and ϕ produced in the small x_p region $x_p \leq 0.3$, the values of $\rho_{00}(\mathrm{K}^{*0}) = 0.33 \pm 0.05$ and $\rho_{00}(\phi) = 0.30 \pm 0.04$ [30] are also well consistent with no spin alignment. For the ϕ produced in the high $x_p \geq 0.7$ region, some indication on unequal population in the three helicity states is observed, with $\rho_{00} = 0.55 \pm 0.10$ [30] and 0.54 ± 0.08 [31]. For the K^{*0}, DELPHI [30] measured $\rho_{00} = 0.46 \pm 0.08$ at $x_p \geq 0.4$ and OPAL [32] obtained $\rho_{00} = 0.66 \pm 0.11$ at $x_p \geq 0.7$. It is interesting that the LEP results on the K^{*0} spin alignment are again very similar to the results of the Mirabelle K^+p experiment [34]. Thus in spite of some preference for occupation of the helicity zero state observed for the K^{*0} and ϕ at large x_p, this can not explain the failure of the quark combinatorics model.

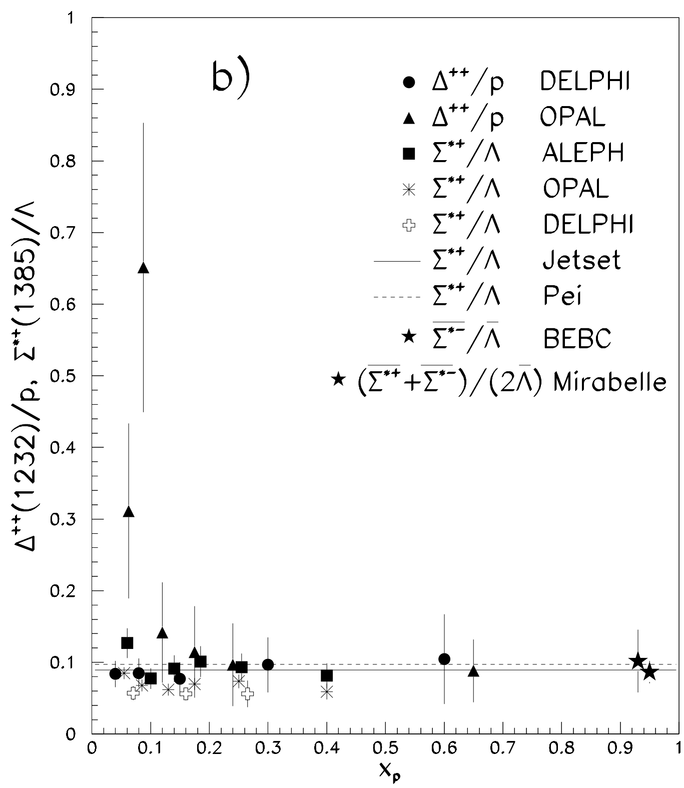

Fig. 4. The Δ^{++}(1232)/p and Σ^{*+}(1385)/Λ ratios as a function of x_p obtained from the LEP experiments and the Σ^{*+}(1385)/Λ ratios predicted by the JETSET and Pei models for the total rates at LEP. The ratios of the total rates $(\overline{\Sigma^{*+}} + \overline{\Sigma^{*-}})/(2\bar{\Lambda})$ from Mirabelle and $\overline{\Sigma^{*-}}/\bar{\Lambda}$ from BEBC are also shown.

The kinematics of the decuplet baryon decays does not allow to obtain information about ratios of promptly produced decuplet and octet baryons at large x_p as have been possible for mesons. Still a study of x_p-dependence of the decuplet-to-octet ratios allows to make several important observations. The $\Delta^{++}(1232)/\mathrm{p}$ ratio as a function of x_p is presented in Fig. 4. The $\Delta^{++}(1232)$ differential cross-section was measured by DELPHI [8] and OPAL [13]. The x_p-dependence of the $\Delta^{++}(1232)/\mathrm{p}$ ratio obtained from the DELPHI measurements is essentially flat, as expected. The OPAL results are well consistent with those of the DELPHI for $x_p > 0.1$, but show quite unexpected behaviour at the smallest x_p. The discrepancy in the $\Delta^{++}(1232)$ total rate in two experiments is obviously due to those suspicious OPAL data points at the smallest x_p, where the extraction of the $\Delta^{++}(1232)$ signal is the most difficult. This is supported by comparison of x_p-dependences for the $\Delta^{++}(1232)/\mathrm{p}$ and $\Sigma^{*+}(1385)/\Lambda$. The latter is also presented in Fig. 4. The data for the $\Sigma^{*+}(1385)$ were taken from ALEPH [6], DELPHI [7] and OPAL [15]. The $\Sigma^{*+}(1385)/\Lambda$ ratio as a function of x_p is essentially flat. This behaviour is very similar to the one observed for the $\Delta^{++}(1232)/\mathrm{p}$ ratio by DELPHI in all x_p range and by OPAL for $x_p > 0.1$. The ratios of the total rates

$$(\overline{\Sigma^{*+}} + \overline{\Sigma^{*-}})/(2\bar{\Lambda}) = 0.086 \pm 0.016, \quad \overline{\Sigma^{*-}}/\bar{\Lambda} \ = 0.102 \pm 0.044 \qquad (1)$$

obtained respectively from Mirabelle [21,22] and BEBC [27] (and also shown in Fig. 4) agree very well with the LEP results for the Σ^{*+}/Λ and DELPHI results for the Δ^{++}/p. The JETSET and Pei model predictions for the ratio Σ^{*+}/Λ of total rates at LEP are also indicated in Fig. 4. They are well consistent with the LEP, Mirabelle and BEBC data.

Finally we compared the ratios Ξ^-/Λ obtained from the LEP [6,7,15], Mirabelle [22,23] and BEBC [27] experiments. With the Ξ^- and Λ total rates averaged over results of all LEP experiments [2], one gets $(\Xi^-/\Lambda)_{tot} = 0.072 \pm 0.004$. From the $\overline{\Xi^-}$ [23] and $\bar{\Lambda}$ [22] total rates in Mirabelle, one obtains $(\overline{\Xi^-}/\bar{\Lambda})_{tot} = 0.086 \pm 0.021$, in good agreement with the LEP value. The corresponding value, 0.14 ± 0.04, from BEBC [27] is consistent within errors with the LEP and Mirabelle results. The JETSET and Pei model predictions for the ratio of the total rates at LEP, 0.090 and 0.072, respectively, are in good agreement with the LEP, Mirabelle and BEBC results.

In view of good agreement between the LEP and bubble chamber experiments on the ratios Σ^{*+}/Λ and Ξ^-/Λ of the total rates, it is reasonable to assume that the corresponding ratios for the promptly produced baryons in these experiments might also be the same. The $\overline{\Sigma^{*+}}$, $\overline{\Sigma^{*-}}$ and $\overline{\Xi^-}$ in the Mirabelle K^+p experiment at 32 GeV/c can presumably be safely considered as promptly produced. Indeed, even at LEP, the fractions of promptly produced Σ^{*+} and Ξ^- equal 0.92 and 0.75 in the JETSET, and 0.91 and 0.41 in the Pei models. The cross-section of the promptly produced $\bar{\Lambda}$ in Mirabelle can be estimated from the $\bar{\Lambda}$ total rate [22] after subtraction of $\bar{\Lambda}$ from the $\overline{\Sigma^{*+}}$, $\overline{\Sigma^{*-}}$ and $\overline{\Sigma^{*0}}$

decays [5] and small fraction of the centrally produced $\bar{\Lambda}$ [24]. This gives

$$[\overline{\Xi^-}/(\bar{\Lambda}+\overline{\Sigma^0})]_{prompt} = 0.14 \pm 0.04, \quad [(\overline{\Sigma^{*-}}+\overline{\Sigma^{*+}})/2(\bar{\Lambda}+\overline{\Sigma^0})]_{prompt} = 0.14 \pm 0.03 \quad (2)$$

where we took into account that one can not separate the prompt $\bar{\Lambda}$ and $\overline{\Sigma^0}$. The JETSET and Pei models predict $[\Xi^-/(\Lambda+\Sigma^0)]_{prompt} = 0.11$ and 0.14, respectively, in good agreement with the Mirabelle result. For the $[\Sigma^{*+}/(\Lambda+\Sigma^0)]_{prompt}$, the same models predict 0.13 and 0.41, respectively. The JETSET estimate is in good agreement with the Mirabelle result. The Pei model prediction is significantly higher, since the fractions of primary produced Λ and Σ^0 are smaller in this model than in JETSET by the factors of 3.7 and 2.2, respectively. Notice that good agreement of the Pei model with the Mirabelle result for the $[\Xi^-/(\Lambda+\Sigma^0)]_{prompt}$ and disagreement for the $[\Sigma^{*+}/(\Lambda+\Sigma^0)]_{prompt}$ is not contradictory, since the fraction of the promptly produced Ξ^- in this model is also smaller by a factor of 1.8 than in JETSET. One can also notice that the Pei model predicts essentially the same ratios Σ^{*+}/Λ and Δ^{++}/p for the promptly produced baryons. Therefore if the Mirabelle result for the $[\Sigma^{*+}/(\Lambda+\Sigma^0)]_{prompt}$ ratio is not biased and indeed represents a good estimate of the corresponding ratio at LEP, as indicated by all results of this paper, this implies that the fractions of promptly produced octet baryons in the Pei model might be underestimated. The quark-combinatorics [4] predicts $[\Xi^-/(\Lambda+\Sigma^0)]_{prompt} = \lambda/2$ and $[\Sigma^{*+}/(\Lambda+\Sigma^0)]_{prompt} = 1$. The former just tests the strangeness suppression factor and agrees with the usually accepted $\lambda \approx 0.3$. The latter is a factor of 7 higher than the Mirabelle value and deviates from it by 29 standard deviations.

In conclusion, we have shown that a study of the vector-to-pseudoscalar ratios at LEP as a function of x_p allows to obtain estimates of these ratios for promptly produced mesons at $x_p \to 1$. These estimates, as well as the $\overline{\Xi^-}/(\bar{\Lambda}+\overline{\Sigma^0})$ and $(\overline{\Sigma^{*-}}+\overline{\Sigma^{*+}})/2(\bar{\Lambda}+\overline{\Sigma^0})$ ratios for the total rates, have been found in very good agreement with the results of the Mirabelle and BEBC K^+p experiments. This shows that the fragmentation properties of the $\bar{s}$ valence quark of the incident kaon and strange quarks produced in e^+e^- annihilation are very similar. In fact, this interesting experimental observation is not unexpected. In the Lund String model [35] (implemented in the JETSET 7.4 generator), quark-antiquark pair in an $e^+e^- \to q\bar{q}$ event is produced in a colour force field stretched between the q and the $\bar{q}$. The hadron production is viewed as a breaking of the string which can be interpreted as virtual $q\bar{q}$ pair production in a colour flux-tube. A soft hadronic collision is also considered in this model as a colour separation mechanism whereby valence quarks of incident meson act as borders of colour strings, analogous to the $q-\bar{q}$ field in e^+e^- annihilation. Therefore it is not surprising that many features in fragmentation of the

[5] Assuming that the $\overline{\Sigma^{*0}}$ cross-section is equal to the averaged value of the $\overline{\Sigma^{*+}}$ and $\overline{\Sigma^{*-}}$ cross-sections.

$\bar{s}$ valence quark of the incident K^+ and strange quarks in e^+e^- annihilation must be similar. Other fragmentation models for soft, low-p_T hadron-hadron interactions such as the Dual Sheet models based on the Dual Topological Unitarization (DTU) (see [36], for example) differ from the Lund model in their prescriptions for the number and topology of colour strings and in the role attributed to valence quarks (as discussed, for example, in [19,25]). Therefore, a comparison of meson induced reactions with e^+e^- data might allow to get better understanding of the fate of meson valence quarks and to discriminate among different approaches.

The predictions of the JETSET model have been found in good agreement with the results of the LEP and K^+p experiments on the vector-to-pseudoscalar ratios for the promptly produced mesons as well as with the $\overline{\Xi^-}/(\bar{\Lambda}+\overline{\Sigma^0})$ and $(\overline{\Sigma^{*-}}+\overline{\Sigma^{*+}})/2(\bar{\Lambda}+\overline{\Sigma^0})$ ratios for the total and direct rates. The Pei model predictions are also in reasonable agreement with the data, apart from the ρ^0/π ratio and significant disagreement with the Mirabelle result on the $(\overline{\Sigma^{*-}}+\overline{\Sigma^{*+}})/2(\bar{\Lambda}+\overline{\Sigma^0})$ ratio for the direct rates. This indicates that the Pei prediction about significantly smaller fraction of promptly produced octet baryons in comparison with JETSET might be too strong. The simplest spin models of fragmentation based on spin counting and, in particular, the quark-combinatorics model of Anisovich et al. are incompatible with the results of the LEP and K^+p experiments.

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