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PRODUCTION OF STRANGE PARTICLES IN THE HADRONIC DECAYS OF THE Z^0

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Abstract

A review of the experimental data on the production of strange particles from e^+e^- annihilations at the Z^0 peak is presented. The constraints to the models obtained from the experimental data are discussed, with emphasis on the information related to the nonperturbative regime of the generation of multihadronic final states.

1 Introduction

After more than three years of operation of the LEP e^+e^- collider at CERN, about four million decays of the Z^0 boson have been recorded by the four experiments ALEPH, DELPHI, OPAL and L3. This huge yield of experimental data allowed extensive tests of the models for multihadron production.

According to the present view of the process, the e^+e^- annihilation in a multihadronic final state at the Z^0 energy can be schematized into 4 phases:

1 In a first phase, the e^+e^- pair, after conversion into a virtual photon or a Z^0, goes into a $q\bar{q}$ pair. The amplitudes of these decays are predicted by the electroweak theory within 2% (the uncertainty is related to the contribution of loops involving the top quark).

2 In a second phase, the primary partons radiate gluons, that in turn can radiate or convert into a $q\bar{q}$ pair, giving rise to a parton cascade. It is generally believed that perturbative QCD can describe quantitatively this phase, although most of the calculations are done only to the second order. Two choices are thus open to describe this phase:

- either to make approximations on the branching probabilities in the cascade, and to follow it down to high orders (the Parton Shower, PS, approach);
- or to use the matrix elements of the strong interaction up to the order (second at present) to which they have been calculated (the Matrix Element, ME, approach). In this second choice, one will have a maximum of four partons at the end of the cascade.

3 In a third phase (hadronization), the partons *hadronize*, i.e., they interact among them and excite the vacuum in order to dress themselves as hadrons.
Two models are commonly used for the description of this phase:

- In the string model [1], fragmentation is described as follows. As the quark and the antiquark come apart, a colour string is stretched between them. A fixed amount of energy per unit length is associated to the string, $k \simeq 1$ GeV/fm ($\simeq 0.2$ GeV^2). As the potential energy stored in the string increases, the string itself may break by the production of a quark-antiquark (or of a diquark-antidiquark) pair, the mass of which

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comes from that potential energy. The creation of a pair from the vacuum is thought to be the result of a tunnelling process. If μ is the quark (diquark) mass, the probability P of exciting a pair is approximately

$$P \propto e^{-\pi\mu^2/k} . \tag{1}$$

As a result, for example, the creation of a $c\bar{c}$ pair is suppressed by a factor $\simeq 10^{-10}$ with respect to the creation of a $u\bar{u}$ pair.
Fragmentation is very poorly known, and the fraction of longitudinal momentum carried by the colour singlets formed during the breakage of the string is described by phenomenological distributions (with some theoretical constraints) called *fragmentation functions*.
The string model is mostly used in its implementation JETSET [2].

- In the cluster model, an attempt is made to give a simpler description of the creation of hadrons.
Cluster models generate parton showers according to leading-log perturbative QCD, and pre-confine quarks and diquarks into colour singlets, called clusters. The creation of a cluster happens at a certain mass (virtuality) cut-off; clusters decay according to phase-space kinematics.
In principle, cluster fragmentation requires less free parameters than string fragmentation. Apart from the quarks and diquarks masses, the cluster decay is defined once the QCD scale Λ_{QCD} and the cutoff for cluster generation (with possibly a spread) are fixed. In the most popular cluster fragmentation models, Webber [3] and Caltech [4], more free parameters are introduced to account for massive cluster decays.
The cluster model is mostly used in its implementation HERWIG [5].

4 In the fourth phase, unstable hadrons decay.

Besides the decays of heavier particles, strange particles can be produced:

1 in the hadronization of a strange leading (di)quark;

2 in the hadronization of a (di)quark produced during the fragmentation.

The study of strange particles is especially interesting related to point 2. Besides the u and d quarks, practically indistinguishable because of the degeneration of their masses, the s seems to be the only quark to which one can access to understand the mechanisms of vacuum excitation.

By using Eq. (1), one obtains that the creation of a $s\bar{s}$ pair should be suppressed with respect to the creation of a $u\bar{u}$ by a factor

$$P(s)/P(u) = e^{-\pi(m_s^2-m_u^2)/k} \equiv \gamma_s/\gamma_u \tag{2}$$

and the creation of a strange diquark should be suppressed with respect to the creation of a nonstrange one by a factor

$$P(sd)/P(ud) = e^{-2\pi m_u(m_s-m_d)} \equiv \delta \times \gamma_s/\gamma_u . \tag{3}$$

By folding the quark masses derived from spectroscopy into (2) and (3), one obtains $\gamma_s/\gamma_u \simeq 0.3$, $\delta \simeq 0.5$ (and the measurements at PEP/PETRA and ARGUS indicate $\gamma_s/\gamma_u = 0.34 \pm 0.02$, $\delta = 0.43 \pm 0.16$, see [6] for a review).

Finally, the study of strange particles can be a useful tool for investigating the mechanisms of baryon production. The compensation of strangeness gives a handle to extract clean information on baryon correlations.

2 Results on Strange Particles

Strange particles are detected:

a. by using the capabilities of particle identification of the detectors (ionization, Cherenkov Counters, Time of Flight techniques) if charged;
b. by reconstructing secondary decays. The lifetimes of strange particles decaying weakly are two orders of magnitude larger than the lifetimes of B hadrons, on which the detector resolutions are tuned.

Up to now, Mark II at SLC and DELPHI, OPAL and ALEPH at LEP have analyzed data (for a total of about one million of events) related to the production of strange particles in multihadronic final states. Results are available on the production of the K^0, K^+, K^{*0}, K^{*+}, ϕ mesons, and of the $\Lambda, \Sigma(1385)^{\pm}, \Xi^-, \Omega^-, \Xi(1530)^0$ baryons.

- K^0 is detected in the decay mode $K^0_S \to \pi^+\pi^-$ (BR $\simeq$ 69%), and Λ in the decay mode $\Lambda \to p\pi^-$ (BR $\simeq$ 64%). Both decays give in general, due to the long lifetimes, secondary vertices well separated from the primary one. The reciprocal reflection can be cancelled by the different kinematics of the decays.
  The results on the differential cross sections of K^0 and Λ are summarized in Fig. 1, and compared with the predictions of HERWIG and JETSET. The tuning of JETSET PS is described in the next section.

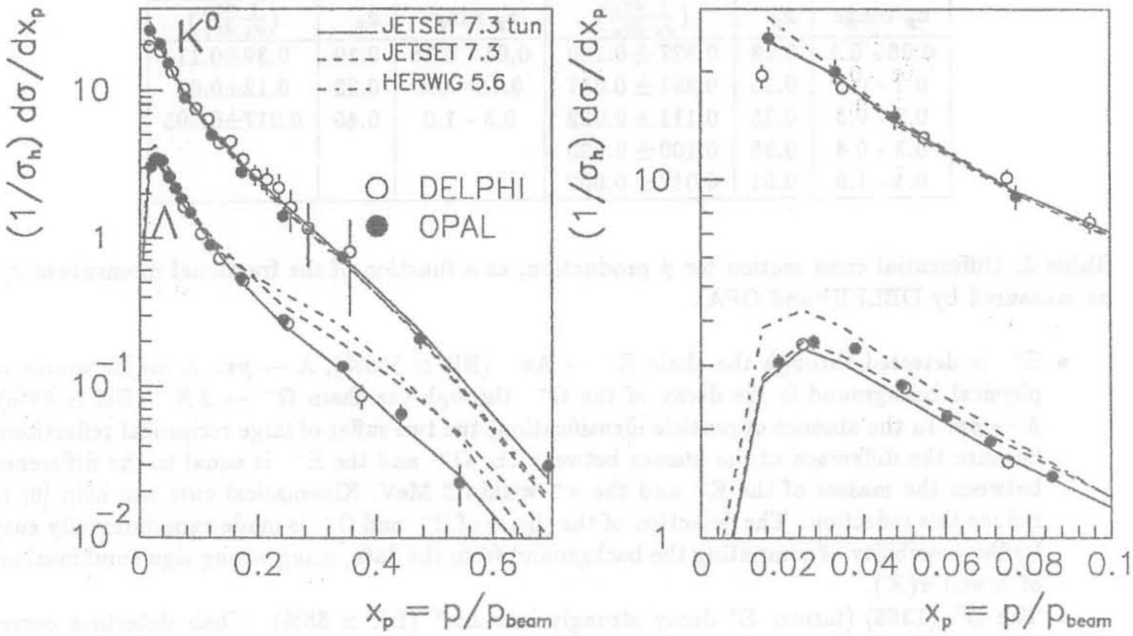

Figure 1: Left: Differential cross section of K^0 and Λ as measured by DELPHI and OPAL. Right: Blow-up at small x.

- K^{*+} is detected in the decay mode $K^{*+} \to K^0\pi^+$ (BR $\simeq$ 67%), and K^{*0} in the decay mode $K^{*0} \to K^+\pi^-$ (BR $\simeq$ 67%). These are strong decays, consistent with coming from the primary vertex. The estimate of the combinatorial background in the invariant mass plots requires modelling via simulation.
  The results on the differential cross sections of K^* and ϕ are summarized in Fig. 2, and in Tables 1 and 2.

K^{*0} OPAL			K^{*0} DELPHI			K^{*+} OPAL		
x_p range	$\bar{x}_p$	$(\frac{1}{\sigma_h}\frac{d\sigma}{dx_p})$	x_p range	$\bar{x}_p$	$(\frac{1}{\sigma_h}\frac{d\sigma}{dx_p})$	x_p range	$\bar{x}_p$	$(\frac{1}{\sigma_h}\frac{d\sigma}{dx_p})$
0.05 - 0.025	0.017	6.71 ± 0.93	0.05 - 0.1	0.075	5.6±2.0	0.00 - 0.061	0.031	6.9±1.3
0.025 - 0.1	0.069	4.00 ± 0.85	0.1 - 0.15	0.125	1.9±0.9	0.061 - 0.088	0.073	3.2±0.7
0.1 - 0.15	0.12	2.14 ± 0.42	0.15 - 0.2	0.175	1.5±0.8	0.088 - 0.132	0.108	2.3±0.6
0.15 - 0.3	0.21	0.95 ± 0.14	0.2 - 0.3	0.25	1.0±0.6	0.132 - 0.177	0.154	1.7±0.4
0.3 - 1.0	0.45	0.10 ± 0.02	0.3 - 0.4	0.35	0.57 ± 0.38	0.177 - 0.275	0.221	0.89 ± 0.23
			0.4 - 0.6	0.48	0.14±0.10	0.275 - 0.879	0.417	0.11 ± 0.03
			0.6 - 0.8	0.66	0.035± 0.018			

Table 1: Differential cross section for K^{*+} and K^{*0} production, as a function of the fractional momentum x_p, as measured by DELPHI and OPAL.

- ϕ is detected in the decay mode $\phi \to K^+K^-$ (BR $\simeq$ 50%). The same considerations hold as in the previous item; in general, however, the ratio signal/background is more favourable since the particle identification can be applied twice to the decay products, in order to remove the pion background.

DELPHI			OPAL		
x_p range	$\bar{x}_p$	$(\frac{1}{\sigma_h}\frac{d\sigma_\phi}{dx_p})$	x_p range	$\bar{x}_p$	$(\frac{1}{\sigma_h}\frac{d\sigma_\phi}{dx_p})$
0.06 - 0.1	0.08	0.327 ± 0.100	0.01 - 0.15	0.10	0.39±0.11
0.1 - 0.2	0.15	0.261 ± 0.037	0.15 - 0.3	0.22	0.12±0.04
0.2 - 0.3	0.25	0.111 ± 0.022	0.3 - 1.0	0.45	0.017±0.005
0.3 - 0.4	0.35	0.100 ± 0.030			
0.4 - 1.0	0.51	0.017 ± 0.007			

Table 2: Differential cross section for ϕ production, as a function of the fractional momentum x_p, as measured by DELPHI and OPAL.

- Ξ^- is detected through the chain $\Xi^- \to \Lambda\pi^-$ (BR $\simeq$ 100%), $\Lambda \to p\pi$. A major source of physical background is the decay of the Ω^- through the chain $\Omega^- \to \Lambda K^-$ (BR $\simeq$ 68%), $\Lambda \to p\pi$. In the absence of particle identification, the two suffer of large reciprocal reflections, because the difference of the masses between the Ω^- and the Ξ^- is equal to the difference between the masses of the K^- and the π^- within 3 MeV. Kinematical cuts can help [6] to reduce this reflection. The detection of the signal of Ξ^- and Ω^- is made experimentally easy by the possibility of computing the background from the data, using wrong-sign combinations of Λ and $\pi(K)$.
- The $\Sigma^\pm(1385)$ (former Σ^* decay strongly into $\Lambda\pi^\pm$ (BR $\simeq$ 88%). Their detection comes from invariant mass studies. In this case, however, the background subtraction requires the parametrization of the background shape, since both positive and negative Σ^* are present.
- Finally, $\Xi^0(1530)$ decays strongly into $\Xi^-\pi^+$ (BR $\simeq$ 67%), and the wrong-sign combinations can be used to subtract the background.

The experimental results on the average multiplicities for the production of strange particles are summarized in Table 3.

In Table 4, the results for the production of identified final states are compared with the predictions of JETSET 7.3 PS and HERWIG 5.6, and with experimental results at lower energies.

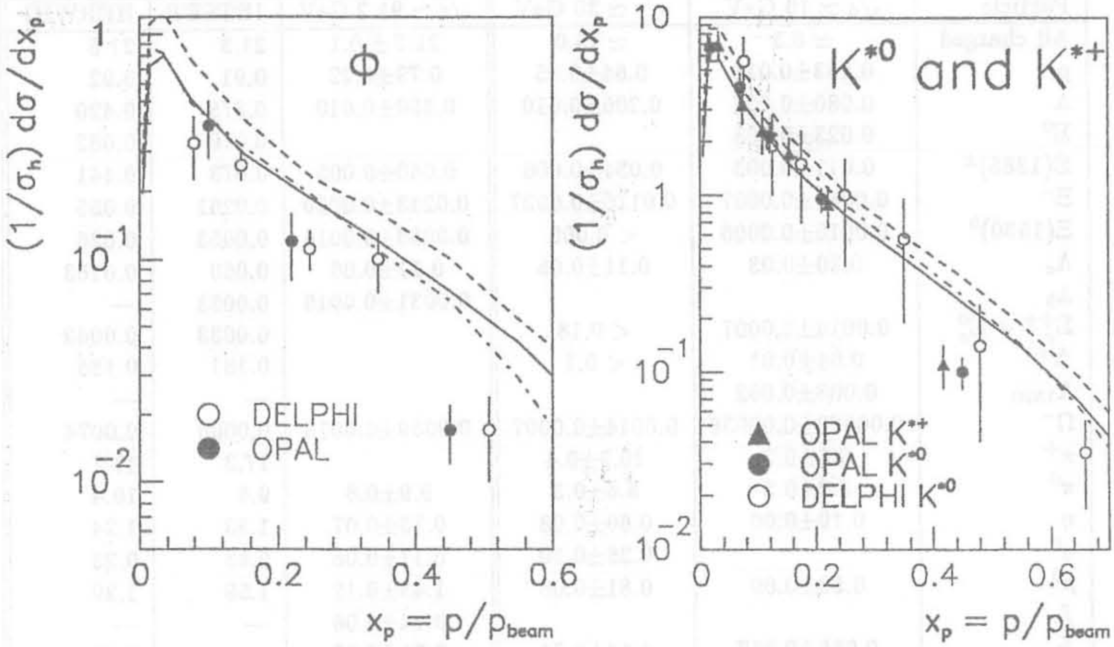

Figure 2: Left: Differential cross section of ϕ (left) and K^* (right) as measured by DELPHI and OPAL. Comparison with models as in Figure 1.

Particle	Mark II	DELPHI	OPAL	ALEPH	Ref.
K^0	1.54±0.28	2.12±0.07	2.10±0.14	2.02±0.07	[7, 8, 9, 10]
K^+	—	2.6±0.5	—	—	[11]
Λ	0.47±0.11	0.341±0.016	0.351±0.019	0.361±0.020	[7, 8, 9, 12, 13]
Ξ^-	—	0.0248±0.0023	0.0206±0.0022	0.0273±0.0021	[8, 13, 14, 15]
Ω^-	—	0.0084±0.0025	0.0050±0.0015	0.0012±0.0005	[13, 14, 15]
ϕ	—	0.097±0.014	0.086±0.018	—	[16, 17]
$\Sigma(1385)^\pm$	—	0.044± 0.009	0.038±0.006	—	[13, 18]
$\Xi(1530)^0$	—	—	0.0063±0.0014	—	[13]
K^{*0}	—	0.97±0.36	0.76±0.09	—	[17, 19]
K^{*+}	—	1.33±0.26	0.72±0.08	—	[8, 20]
$\Lambda\bar{\Lambda}$	—	0.098±0.017	0.083±0.010	—	[12, 21]
$\Lambda\Lambda+\bar{\Lambda}\bar{\Lambda}$	—	0.027±0.014	0.021±0.005	—	[12, 21]
$\Xi^-\bar{\Lambda}+\bar{\Xi}^+\Lambda$	—	—	0.0096±0.0023	—	[21]

Table 3: Measured multiplicities for strange particles production and correlations of strange baryons at the Z^0 peak. Statistical and systematic errors have been summed in quadrature.

Particle	$\sqrt{s} \simeq 10$ GeV	$\sqrt{s} \simeq 30$ GeV	$\sqrt{s} \simeq 91.2$ GeV	JETSET	HERWIG
All charged	$\simeq 8.3$	$\simeq 13.0$	21.3 ± 0.1	21.3	21.5
p	0.253±0.016	0.64±0.05	0.79±0.22	0.91	0.92
Λ	0.080±0.007	0.205±0.010	0.350±0.010	0.375	0.420
Σ^0	0.023±0.008			0.070	0.062
$\Sigma(1385)^\pm$	0.011±0.003	0.034±0.006	0.040±0.005	0.073	0.141
Ξ^-	0.0059±0.0007	0.0176±0.0027	0.0243±0.0020	0.0261	0.055
$\Xi(1530)^0$	0.0015±0.0006	< 0.006	0.0063±0.0014	0.0053	0.026
Λ_c	0.10±0.03	0.11±0.05	0.11±0.06	0.060	0.0153
Λ_b			0.0031±0.0016	0.0033	—
$\Sigma_c^{++} + \Sigma_c^0$	0.0014±0.0007	< 0.18		0.0033	0.0042
Δ^{++}	0.04±0.01	< 0.1		0.181	0.186
Λ_{1520}	0.008±0.002			—	—
Ω^-	0.00072±0.00038	0.0014±0.0007	0.0059±0.0013	0.0006	0.0074
π^+	6.6±0.2	10.3±0.4		17.3	17.7
π^0	3.2±0.3	5.6±0.3	9.9±0.8	9.8	10.4
η	0.19±0.06	0.60±0.08	0.73±0.07	1.23	1.24
η'		0.26±0.10	0.17±0.05	0.68	0.23
ρ^0	0.50±0.09	0.81±0.08	1.43±0.12	1.59	1.29
f_0			0.14±0.06	—	—
f_2	0.085±0.017	0.14±0.04	0.31±0.12	—	0.19
ϕ	0.045±0.007	0.085±0.011	0.093±0.011	0.191	0.132
K^+	0.90±0.04	1.48±0.09	2.6±0.5	2.28	2.42
K^0	0.91±0.05	1.42 ±0.07	2.06±0.06	2.15	2.33
K^{*+}	0.45±0.08	0.64±0.05	0.77±0.07	1.10	0.89
K^{*0}	0.38±0.09	0.56±0.06	0.77±0.09	1.06	0.87
K_2^{*+}		0.09±0.03		—	0.14
K_2^{*0}		0.12±0.06		—	0.14
D^+	0.16±0.03	0.17±0.03	0.195±0.028	0.21	0.36
D^0	0.37±0.06	0.45±0.07	0.414±0.042	0.46	0.37
D^{*+}	0.22±0.04	0.43±0.07	0.192±0.020	0.25	0.25
D^{*0}	0.23±0.06	0.27±0.11		0.25	0.26
$\Lambda\bar{\Lambda}$	0.012±0.002	0.047±0.010	0.087±0.009	0.086	0.173
$\Lambda\Lambda + \bar{\Lambda}\bar{\Lambda}$			0.021±0.004	0.028	0.042
$\Xi^-\bar{\Lambda} + \bar{\Xi}^+\Lambda$			0.0096±0.0023	0.019	0.063

Table 4: Observed average multiplicities of particle production/event at three different center of mass energies. Values at the Z^0 peak are compared with the predictions of JETSET 7.3 and HERWIG 5.6 with default parameters. References for strange particles are in Table 1. Other references and the procedure used for averaging are discussed in [6].

3 Comparison with the Models

The idea of explaining the average multiplicities of final state particles through considerations based on parton-hadron duality, and saying that *grosso modo* the number of particles of a given mass produced is equal to the number of gluons of virtuality larger than the particle mass, divided by the number of available hadronic states (each weighted by a factor accounting for the phase space available) is fascinating for its simplicity. Unfortunately, the agreement with experimental data is only qualitative [6].

Models making use of free parameters are thus needed. A look at Table 4 shows that the JETSET PS and HERWIG Monte Carlo programs, with parameters essentially tuned at PEP/PETRA energies, reproduce reasonably the data on the average multiplicities.

OPAL [13] has recently studied the impact of the data on baryon production on the free parameters in the JETSET PS model. When JETSET PS with default parameters is used, the multiplicities of the octet strange baryons are well described, while the decuplet ones are not. Correspondingly, the HERWIG Monte Carlo program, even with the best tuning of the cluster mass to reproduce the Λ yield, fails by up to a factor of 3 in describing the multiplicities of the other baryons, apart from the Ω^- , which is well described. The parameters in the strange sector of JETSET are of course highly correlated. OPAL concludes that no tuning can reproduce correctly the Ξ/Σ^* and the Ξ/Ω ratios at better than two standard deviations, because there ratios cannot be varied independently with the current set of parameters.

DELPHI [22] is working to a simultaneous tuning of the free parameters related to the production of strangeness in JETSET PS, in order to account for the measurements. The following parameters are considered:

- γ_s/γ_u;
- δ;
- $\frac{1}{3} \times \frac{qq_1}{qq_0}$, the ratio of probabilities of generating a spin=1 diquark with respect to spin=0;
- $\rho_{popcorn}$, a parameter related to the popcorn probability (i.e., to the probability that a meson is formed in the fragmentation between a baryon and an antibaryon). Approximately, $P(BM\bar{B})/[P(B\bar{B}) + P(BM\bar{B})] = \rho/(0.5 + \rho)$;
- δ_{fr}, the additional suppression factor for a diquark in the endpoint of a string;
- $V/(P + V)$, the fraction of spin 1 strange mesons.

The best tuning gives:

JETSET param.	Default values	DELPHI tuned
γ_s/γ_u	0.3	0.287±0.009
δ	0.4	0.58±0.07
$\frac{1}{3} \times \frac{qq_1}{qq_0}$	0.05	0.096±0.018
$\rho_{popcorn}$	0.5	0.81±0.21
δ_{fr}	1.0	0.37±0.08
$V/(P+V)$	0.6	0.38±0.05

In order to consider the results of this tuning as measurements of physical quantities, one has to estimate the effects of removing some of the observables which are anyway badly reproduced by the simulation (like the Σ^* multiplicity), removing from the fit some of the free parameters, modify the decay tables, etc. Preliminary result, including these effects in the uncertainties, are:

$$\begin{aligned}
\gamma_s/\gamma_u &= 0.29 \pm 0.02 \\
\delta &= 0.5 \pm 0.2 \\
\frac{1}{3} \times \frac{qq_1}{qq_0} &= 0.09 \pm 0.03 \\
\rho &= 0.8 \pm 0.3
\end{aligned}$$

$$\delta_{f_r} = 0.45 \pm 0.10$$
$$V/(P+V) = 0.38 \pm 0.05 .$$

Once the parameters are tuned, JETSET PS gives a satisfactory description of the differential cross sections for the particles for which the average multiplicities are well described (i.e., excluding Ω^- and Σ^*). HERWIG overestimates the Λ cross section at high x.

The cross section at small x is well described by the JETSET and HERWIG, as well as by QCD calculations in the modified leading log approximation (MLLA [23], see Fig. 3).

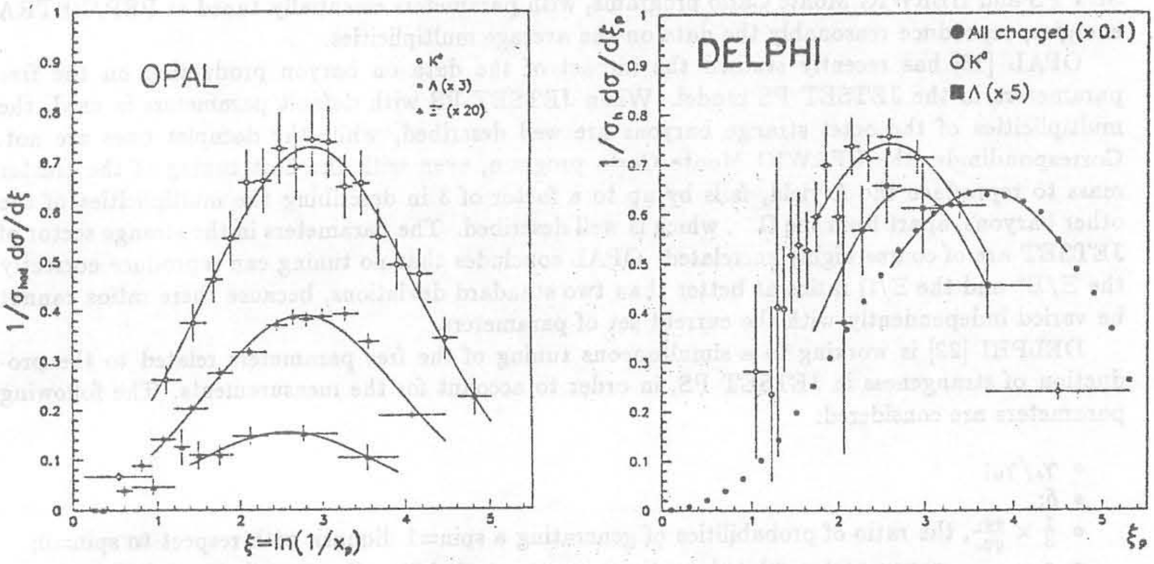

Figure 3: Cross sections in $\ln(1/x_p)$ from OPAL (left) and DELPHI (right). Fits to the shape predicted by MLLA are superimposed.

3.1 Correlations

The measurement of inclusive cross sections for the production of strange particles does not display a high discriminating power among different models, since in general they contain adjustable parameters that can account for the observations. It is thus more interesting to look at particle correlations.

In Fig. 4a, the distribution of the absolute difference in rapidity with respect to the sphericity axis for $\Lambda\bar{\Lambda}$ pairs detected in the same event, as measured by DELPHI, is plotted. The distribution is compared with the predictions of JETSET PS, for a popcorn parameter equal to 0, to 50%, and to 100%. The distribution indicates likelihood for popcorn. OPAL [21] finds also a better agreement with the data of the Δy distribution predicted by JETSET , when increasing the popcorn fraction.

The $\Xi^- \bar{\Lambda}$ correlation offers an even more sensitive probe of baryon production, since one of the two s quarks in the Ξ^- is likely to be a primary quark, and the production via diquark should involve a ds diquark. In the diquark model without popcorn the partner of a Ξ^- should be a baryon containing one strange antiquark, to compensate the strangeness. Thus one expect the rate of $\Xi^- \bar{\Lambda}$ events to decrease as the rate of baryon produced via popcorn increases. TPC/2γ [24] and OPAL [21] have studied the rate of $\Xi^- \bar{\Lambda}$ events, finding likelihood for popcorn.

Finally, $\Lambda\bar{\Lambda}$ correlations offer a nice way of distinguishing between cluster and string models. The two models predict a substantially different distribution of the angle ϑ^* between the momentum difference of a baryon-antibaryon pair, in its center-of-mass system, and the sphericity axis. If the

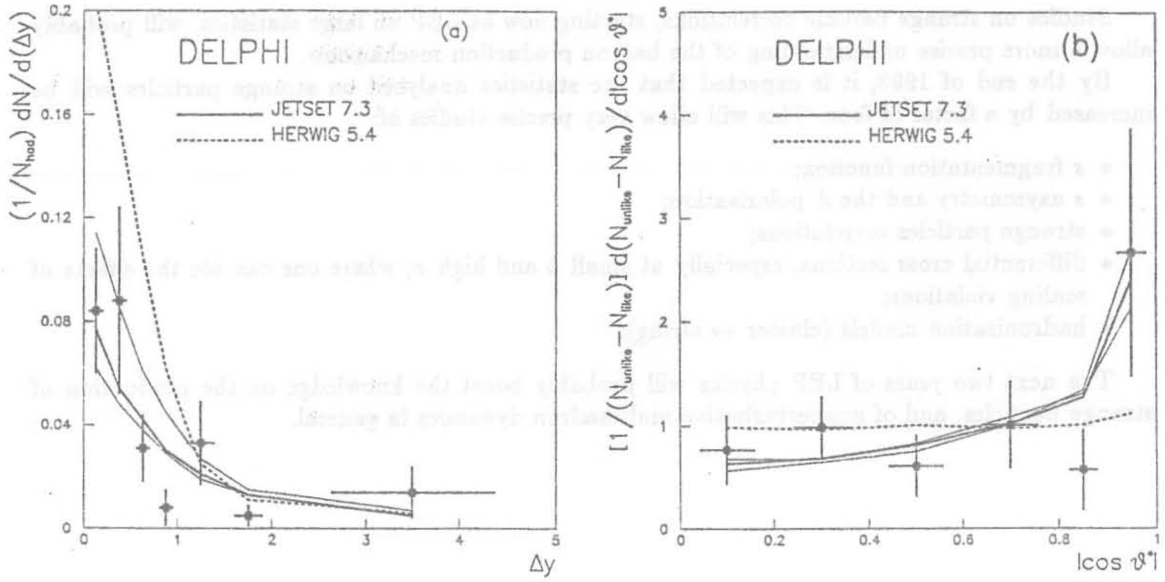

Figure 4: (a) Differential cross section for the production of $\Lambda\bar{\Lambda}$ pairs, as a function of the difference Δy in rapidity with respect to the sphericity axis, compared to the predictions of JETSET PS (solid) with $\rho = 0.5$ (bold), $\rho = 0$ (upper) and $\rho = 1$ (lower), and HERWIG (dashed). (b) Distribution of $\Lambda\bar{\Lambda}$ in the cosine of the angle ϑ^* in the center of mass between the Λ direction and the sphericity axis, after subtraction of like-sign combinations. Distributions normalized to 1. Predictions from JETSET PS (solid) and HERWIG (dashed).

baryons are produced in the decays of unpolarized clusters with baryon number equal to 0, the distribution in $|\cos\vartheta^*|$ will be flat. In a string model, the momentum difference will tend to align to the sphericity axis, since baryon and antibaryon are pulled apart by the string tension.

Experimentally, one expects a background from the combination of baryon pairs coming from different clusters, or different diquark-antidiquark pairs. This contamination can be removed by subtracting the yield of pairs with the same baryon number, that should have, in both models, this origin.

This test has been done by DELPHI [12] and ALEPH [9]. The level of statistics is not yet sufficient to distinguish among the models (Fig. 4b).

4 Conclusions

Results on strange particle production in the decays of the Z^0, based on the analysis of about 10^6 events, do not display severe contradictions, from a qualitative point of view, with respect to the predictions from models based on mass effects only. Such mechanisms however fail in reproducing *quantitatively* the observed yields.

Data accumulated up to now do not allow discrimination between cluster models and string models.

After an adequate tuning, JETSET PS gives a description of the production of strange particles that is more complete than the description given by HERWIG. The only failure seems to be a too low rate of Ω^- and a too high rate of Σ^*. As a drawback, the number of free parameters associated to the production of strange particles in JETSET is larger than in HERWIG.

The behaviour of the cross sections at small x does not display any peculiar behaviour, and is consistent with the predictions of models based on local parton-hadron duality.

Studies on strange particle correlations, starting now at LEP on large statistics, will probably allow a more precise understanding of the baryon production mechanisms.

By the end of 1993, it is expected that the statistics analyzed on strange particles will be increased by a factor of four. This will allow very precise studies of:

- s fragmentation function;
- s asymmetry and the Λ polarization;
- strange particles correlations;
- differential cross sections, especially at small x and high x, where one can see the effects of scaling violations;
- hadronization models (cluster $\leftrightarrow$ string).

The next two years of LEP physics will probably boost the knowledge on the production of strange particles, and of nonperturbative multihadron dynamics in general.

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