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Baryon Production in e^+e^- Annihilations

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Abstract

A review of the experimental data on the production of baryons from e^+e^- annihilations in the continuum and at the Z^0 peak is presented, with emphasis on the new data available from LEP. The constraints to the models obtained from the experimental data are discussed.

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1 Introduction

During the last decade, many experimental data on baryon production in the continuum e^+e^- have been reported. The implications of these data for the current models of hadronization are huge and often complementary to those provided by the studies of meson production.

The rates of baryon production measured at PEP/PETRA energies and at LEP are relatively high, compared to what could be expected from the growth with the energy of the average charged multiplicity. The production of baryons is thus strictly related to the fragmentation phenomenology, and it is hoped that it can yield new light on this poorly known phenomenon.

In the last years, the main new fact on the study of baryon production in e^+e^- collisions is the availability of LEP data. These data are taken at a center of mass energy three times larger than PEP/PETRA, far enough to observe scaling violations due to QCD effects. In addition, as the center of mass energy increases, the fraction of baryons produced in the fragmentation chain (i.e., not inheriting the flavour of the primary quarks produced by the e^+e^- annihilation) becomes more important.

In this article, we present a review of the experimental data in e^+e^- interactions, from the continuum above the Υ mass to the Z^0 peak. Particular attention is paid to the LEP data, where available. Emphasis is given to the detection techniques, and to the relation of data to the Monte Carlo programmes playing the role of "standards" in e^+e^- physics, the one based on the Lund model [1], JETSET [2], and the one based on the Webber model, HERWIG [3]. For more detailed reviews of the pre-LEP data, we refer to [4–6]. For more exhaustive information on data on differential cross sections, we refer to the HEPDATA database.

The article is organised as follows. In Section 2, a review of the models for baryon production is carried out, and the predictions of the current models of the production of multihadronic final states from the annihilation of e^+e^- pairs are discussed. In Section 3, a summary is given of the experimental data on the cross sections for baryon production in e^+e^- annihilations, with an outlook on the experimental techniques, and of the implications of the inclusive measurements on the models. In section 4, the results of the studies of correlations between baryons, together with the implications on the models, are discussed. Finally, in section 5 the conclusions are drawn, and the future prospects of the study are outlined.

2 Models

Baryons (B) are made up by three quarks. One could think of a baryon as a random combination of them, neglecting correlations among the individual quarks, or to a unique entity, or one can consider as dominant the correlations among a couple of quarks in the triplet.

Whenever a system of two quarks has to be considered collectively, because of correlations among them, we speak of *diquarks* (D). A two-quark correlation in a baryon can thus be defined as a diquark [7]. A diquark in its ground state has positive parity, and can be a vector or a scalar state.

According to the present view of the process, the e^+e^- annihilation in a multihadronic final state, above the Υ and below the W^+W^- threshold, can be schematized into 4 phases (Fig. 1):

Figure 1: *Schematic view of the generation of a multihadronic final state from e^+e^- interaction.*

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), for center of mass energies up to the Z^0 peak.
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 approach);
 - or to use the matrix elements of the strong interaction up to the orders to which they have been calculated (the Matrix Element approach). In this second choice, one will have a maximum of four partons at the end of the cascade, since up to now calculations have been carried out at second order only.
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.
 - 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, $k \simeq 1 \text{ GeV/fm}$ ($\simeq 0.2 \text{ GeV}^2$). As the potential energy stored in the string increases, the string itself may break by the production of, say, a quark-antiquark pair, the mass of which 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 mass, the probability of exciting a $q\bar{q}$ pair is roughly

proportional to $e^{-\pi\mu^2/k}$. As a result, for example, the creation of a $c\bar{c}$ pair is suppressed by a factor $\simeq 10^{-11}$ 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 creation of diquarks should mainly take place in this phase. Since the fundamental processes are hidden by this largely unknown chain, it is difficult to extract from the experimental data clean information on diquarks.

- 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, the Webber model [3] and the Caltech model [8], more free parameters are introduced to account for massive cluster decays.

4. In the fourth phase, unstable hadrons decay.

The models of baryon production should be inserted in the framework described above, for which, as we have seen, the first and the last step are quite clear, while what happens in between seems a matter of taste. Inferring from this complicated chain the basic processes of baryon production, and unfolding the fundamental parameters associated to them, is thus a difficult task. The interpretation of the data is made easier, if there is the possibility to use for comparison models that reproduce well the main features of the e^+e^- interaction. The models strictly related to baryon production are thus, in general, inserted inside a complete generator of final states from e^+e^- interaction. At present, there are two "standards" for such simulation programs: the JETSET Monte Carlo programme, based on string fragmentation, and the Marchesini-Webber programme, based on the decay of mass clusters (HERWIG).

Naively, one could imagine basically five mechanisms for direct baryon production in e^+e^- annihilations.

1. Baryons can come from the random recombination of triplets of quarks separately created [9] (Fig. 2a).
2. The conversion of the e^+e^- pair into a virtual photon gives rise to a diquark-antidiquark ($D\bar{D}$) pair (or possibly to a baryon-antibaryon pair, directly), as in Fig. 2b [10]. The baryon and the antibaryon should be leading particles in opposite jets. One expects that the contribution of this graph becomes small when the radius of the region of interaction between the electron and the positron becomes smaller than the typical radius of a diquark. If one makes the hypothesis that the typical radius of a diquark is about 1 fm, the contribution of this graph should be negligible at high energies. However, nobody knows what the radius of a diquark is.

Figure 2: *Four basic mechanisms for baryon production.*

3. Baryons can be produced from diquarks in the fragmentation (Fig. 2c). In this case, one expects that the baryon-antibaryon pair is close in phase space, and in general in the same jet [11]. The production of diquarks should be suppressed with respect to the production of quarks, because of the higher mass (in particular, when the creation of a $q\bar{q}$ pair or of a $D\bar{D}$ pair from the vacuum is considered the effect of a tunnelling process). However, as it is difficult to assign a radius to a diquark system, it is also difficult to assign its mass. It is in general thus preferred to leave as a free parameter in many models the relative probability of producing a $D\bar{D}$ pair with respect to a $q\bar{q}$ pair. In JETSET, the default for this ratio $\gamma_{q\bar{q}}/\gamma_q$, where q is a light quark, is set to 0.1 (this parameter was tuned by comparing model and data at PEP/PETRA energies with, as final answer, better than a 10% relative error, including many possible sources of correlations).
- 3b. Baryons can be produced from diquarks in the fragmentation, with the possibility that the gap in the string due to the creation of a $D\bar{D}$ pair is broken [12] by a $q\bar{q}$ pair (Fig. 2d). In this case, the strict ordering of baryon-antibaryon pairs, predicted by model 3., is broken by a meson ("popcorn" model).
4. A cluster (or a parton in the showering process) can decay (convert) into a $B\bar{B}$ pair.

To the above processes, the contribution given by baryons not directly produced, but coming from the decays of heavier baryons, or of B mesons, has to be added.

Experimental data on baryon production, and especially on baryon-antibaryon correlations, essentially rule out models 1 and 2 as major sources of baryons, as will be detailed in Section 4. Model 3, without "popcorn" contribution, is unfavoured.

To account for "popcorn", the JETSET Monte Carlo programme offers the possibility of defining a parameter $\rho_{popcorn}$, controlling the ratio of $BM\bar{B}$ to $(B\bar{B} + BM\bar{B})$ events (being this ratio approximately equal to $\rho/(0.5+\rho)$). In principle, JETSET does not allow, at present, to have more than one meson interposed among a baryon and an antibaryon, although the popcorn model in itself can account for more.

The Webber model allows gluons to branch into diquark-antidiquark pairs, with a certain probability. This may cause the creation of baryon-like clusters, that decay into a baryon and a meson, thus weakening the strict ordering baryon-antibaryon predicted by pure diquark models.

The predicted average numbers of hadrons/event by the JETSET Monte Carlo programme based on parton showers in leading-log approximation for the evolution of the quark-gluon showers (PS), and by the HERWIG¹ Monte Carlo programme (both with default values of the parameters), at the three centre of mass energies of 10, 30 and 91.2 GeV, are displayed in Table 1.

3 Experimental Data on Inclusive Production

As stated in the introduction, many experimental data have been collected on baryon production during the last years at PEP/PETRA, and much more information has been and will be extracted from the studies in progress at LEP. Experimental data should be treated with caution, in particular for three reasons:

¹Unless otherwise stated, we will refer in the following to the version 7.3 of JETSET PS and to the version 5.4 of HERWIG, both with default parameters.

1. Very often it is difficult, if not impossible, to estimate the detector performance from the data. Experimentalists then proceed as follows. A detector simulation is used, that operates in two steps. In the first one, a simulator of the generation of physics events is used to simulate a final state at the primary vertex. In the second, the products of the primary interaction are tracked through the detector. In a given momentum region, the detection efficiency of the detector is then estimated as the ratio between the reconstructed events and the generated events in the simulation. Of course, this procedure may introduce (at second order) biases given by the dynamics of the generator used in the simulation.
2. In general, the detectors are sensitive to the production of baryons only in a restricted range of momentum. In particular, regions of small momentum fraction x_p , where the cross section is maximal, tend to escape the detection. The values of “average number of baryons/event” quoted by the experiments come from an extrapolation to the unobserved momentum region. These values contain thus a hidden model dependence, that experimentalists often estimate by comparing different models, and using the standard deviation between the obtained results as an estimate of the systematic extrapolation error. Nowadays, many of the tunings of the different models are done by using JETSET PS as a reference, and this introduces circularity and a possible bias.
Also the region of large momentum fraction, interesting for the physics of leading objects, tends unfortunately to be affected by large errors in the momentum reconstruction, or, for strange baryons decaying weakly, to escape detection due to the boost in the decay length. In general, also the behaviour in that region is somewhat affected by biases towards the generator used in the simulation.
3. In the cases of very rare baryons, the number of cuts introduced by the analyst is comparable with the cardinality of the final sample of events. The detection of baryons coming from multistep decay chains offers, in particular, this possibility. This introduces a bias that is impossible to estimate, and became especially dramatic due to the use of automatic programs for seeing in real time the effects of cuts. Using an automatic program for event analysis, like PAW, an analyst that expects to detect a sample of, say, $10 \Omega^-$ can tune his/her cuts until a signal appears, without spending much time. The reliability of this signal gives then no guarantee that one has not caught accidental correlations.

Experimentally, baryons are detected, in general,

- a. by using the capabilities of particle identification of the detector;
- b. by reconstructing secondary decays. For example, most of the studies of the cross section of baryons use as a tag the production of a secondary Λ , that has a clearly detectable decay into $p\pi$ as a signature.

The experimental data on the average baryon multiplicity per event are summarized in Table 1, and compared with the predictions of HERWIG and JETSET PS.

Particle	JETSET	HERWIG	Experimental	References
$\sqrt{s} \simeq 10 \text{ GeV}$				
p	257	204	253 ± 16	[13,14]
Λ	99	132	80 ± 7	[13,15]
$\Sigma^-(1385)$	6.8	18.6	5.5 ± 1.5	[15]
Σ^0	19.6	20.3	23 ± 8	[15]
$\Sigma^+(1385)$	8.9	23.0	5.1 ± 1.3	[15]
Ξ^-	7.0	15.3	5.9 ± 0.7	[13,15]
$\Xi^0(1530)$	1.2	8.4	1.5 ± 0.6	[15]
Λ_c	42.3	30.0	100 ± 30	[16,17] (a)
$\Sigma_c^{++} + \Sigma_c^0$	4	7	14 ± 7	[16] (b)
Δ^{++}	48	67.7	40 ± 10	[18]
Λ_{1520}	—	—	8 ± 2	[15]
Ω^-	0.13	2.1	0.72 ± 0.38	[15]
$\sqrt{s} \simeq 30 \text{ GeV}$				
p	530	373	640 ± 50	[19,20]
Λ	204	237	205 ± 10	[22-28]
$\Sigma^-(1385)$	16.5	35.4	17 ± 4	[29]
Σ^0	40.4	35.2		
$\Sigma^+(1385)$	20.0	41.2	17 ± 4	[29]
Ξ^-	14.1	29.8	17.6 ± 2.7	[29-31]
$\Xi^0(1530)$	2.6	15.9	< 6	[31]
Λ_c	65.0	29.6	110 ± 50	[32,33] (c)
Σ_c^{++}	3	5	< 80	[32] (d)
Σ_c^0	3	3	< 100	[32] (d)
Δ^{++}	105	117	< 100	[34]
Ω^-	0.36	3.7	14 ± 7	[35]
$\sqrt{s} \simeq 91.2 \text{ GeV}$				
p	915	638	790 ± 220	[36]
Λ	373	416	348 ± 13	[37-40]
$\Sigma^\pm(1385)$	71.8	138	38.0 ± 6.2	[39]
Σ^0	70.2	60.8		
Ξ^-	26.5	54.7	23.8 ± 2.4	[38,39,41]
$\Xi^0(1530)$	5.2	26.1	6.3 ± 1.4	[39]
Λ_c	59.6	14.7	110 ± 60	[42]
Λ_b	33.4	—	31 ± 16	[43,44]
Δ^{++}	181	187		
Ω^-	0.68	7.2	5.1 ± 1.3	[39,41,45] (e)

Table 1: Observed average multiplicities of baryon production/1000 events around three different center of mass energies, compared to the predictions of JETSET PS and HERWIG with default parameters.

Particle	$\sqrt{s} \simeq 10$ GeV	$\sqrt{s} \simeq 30$ GeV	$\sqrt{s} \simeq 92$ GeV	References
All charged	$\simeq 8.3$	$\simeq 13.0$	21.3 ± 0.1	
π^+	6.6 ± 0.2	10.3 ± 0.4		
π^0	3.2 ± 0.3	5.6 ± 0.3	9.9 ± 0.8	[46]
η	0.19 ± 0.06	0.60 ± 0.08	0.73 ± 0.07	[47]
η'		0.26 ± 0.10	0.17 ± 0.05	[47]
ρ	0.50 ± 0.09	0.81 ± 0.08	1.43 ± 0.12	[49]
f_0			0.14 ± 0.06	[49]
f_2	0.085 ± 0.017	0.14 ± 0.04	0.31 ± 0.12	[49]
ϕ	0.045 ± 0.007	0.085 ± 0.011	0.093 ± 0.011	[50,51]
K^+	0.90 ± 0.04	1.48 ± 0.09	2.6 ± 0.5	[36]
K^0	0.91 ± 0.05	1.42 ± 0.07	2.12 ± 0.06	[38,52]
K^{*+}	0.45 ± 0.08	0.64 ± 0.05	0.78 ± 0.08	[38,48]
K^{*0}	0.38 ± 0.09	0.56 ± 0.06	0.80 ± 0.08	[50,49]
K_2^{*+}		0.09 ± 0.03		
K_2^{*0}		0.12 ± 0.06		
D^+	0.16 ± 0.03	0.17 ± 0.03	0.195 ± 0.028	[53]
D^0	0.37 ± 0.06	0.45 ± 0.07	0.414 ± 0.042	[53]
D^{*+}	0.22 ± 0.04	0.43 ± 0.07	0.192 ± 0.020	[53]
D^{*0}	0.23 ± 0.06	0.27 ± 0.11		

Table 2: Observed average multiplicities of meson production/event, and of production of charged particles, around three different center of mass energies. Values at 10 and 30 GeV are taken from the Particle Data Book 1992. Values at the Z^0 peak come from the references in the rightmost column; data related to η , η' , π^0 , f_0 and f_2 were extrapolated to the unobserved region using the shape predicted by JETSET PS.

These result can be compared with an (incomplete) list of average meson multiplicities (Table 2). This shows that the $\sqrt{s}$ dependence of mean multiplicities is steeper for baryons than for mesons.

In the following, we will give a review of the methods used in the literature to detect baryons.

^aThe value was taken from the cross section of the Λ_c into $p\pi K$, assuming the branching fraction to be $(3.2 \pm 0.7)\%$ (Particle Data Group 92).

^bThe ratio $(\Sigma_c^{++} + \Sigma_c^0)/\Lambda_c = 0.36 \pm 0.12 \pm 0.11$ is given in the reference.

^cThe value from Ref. [32] was taken from the production cross section of the Λ_c into $\Lambda e X$, assuming the branching fraction to be $(1.2 \pm 0.4)\%$ (Particle Data Group 92). The authors prefer to quote an upper limit of $170 \pm 70 \pm 50$.

^dUpper limits to the ratios of Σ_c^{++} and Σ_c^0 to Λ_c are given in the reference.

^eThe only published result is OPAL's 5.0 ± 1.5 , while at the Dallas conference ALEPH has presented 1.2 ± 0.5 , and DELPHI 5.4 ± 2.4 . The result from ALEPH, being inconsistent with the other two, has been neglected in the average.

3.1 Experimental Detection of Baryons

3.1.1 Light-Quark Baryons

Protons are detected by particle identification, in particular dE/dX , time-of-flight techniques, and by the use of threshold Cherenkov counters. The technique of Ring Imaging Cherenkov Detectors, open to the DELPHI experiment at LEP, promises new results especially in the high momentum region [36]. At present, the preliminary data from LEP are restricted to a region of momentum fraction with respect to the beam $x_p < 0.3$, while data from PEP/PETRA are available up to $x_p \simeq 0.8$.

The decuplet baryon Δ^{++} is detected through its decay into $p\pi^+$. The identification of the proton is essential, the Δ^{++} mass being close to the peak in the phase space of $p\pi$ pairs. In addition, the detection is made difficult by the necessity of parametrizing the background. The combinatorial background grows faster than the expected cross section; this makes the detection of Δ^{++} difficult at high energies.

3.1.2 Strange Baryons

The bulk of the data available on baryon production is concentrated on strange baryons. The relatively high cross section and the long lifetime allow in general an easy detection. The requirement of a secondary vertex well separated from the primary one pushes down the combinatorial background to a reasonable level.

The detection of Λ is done through the reconstruction of the neutral decay $\Lambda \rightarrow p\pi$. The relatively long Λ lifetime ($c\tau \simeq 8$ cm) allows a rather clean detection also at small x_p . In addition, the kinematics of the decay (proton much heavier than the pion, small Q -value of the decay) is such that the proton can be recognised from the pion also in the absence of particle identification, being in general the particle with larger momentum.

The major “physical” (i.e., not combinatorial) background is given by the decay $K_S^0 \rightarrow \pi^+\pi^-$, where one pion is misidentified as a proton. Techniques based on the kinematics of the decay allow cuts in the transverse and longitudinal momenta (in the laboratory frame) of the secondary products, that severely reduce the K^0 background. This finds an elegant representation when the variable $\alpha = (p_L^+ - p_L^-)/(p_L^+ + p_L^-)$ (where p_L^+ (p_L^-) is the component of the momentum of the positive (negative) decay product projected along the vector sum of the two momenta) is plotted versus the transverse momentum p_T (“Armenteros” plot, Fig. 3). A cut in the Armenteros plot leaves the signal substantially unaffected. These features make the Λ the baryon most extensively studied.

Ξ^- is detected through the chain $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow p\pi$. A major source of physical background is the decay of the Ω^- through the chain $\Omega^- \rightarrow \Lambda K^-$, $\Lambda \rightarrow p\pi$. In the absence of particle identification, the two suffer large reciprocal reflections, because the difference of the masses between the Ω^- and the Ξ^- is equal to the difference of the masses of the K^- to the π^- within 3 MeV. Cutting in the “Armenteros” variables can remove effectively most of the reflection for a detector having a resolution better than 0.2 in α [21], since reflection is concentrated in half of the phase-space in the Armenteros variables (Fig. 4).

The detection of an unresolved 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 $\pi(K)$.

Figure 3: $\Lambda - K_S^0$ separation in an Armenteros plot. The bands correspond to the experimental resolution of the DELPHI detector at LEP.

Figure 4: $\Xi - \Omega$ separation in an Armenteros plot.

The $\Sigma^\pm$ (1385) decay strongly into $\Lambda\pi$. 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 sigmas are present. The requirement that the tracks come from the primary vertex is needed to reduce combinatorial background (Fig. 5).

Figure 5: $\Lambda\pi$ invariant mass plot from OPAL. The $\Sigma^\pm$ (1385) and Ξ^- peaks are visible.

Other strange baryons for which the production cross section has been measured are the Σ^0 (through its electromagnetic decay into $\Lambda\gamma$), the $\Xi^0(1530)$, that decays strongly into $\Xi\pi$, and the Λ_{1520} , that has a branching fraction of $(10 \pm 1)\%$ into $\Lambda 2\pi$.

The suppression of strange diquarks — The production of strange baryons is suppressed with respect to the production of nonstrange ones. In the Lund model, as we saw, this is essentially due to the higher mass, and the suppression factor can be in principle quantified by the probability of tunnelling. The JETSET Monte Carlo programme leaves anyway an adjustable parameter δ to account for this suppression. This parameter is defined as the suppression of strange diquarks with respect to nonstrange ones, divided by the suppression γ_s/γ_u of strange quarks, that is also left as a free parameter.

By considerations based on the mass of the quarks, one would expect $\gamma_s/\gamma_u \simeq 1/3$. This parameter has been measured from the yields of strange to nonstrange mesons, and from the momentum spectrum of strange mesons. Due to the fact that most of the mesons come from secondary interactions, in practice the parameter γ_s/γ_u in the simulation is tuned until the distribution under study is reproduced. It has been observed that the assumptions done in the simulation have little effect on the measurement of this quantity. The experimental data are summarized in Table 3, and they agree on a value of 0.30, that is taken as the default in JETSET.

Considerations on the measurement of the parameter δ are not so easy. For example, measuring δ from the differential cross section of Λ suffers from large correlations to the value of γ_s/γ_u assumed (DELPHI [40] measures an additional suppression $\delta = 0.34 \pm 0.03(stat)$, but a variation of ± 0.02 in γ_s/γ_u causes a variation of ∓ 0.07 in δ), and to the value of the popcorn parameter ρ .

Experiment	Technique	Result	References
TASSO	Ratio $K^0/\pi^\pm$	0.35 ± 0.03	[22]
JADE	Ratio $K^0/\pi^\pm$	0.27 ± 0.06	[54]
TPC	Ratios ϕ/K^{*0} , K^*/ρ	0.33 ± 0.09	[20]
HRS	Ratios K^0/π^0 , K^*/ρ	0.34 ± 0.03	[55]
OPAL	K^0 momentum spectrum	0.285 ± 0.015	[52]
DELPHI	K^0 momentum spectrum	0.30 ± 0.02	[38]
AVERAGE		0.30 ± 0.01	

Table 3: *Measurements of γ_s/γ_u in e^+e^- annihilations*

Measurements of δ are mostly based on the study of the Λ differential cross section, or on the comparison of the Λ average multiplicity to the proton multiplicity. When doing this, one has to subtract the Λ coming from the decay of heavier baryons and of B mesons. The first measurements of δ assumed a branching fraction of Λ_c into ΛX of 50% (while the currently accepted value is $(27 \pm 9)\%$ [56]), and suffer thus from the bias of subtracting too many Λ with the momentum spectrum typical of the Λ_c decay. In addition, the values of γ_s/γ_u taken for the tuning are in general different.

These problems make the measurements of δ in the literature difficult to compare. In JETSET, the situation is even more fuzzy due to the existence two additional degrees of freedom: the suppression of the creation of a $s\bar{s}$ pair from the vacuum in a “popcorn” process, and the creation of a strange meson in the “popcorn”, are treated independently from the same processes in the fragmentation. This introduces two other parameters strongly correlated to δ , and makes correlation studies based on the ratio of events with two strange baryons to one single baryon less sensitive to this parameter. Ref. [57] shows that it is possible to reproduce the correct value of the ratios $N(\Lambda\bar{\Lambda})/(N(\Lambda)+N(\bar{\Lambda}))$ and $N(\Xi\Lambda)/\text{event}$, observed by TPC/ 2γ , by putting $\delta = 1$ (i.e., no additional suppression for strange diquarks) by means of an adequate choice of the popcorn parameters.

More detailed systematic studies of correlations are needed to determine if the production of baryons is consistent with the Lund picture. It is hoped anyway that the amount of strange baryons produced by LEP will allow to solve the problem soon.

A short summary of the results on δ up to now is given in Table 4. Among the measurements affected by the “wrong” Λ_c branching fraction, we have chosen the ones that were quoting a systematic error for the uncertainty on this quantity. In addition, the measurements of δ were scaled to the same value, $\gamma_s/\gamma_u = 0.30$.

The problem of the correct modelling of the Λ_c decays should not be so crucial at LEP, because the fraction of Λ from Λ_c is less than 10%. The fact that most of the Λ at LEP are indirect makes LEP the best place to study the fragmentation of baryons (the price to pay is that LEP is not so good for studies related to primary Λ , like Λ polarization).

Experiment	Technique	Result	References
ARGUS	Ratio Ξ^- / Σ^0	1.10 ± 0.40	[15] (f,g)
HRS	Λ prod., Ratios Ξ/Λ , $N(\Lambda\bar{\Lambda})/(N(\Lambda) + N(\bar{\Lambda}))$	0.72 ± 0.23	[58,24]
TASSO	Ratio Λ/p	0.32 ± 0.11	[22] (g)
DELPHI	Λ momentum spectrum	0.34 ± 0.11	[40]
AVERAGE		0.39 ± 0.10	(h)

Table 4: Measurements of δ in e^+e^- annihilations

3.1.3 Charmed and Bottom Baryons

Information on the production of charmed and bottom baryons is still very scarce.

The lightest charm baryon is Λ_c . All models suppress at the level of 10^{-10} or more the creation of a $c\bar{c}$ pair. Λ_c from the primary interaction are thus (almost) exclusively produced from a primary c quark, exciting a nonstrange $D\bar{D}$ pair from the vacuum. The rate of this hadron creation is low. This makes its detection difficult, together with the very short lifetime, and with the fact that the branching fractions of Λ_c are shared among many exclusive channels, taking a few percent each. Up to now, the yield of Λ_c in e^+e^- annihilations has been measured through its semileptonic decays (and, thus, by detecting Λ -lepton correlations) and through the hadronic decays into $p\pi K$, $\Lambda\pi$, $\Lambda 3\pi$, pK^0 .

Preliminary results from LEP have been reported, in the $p\pi K$ channel [59,42] (Fig. 6). The signal observed by DELPHI is reduced by only roughly 20% by a cut in apparent

Figure 6: $pK\pi$ invariant mass plot from DELPHI. The Λ_c peak is visible.

lifetime of the Λ_c at 1 ps; DELPHI thus claims that its Λ_c signal is b-dominated.

Other charmed baryons have been detected through channels involving the Λ_c . Σ_c for example is detected through the strong decay $\Sigma_c \rightarrow \Lambda_c \pi$.

^f The measurements have been rescaled to a value of $\gamma_s/\gamma_u = 0.30$.

^g A systematic error of ± 0.07 has been added in quadrature, to account for correlation to γ_s/γ_u .

^h The errors have been scaled to give $\chi^2/NDF = 1$.

Recently, evidence for Ω_c in the channel $\Xi K 2\pi$ [60], Ξ_c^0 in the channels $\Xi\pi$ and $\Xi 3\pi$ [61,62] and Ξ_c^+ in the channel $\Xi 2\pi$ [62] has been reported by ARGUS and CLEO. The decay branching fractions of Ξ_c and Ω_c are unknown, and thus the experiments quote only values of production cross section times the relevant branching fractions.

About bottom baryons, only evidence for Λ_b baryon has been reported up to now, in LEP experiments [44,43,63]. Λ_b is detected through Λ -lepton correlations, with opposite sign with respect to what expected from Λ_c decays, and higher transverse momentum of the lepton with respect to the event axis (Fig. 7, from Ref. [43]). What one

Figure 7: The $p \pi^-$ invariant mass distribution of the Λ particles for $\Lambda \ell^-$ candidates in OPAL (a). Same, for $\Lambda \ell^+$ candidates (b).

experimentally measures is the production rate of Λ_b , times the branching fraction of Λ_b into $\Lambda_c \ell X$ (where ℓ is a muon or an electron), times the branching fraction of Λ_c into ΛX . Since the branching fraction of Λ_c into ΛX is known with 30% relative accuracy, one can rescale the observed signal to the production cross section if it is possible to make a guess on the branching fraction of Λ_b into $\Lambda_c \ell X$. OPAL [43] guesses $\Gamma(\Lambda_b \rightarrow \Lambda_c \ell X)/\Gamma(\Lambda_b) = (8.8 \pm 2.2)\%$, motivated by considerations based on B-meson decays, and can thus quote the average multiplicity/event that is reported in Table 1.

3.2 Momentum Spectrum of Baryons

Before LEP, studies of the scaling of the differential cross section for baryon production with respect to the momentum fraction x_p were almost impossible. When making comparisons to center of mass energies around 10 GeV, no scaling was in fact expected, since the mass of the baryon pair is non-negligible at that energy (Fig. 8, from [5]). At PEP/PETRA energies, there was too small lever arm.

When the fraction of baryons from fragmentation becomes important, one could expect an approximate scaling in $(1/\sigma)d\sigma/dx_p (= (1/\sigma\beta)d\sigma/dx_E)$, where x_E is the energy fraction

Figure 8: (a) Inclusive scaled cross sections $(1/\sigma\beta)(d\sigma/dx)$ for p , Λ and Ξ in e^+e^- annihilations at center of mass energy of about 30 GeV. Lines indicate predictions for Λ and Ξ . (b) Comparison of scaled Λ and Ξ cross sections at center of mass energies of 10 and 29 GeV.

carried by the final state particle [64]. The first data from LEP, compared with the PEP/PETRA data, show evidence for this approximate scaling (Fig. 9).

Results from analytical formulae like the one given in [64] do not give a quantitative description of the differential cross section. The cross section at small x is well described by QCD calculations in the modified leading log approximation (MLLA, [65]), as can be seen in Fig. 10.

The data available from LEP in the sector of differential Λ cross section at high x [39,40] show that the spectrum of Λ production is softer than predicted by both JETSET PS and HERWIG (Fig. 11), as it was at 30 GeV (see Fig. 8).

About the dependence of the cross section on the transverse momentum with respect to the event axis, p_T , both HERWIG and JETSET predict a Gaussian shape in p_T for baryons, that is roughly verified. It should be underlined, anyway, that the spread in transverse momentum is a free parameter in JETSET, while it is related to the cluster mass in HERWIG. In cluster models, the width of the p_T distribution displays thus correlation to the average number of baryons per event.

In conclusion, essentially no resolving power among the different models is seen in the x and p_T differential cross sections, for which the trend could be essentially understood from considerations based on the masses. Both HERWIG and JETSET PS predict however at high momentum fractions a spectrum harder than observed.

3.3 Relative Rates of Baryons

As already said, the growth of the baryon cross section with the energy is steeper than the corresponding growth for mesons.

The momentum spectrum for baryons is harder than for mesons. This has been observed experimentally, by studying the momentum dependence of the differential cross

Figure 9: Comparison of the Λ scaled differential cross section in the energy fraction x_E , between OPAL, DELPHI and CELLO.

Figure 10: Cross sections in $\ln 1/x_p$ from OPAL. Fits to the shape predicted by MLLA are superimposed.

Figure 11: (a) Differential cross section for Λ , $\Sigma^\pm(1385)$, Ξ^- and Ξ^0 by OPAL. The lines show the predictions from JETSET PS. (b) Differential cross section for Λ measured by DELPHI. Comparison with JETSET PS and HERWIG.

section for baryon production relative to the differential cross section for pions (or all charged particles unresolved), see Fig. 12.

The hardening of the spectrum of baryons is expected in a natural way both in cluster models (the heaviest particle tends to carry most of the cluster momentum), and in the Lund model, where the Lund Symmetric Fragmentation Function $dN/dz \propto (1-z)^a e^{-b(m^2+p_T^2)/z}/z$ (m is the hadron mass and $z = (E + p_L)_{\text{hadron}}/(E + p)_{\text{quark}}$), is such that the spectrum moves to higher z (and thus high x) as m increases.

There are essentially two ways of implementing a model that accounts for the relative production of baryons with respect to mesons, and of the different flavour and spin configurations inside baryons. One is to essentially leave the different masses to play the game, the other is to define free parameters associated to the diquark production. This last approach obviously weakens the dependence on the mass value.

The idea of explaining everything 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 (Fig. 13, from [5]).

Models making use of free parameters are thus needed. A look at Table 1 shows that the JETSET PS Monte Carlo programme, with parameters essentially tuned at PEP/PETRA energies, satisfactorily reproduces the data on the production of baryons at LEP. The description from HERWIG, with fewer parameters, is only qualitative.

OPAL [39] 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 are not. Correspondingly, the HERWIG Monte Carlo programme, even with the best tuning

Figure 12: Momentum dependence of the ratio baryons/mesons at PEP/PETRA (a) and LEP (b).

Figure 13: Yields of the various particles as a function of mass, together with the number of gluons, and the number of gluons divided by the number of hadronic states available (weighed by phase space, and smoothed).

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^- , that is well described.

The parameters in the diquark 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 these ratios cannot be varied independently with the current set of parameters (Fig. 14).

Figure 14: The ratio $\Xi(1530)/\Sigma^\pm(1385)$ versus the ratio Ξ^-/Λ from OPAL (a), and the ratio $\Omega^-/\Xi(1530)^0$ versus the ratio Ξ^-/Λ (b). The shaded areas define regions covered by JETSET PS with different tunings.

In addition, the tuning of parameters associated to the production of diquarks converges only when the popcorn parameter ρ is fixed.

4 Correlations

The measurement of inclusive cross sections for baryon production does not display a high discriminating power among different models, since in general they contain adjustable parameters that can account for the observations. This is especially dramatic in JETSET, where at least seven free parameters control the baryon production in the fragmentation phase (OPAL [39] demonstrated however, as seen in the previous section, that a completely satisfactory tuning to the LEP data in the sector of strange baryons is impossible). In cluster models, by decreasing the maximum allowed cluster mass one decreases the rate of baryon production. It is thus more interesting to look at baryon correlations, that are more effective in distinguishing among different models.

Short-range baryon-antibaryon correlations have been proven experimentally at PEP/PETRA energies [66]. For example, $p\bar{p}$ pairs are more likely to occur close in phase space than pp or $\bar{p}\bar{p}$ pairs. Leading diquarks (or leading baryon pairs) are thus not a major source, at least around 30 GeV (and thus presumably at higher energies), of

baryon production. Results on $\Lambda\bar{\Lambda}$ correlations from OPAL [67] and preliminary results from DELPHI [40], based on a larger statistics than available at PEP/PETRA, strongly support this conclusion.

Also the ruling out of the recombination model can be seen from baryon correlations. In Fig. 15, the results from Ref. [68] are reported, in which the yield of $p\bar{p}$ pairs versus the difference in rapidity is compared to the predictions of the diquark model, and of the recombination model, in which baryons and antibaryons forget their parentage to quarks and mix in rapidity. The recombination model is highly unfavoured (see also [69,25]).

Figure 15: *Difference in rapidity of $p\bar{p}$ pairs, compared to recombination and diquark models, from TASSO.*

It seems thus that the major source of baryon production is the creation of a $D\bar{D}$ pair within the fragmentation, possibly with popcorn.

We have seen that a pure diquark model predicts much stronger baryon-antibaryon correlations (i.e., a much more strict ordering) than diquark models including popcorn: correlation studies should thus be suited also for extracting the weight of the popcorn graphs. The problem is to find distributions sensitive to the popcorn, not dominated by energy-momentum conservation (kinematical correlations between hadrons occur naturally due to energy-momentum conservation), and displaying little correlation on other parameters related to the hadronization.

Studies of correlations of transverse momentum are well suited for demonstrating the popcorn mechanism, since in a pure diquark model these should be strong, whereas popcorn attenuates them, because the transverse momentum can be compensated by mesons. These studies should not in addition be closely correlated to the flavour of the quarks involved in the "popcorn", thus displaying a small correlation to the two parameters that take into account this flavour in JETSET. ARGUS [70] shows likelihood for popcorn by the study of the correlations in transverse momentum, although with not enough sensitivity to measure ρ (Fig. 16, from Ref. [70]).

Figure 16: *Distribution in angle in the transverse plane for $p\bar{p}$ pairs in the same hemisphere, by ARGUS. The histograms show the Lund model predictions for $\rho = 0$ (upmost), 0.5 (medium), and 1 (lowmost).*

The bulk of the studies on particle correlations is however concentrated on strange baryons, that are, as we have seen, relatively abundant and easy to detect. Baryons made by u and d quarks only, although more frequent than strange baryons, suffer from the difficulty of particle identification, and in addition do not offer, unlike strange baryons, the possibility of verifying the presence of popcorn by means of the violation of the local compensation of flavour.

In Fig. 17, 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 best fit, using also the rate of $\Lambda\bar{\Lambda}$ events, yields $\rho_{\text{popcorn}} = 0.70 \pm 0.20$, where the error is dominated by the uncertainty on δ . This is not yet evidence for popcorn, since the result was obtained within JETSET, but can be taken as another indication. OPAL [67] finds also a better agreement with the data of the Δy distribution predicted by JETSET, when increasing the popcorn fraction.

The rate of $B\bar{B}$ (where B is an identified baryon) to single-baryon events gives in itself information on the popcorn contribution in the formation of baryons. The popcorn may in fact break not only the ordering baryon-antibaryon, but also the flavour compensation. If one defines for example $\lambda = 2N(\Lambda\bar{\Lambda})/(N(\Lambda) + N(\bar{\Lambda}))$, this quantity will depend on the popcorn parameter, because popcorn can cause the production of a strange meson among a strange $D\bar{D}$ pair, and thus one of the two baryons in the final state will not be strange. Fig. 18 shows the prediction of the Lund string fragmentation model of λ as a function of the popcorn parameter ρ_{popcorn} , compared with the result by TPC/2 γ . The level of statistics in that experiment allows a little sensitivity on ρ , once the variation of all parameters related to baryon production is allowed in JETSET PS. The result obtained by TPC, $\lambda = 0.48 \pm 0.10$, is consistent with the DELPHI result $\lambda = 0.58 \pm 0.11$, at an energy three times higher [40].

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

Figure 17: (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) Same, as a function of the cosine of the angle α .

Figure 18: Ratio $\lambda = 2N(\Lambda\bar{\Lambda})/(N(\Lambda) + N(\bar{\Lambda}))$, as a function of the popcorn parameter ρ in JETSET PS, compared to TPC data. Optimized simulations are indicated by "mod".

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 expects the rate of $\Xi^- \bar{\Lambda}$ events to decrease as the rate of baryon production via popcorn increases. TPC/2 γ [57] has studied the rate of $\Xi^- \bar{\Lambda}$ events, still finding likelihood (but not evidence) for popcorn.

This kind of correlation studies on different hadronic states can help in constraining the many parameters related to popcorn in JETSET. Without popcorn, in the Lund model one needs to strongly suppress the production of strange diquarks, in order to reproduce the observed correlations between strange baryons ([57]). The price to pay is that the production of Ξ^- , Ω^- decreases much below the observed yields. With 0.9 popcorn, the Lund model predicts correctly the rate of Ξ^- and Ω^- at 30 GeV, but one needs to drop the additional suppression of strange diquarks (i.e., to set it to 1), that is inconsistent with the measurements at LEP. Cluster models fail in describing quantitatively hadron correlations and production at the same time, although a qualitative agreement exists without introducing many more parameters.

Finally, a nice way of using baryon-antibaryon correlations for distinguishing between cluster and string models was explored by TPC [71]. 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 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 $D\bar{D}$ 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.

The TPC results on the distribution of the proton-antiproton pairs in $|\cos \vartheta^*|$, after subtraction of proton-proton pairs, is displayed in Figure 19. In order to remove differences between model and data concerning the rate for the production of pairs, all distributions were normalized to 1. The level of statistics is not sufficient to distinguish among the models, but the string model looks marginally favoured.

In conclusion, data on baryon correlation provide important information on the models of baryon production. Although the sensitivity is at present not enough to allow distinguishing among Webber and Lund models, only models based on diquarks can explain the experimental short-range correlations observed. The sector of correlations will receive important inputs from the huge statistics soon available from LEP.

5 Conclusions

Data on baryon production 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.

The experimental data indicate that mechanisms involving the creation of diquark-antidiquark pairs dominate the production of baryons. The simple diquark model is how-

Figure 19: Distribution of $p\bar{p}$ pairs in the cosine of the angle ϑ^* between the p direction and the sphericity axis, after subtraction of like-sign combinations. Distributions normalized to 1. (a) Predictions from JETSET PS (solid) and HERWIG (dashed). (b) Same, for p and $\bar{p}$ momenta between 0.5 and 1.5 GeV/c, compared to the TPC data.

ever unfavoured with respect to diquark models including contributions from popcorn mechanisms.

Measurements of quantities related to baryon fragmentation require accurate models. Data accumulated up to now do not allow discrimination between cluster models and string models.

JETSET PS gives a description of the baryon production that is better than HERWIG. The only failure seems to be a too low rate of Ω^- produced; however, the LEP data disagree on the Ω cross section, and better studies are awaited. As a drawback, the number of free parameters associated in JETSET to the mechanisms of baryon production is so large, that the amount of analyses done up to now does not allow even an adequate tuning of them. The correlations among these free parameters reduce at present the possibilities of using this Monte Carlo programme as a tool for measuring physical quantities.

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

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