B_s^0, Λ_b AND Ξ_b PRODUCTION AT LEP*

P. ROUDEAU

Laboratoire de l'Accélérateur Linéaire IN2P3-CNRS
et Université de Paris-Sud
91405 Orsay Cedex, France

(Received November 17, 1994)

Recent results obtained at LEP on the production and decays of these "new" B states are presented.

PACS numbers: 12.15. -y, 14.20. Mr

1. Introduction

In the Standard Model, theory deals with quarks and gluons whereas, in the laboratory, only hadrons are produced. As a consequence effects, mainly of non-perturbative QCD origin, have to be understood so that experimental data of high accuracy on hadron weak decays can be used to extract valuable results on quark transitions.

These effects, from strong interactions are present in the production and decays of hadrons.

In the weak decays of hadrons the control of these effects determines the accuracy of the C.K.M. matrix elements measurements. Rather surprisingly, when these effects happen to be the largest, they are the best understood. For light u and d flavours, the use of current algebra, based on Isospin symmetry, allows to measure V_{ud} with an extremely high accuracy (10^{-3}). For strange hadrons, SU(3) symmetry can be invoked to measure V_{us} from K or hyperon decays. At the other extreme in mass, the top quark is expected to decay before a T hadron has been produced. Experiments are then directly sensitive to transitions between quarks and hadronic effects can be computed using perturbative QCD. But it is known already that $V_{tb} \sim 1$ and that other elements involving the t quark will not be measurable directly from t decays. In between light and very heavy

* Presented at the XXXIV Cracow School of Theoretical Physics, Zakopane, Poland, June 1–10, 1994.

flavours, there are the charm and beauty for which it is well known that SU(4) and SU(5) are not good symmetries of strong interactions. Hopefully charm and beauty can be seen as two very complementary systems. For charm the weak transition elements V_{cd} and V_{cs} are known to a very good approximation (they can be obtained with a per mill accuracy once the unitarity of the CKM matrix is assumed) and thus, the study of charmed hadrons decays, can be a laboratory to measure and interpret the effects of strong interactions in systems made with a light and heavy quarks.

For beauty, the main interest is to extract not only the elements $|V_{bc}|$ and $|V_{bu}|$ (by studying B semileptonic decays) $|V_{td}|$ and $|V_{ts}|$ (by measuring $B^0 - \bar{B}^0$ oscillations) and also to measure the phase of the CKM matrix (from the study of CP violation in the B system). The understanding of the effects coming from strong interactions, gained in the charm sector, can be used to obtain accurate values for these quantities.

Strong interactions govern also the different production rates of heavy hadrons. This will be the subject of this article in which the emphasis is placed on the recently identified hadrons like the B_s^0, the Λ_b^0 and the $\Xi_b^{0,-}$.

2. Is there any interest in these measurements ?

Such studies concern three aspects.

2.1. *Understanding of hadronization mechanisms*

For strange heavy mesons, it would be nice to compare the production rates in jets of D_s, B_s and other strange particles to verify if these rates can be described by the same universal parameter, which in the JETSET Monte-Carlo [1] is the probability to produce an $s\bar{s}$ pair during string hadronization. At present, experimentally, these rates are rather uncertain ($\sim$ 30 % ?) because they depend on the knowledge of any absolute value for the D_s branching fractions. Another possibility to evaluate the B_s^0 production rate [1] in b jets is to measure the $B^0 - \bar{B}^0$ oscillation rate which is different at LEP, where B_s^0 contribute, and at the $\Upsilon(4S)$ where only B_d^0 are produced. We call χ the probability to observe a $\bar{B}^0$ state when a B^0 state has been produced at $t = 0$. From $\Upsilon(4S)$ and LEP (using the time dependence of the signal) measurements one gets [2]:

$$\chi_d = 0.183 \pm 0.017\,, \tag{1}$$

[1] I heard for the first time about this approach to measure P_s in the Seminars on Heavy Flavours (I. Bigi *et al.* CERN 1994).

and one can assume with a good approximation that $\chi_s = 0.5$. The oscillation probability measured at LEP or SLD or, more generally, in a b jet is [2]:

$$\chi_b = P_d\chi_d + P_s\chi_s = 0.122 \pm 0.008\,. \tag{2}$$

P_d and P_s are the respective probabilities to produce a B_d^0 or a B_s^0 in a b jet. Assuming that $P_u = P_d$ and using $P_{\Lambda b} = 0.10 \pm 0.05$ (see section 5.3) one obtains:

$$P_s = 0.10 \pm 0.03\,. \tag{3}$$

The largest contribution to the uncertainty is not from the Λ_b rate and with more statistics one expects to have a better precision on χ and χ_d and thus a better evaluation for P_s. Its value is in agreement with the naïve expectation of 12 % from the LUND model.

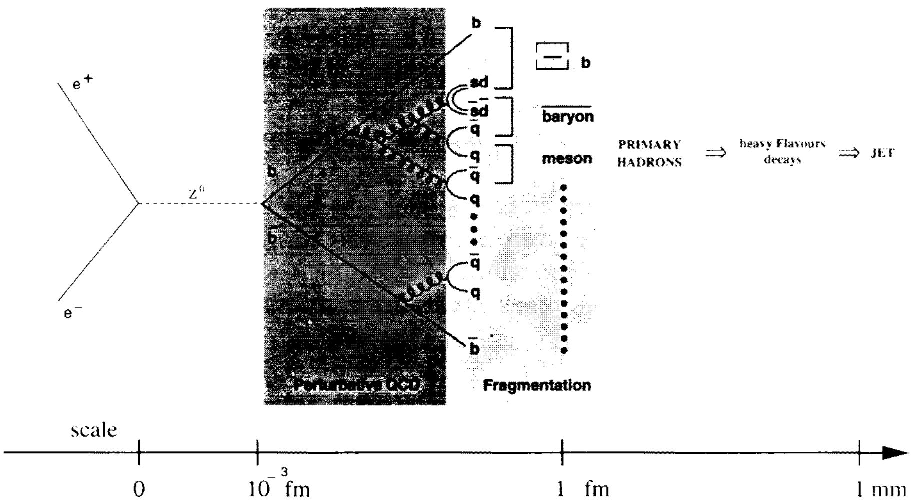

Fig. 1. Schematic description of B baryon production in a b jet using the LUND model for hadronization.

The measurements of heavy baryon production rates is also of interest because, unlike other situations involving baryon production, heavy baryons contain always the primary quark of the jet (Fig. 1). It can then be tried to determine if this quark recombines with a diquark or is randomly associated with two other quarks to form a baryon. Of course large statistics are needed in such measurements which require the study of baryon-meson and baryon-baryon correlations and this is not yet the present situation. The notion of diquark emerge naturally from QCD. Expressed in terms of $SU(3)_{colour}$

representations, the combination of a quark and an anti-quark or of two quarks gives:

$$3 \otimes \bar{3} = 1 + 8\,,$$
$$3 \otimes 3 = \bar{3} + 6\,. \qquad (4)$$

It can be shown that, whereas the potential in the representations 6 and 8 is repulsive, it is attractive in 1 and $\bar{3}$ and that [3]:

$$\langle \bar{3}|V|\bar{3}\rangle = \tfrac{1}{2}\langle 1|V|1\rangle\,. \qquad (5)$$

A diquark has thus some legitimacy in QCD and it behaves as an anti-quark.

The process of diquark creation in jets is not yet firmly established [4]. In the JETSET Monte-Carlo program, diquark production rates are put by hand and tuned to reproduce actual measurements on baryon [5] production. More elaborate approaches can be envisaged in which, in a first step, diquarks are produced by association of 2 quarks and using the expression (5) [6]. Baryon rates can be also related to gluon radiation in jets [7], but such models have not been implemented in Monte-Carlo simulation programs. It has to be noted that, only, these last considerations are able to explain the relative increase of baryon production measured in $\Upsilon(1S)$ decays.

Once a baryon is formed it is not clear at all if it can be considered as a bound quark-diquark system because of the symmetries which have to be satisfied by the wave function. According to the authors of [8] the only situations in which a diquark structure remains, happen in high spin baryons made with light quarks and in those containing two heavy quarks.

2.2. Extraction of a quantity of interest from inclusive measurements

We have already seen an example when considering the integrated measurement of $B^0 - \bar{B}^0$ oscillations in b jets (χ_b). This quantity is not of great interest because it corresponds to a mixture of B^0_d and B^0_s states. The interesting parameters are χ_d and χ_s which can be accessed only if we know P_d and P_s.

Another example is the inclusive B hadron lifetime which has been measured by LEP and SLD collaborations [9]:

$$\tau_B = 1.55 \pm 0.06\ ps\,. \qquad (6)$$

It corresponds to a weighted mean of individual lifetimes:

$$\tau_B = P_d \tau_{B^0_d} + P_+ \tau_{B^+} + P_s \tau_{B^0_s} + P_\Lambda \tau_{\Lambda b}\,, \qquad (7)$$

where the τ_i's are the lifetimes of the different B hadrons produced in a jet with the probabilities P_i. Present theoretical considerations [10] predict the following relative differences between B hadron's lifetimes:

$$\frac{\tau_{B^+}}{\tau_{B_d^0}} = 1.05\left(\frac{f_B}{200\text{MeV}}\right)^2, \ \frac{\tau_{B_s^0}}{\tau_{B_d^0}} = 1.00 \pm .01, \ \frac{\tau_{\Lambda_b}}{\tau_{B_d^0}} \sim 0.9\,. \tag{8}$$

Experimental results have not yet the required accuracy to verify these predictions. It seems that the difference between the Λ_b lifetime and the mean B lifetime is larger than expected:

$$\frac{\tau_{\Lambda_b} - \tau_B}{\tau_B} = -25 \pm 8\%\,, \tag{9}$$

(but the sign is correct).

The value of the inclusive B lifetime can be used to extract $|V_{cb}|$, having measured, also on a sample with similar proportions of B hadrons, the inclusive semi-leptonic B branching fraction.

$$\tau_B = \frac{192\pi^3}{G_F^2 m_b^5}\text{BR}(\text{B} \to X\ell\bar{\nu}_\ell)\frac{1}{F_c|V_{bc}|^2 + F_u|V_{bu}|^2}\,. \tag{10}$$

This approach suffers at present from the inaccurate determination of the quark masses m_b and m_c. This could be improved by a detailed analysis of the lepton energy distribution in semileptonic decays.

The expression (7) can be used also to extract the B_d^0 or the B^+ lifetimes once the other parameters have been measured or obtained from theory. As an example it can be written:

$$\tau_\text{B} = \tau_{\text{B}_d^0}(1 + P_+\delta_+ + P_s\delta_s + P_\Lambda\delta_\Lambda)\,, \tag{11}$$

where δ_i is the relative lifetime difference between the state B_i and the B_d^0 $\left(\text{Ex} : \delta_+ = \frac{\tau_{\text{B}^+} - \tau_{\text{B}_d^0}}{\tau_{\text{B}_d^0}}\right)$. Numerically, using (8) and (9), it happens that:

$$\tau_B \simeq \tau_{\text{B}_d^0}(1 + .02 + 0.00 - .025)\,, \tag{12}$$

and $\tau_{B_d^0} \simeq \tau_B$ with a relative error $\lesssim 2$ %. An accurate measurement of the inclusive B lifetime (at 1 to 2 % level) can be, at present, the best way to obtain the B_d^0 lifetime ; of course this result assumes that one is confident in the theoretical predictions concerning the expected lifetimes ratios between the different B meson states.

2.3. Properties of a given state which are of interest in themselves

For B^0_s mesons there are at least two quantities which are important to measure:

— the $B^0_{s,L}$ and $B^0_{s,S}$ lifetime difference :

For B^0_s mesons it is expected [11] that the lifetime difference between the short and long living states be measurable and be in the range of 10 to 20 %.

— the oscillation frequency between B^0_s and $\bar{B}^0_s$ states (x_s) :

For a neutral B meson state we define $x = \frac{\Delta M}{\Gamma}$, where ΔM is the difference between the two mass eigenstates and Γ is the total width.

The ratio of these parameters measured for B^0_d and B^0_s mesons can be expressed in the following way:

$$\frac{x_d}{x_s} = \underbrace{\frac{\tau_{B^0_d}}{\tau_{B^0_s}}}_{\text{measured}} \times \underbrace{\frac{\eta_{B^0_d}}{\eta_{B^0_s}}}_{\substack{\text{pert.QCD}\\ \text{corrections}\\ \text{(calculable)}}} \times \underbrace{\frac{M_{B^0_d}}{M_{B^0_s}}}_{\text{measured}} \times \underbrace{\frac{f^2_{B^0_d} B_d}{f^2_{B^0_s} B_s}}_{\substack{\text{non-pert QCD}\\ \text{corrections}\\ \text{(estimated)}}} \times \frac{|V_{td}|^2}{|V_{ts}|^2}$$

This expression illustrates the argument developed in the introduction concerning the control of non-perturbative QCD corrections when CKM matrix elements have to be extracted from actual measurements. These corrections have been gathered in the ratio [12]:

$$\frac{f^2_{B_d} B_d}{f^2_{B_s} B_s} = 0.74 \pm 0.15\,, \tag{13}$$

which is expected to be in a better control from theory than the absolute value of each of the two terms.

Assuming the unitarity of the CKM matrix, a simultaneous measurement of $|V_{bu}|$ and of x_s allows to extract a value for the phase expected to be at the origin of CP violation.

At LEP, time oscillations of B^0_d mesons have been observed and the present constraint from the unitarity of the CKM matrix implies that x_s will be in the range 5.6 to 33.2 [12]. A recent limit from ALEPH gives $x_s > 9$ [2]. It is quite challenging for LEP experiments to measure x_s. The new harvest of Z^0 collected in 1994 and expected for 1995 may allow to measure $x_s \sim 15$ or to put a limit for $x_s \sim 20$... .

For heavy baryons, in addition to the study of their production mechanisms, the measurement of their decay characteristics allows to access to the b quark polarization. More precisely what can be studied is how the initial polarization of the b quark ($P_b = -94\%$ at LEP) is transmitted to the baryon during the hadronization process. Baryons are a priori the only hadrons which have a memory of the initial quark polarization which is lost in case of B or B* meson production.

3. How to isolate the different types of B hadrons ?

The different flavours of B hadrons can be distinguished using exclusive decay modes. Unfortunately, individual branching fractions are of the order of a few 10^{-4} and very large statistics of B hadrons have to be produced. This approach can be used at hadron colliders. At the Z^0, semileptonic decays of B hadrons provide larger events samples of good purity. When an $L = 0$ charmed hadron is produced and reconstructed in a semileptonic B decay, the flavour of the D state is the same as the one of the B state (see Fig. 2a). Furthermore, the presence of a lepton emitted at large transverse momentum relative to the jet axis allows to purify the studied sample in direct B semileptonic decays. Finally, the background from other channels can be checked by looking at the correlation between the c quark and lepton charges. For instance, a signal is expected in the $D_s^+ - \ell^-$ channel and not in $D_s^+ - \ell^+$. This perfect correlation between the B and D flavours can be diluted if D states of higher masses are produced like L = 1 or N > 1 excited D hadrons (Fig. 2b).

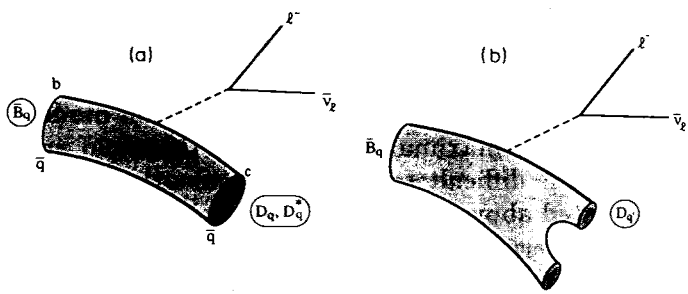

Fig. 2. Schematic description of B hadron semileptonic decays (a) — B meson semileptonic decay into a D or a D* state which is measured in the final state; (b) — B meson semileptonic decay into a high mass charmed state from which only the D or the D* is reconstructed in the final state.

3.1. Isolation of B_s^0 hadrons

In Fig. 3 are displayed the mechanisms which give rise to the presence of a D_s and a lepton of opposite charges in the same jet. The contribution from mechanisms where the lepton originates from a cascade B decay can be reduced by requiring a large transverse momentum of the lepton relative to the jet axis (or a large $D_s - \ell$ mass).

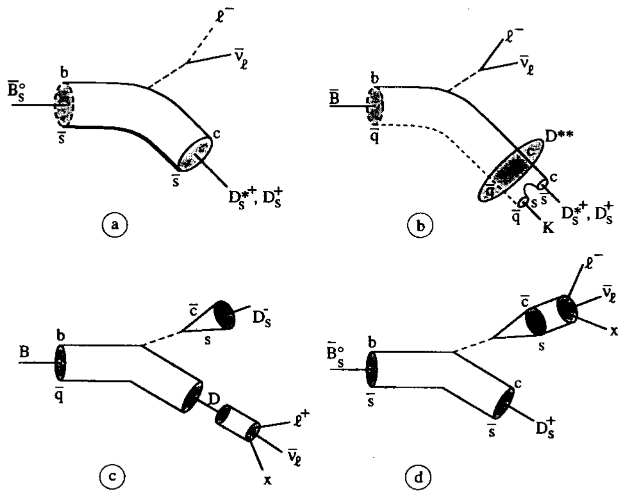

Fig. 3. $D_s - \ell$ production mechanisms in a jet (a) — B_s^0 direct semileptonic decay (b) — B_d^0, B^- direct semileptonic decay (c) — B meson cascade decay in which the virtual W is coupled to $\bar{c}s$ (d) — B_s meson cascade decay.

The mechanism 3b is analogous to the one previously mentioned in figure 2b. It corresponds to a semileptonic decay of a non strange B meson with production of an excited charmed state which decays into D_sK or D_s^*K. The expected mass distribution of the hadronic system produced in a semileptonic decay can be evaluated in a parton model [13] (Fig. 4). This distribution has a maximum close to the threshold and falls rapidly at large masses. It is difficult to obtain an evaluation of the contribution from the tail situated above the $D_s - K$ threshold because it depends a lot on the value of the Fermi momentum. A more precise evaluation has been obtained using a quark model which takes into account the production of the different resonant states [14]. Selection rules have also to be satisfied which restrict the possible decay channels. As an example:

$D_1(2420) \not\to D_sK$ (parity, angular momentum conservation),
$D_1(2420) \not\to D_s^*K$ (mass constraints).

From these considerations and also because the lepton transverse momentum distribution, produced in these non-strange B decays, is peaked at lower values as compared to the corresponding distribution of direct leptons from B_s^0 decays, one expects that more than 90 % of the selected $D_s - \ell$ candidates satisfying $P_T^\ell > 1.2$ GeV/c originates from B_s^0 mesons[2].

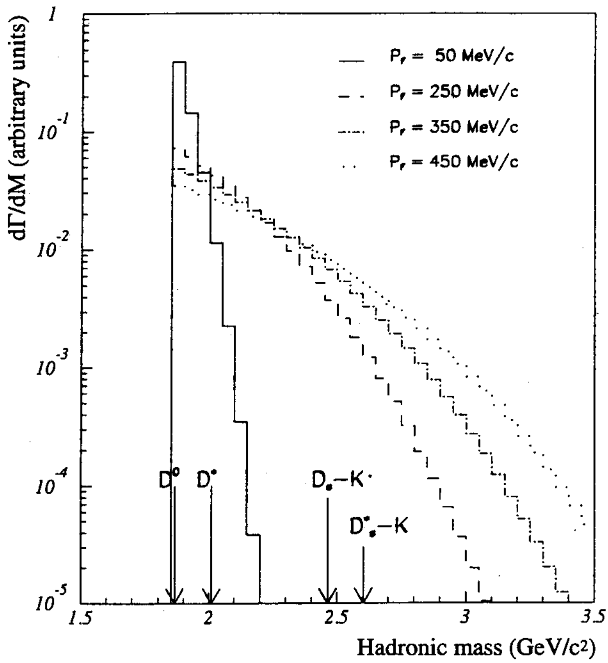

Fig. 4. Expected mass distribution of the hadronic system produced in a B meson semileptonic decay using a parton model (from formulae provided by A. Dobrovolskaya). The tail at high masses depends on the assumed value for the Fermi momentum of the spectator quark.

3.2. Isolation of B baryons

For B baryons the strategy is rather similar as the one for B_s^0 mesons. More inclusive final states are considered consisting simply in isolating lepton-baryon final states. B baryons decays populate lepton-baryon pairs whereas the other sources have a rather similar contribution to lepton-baryon and to lepton-antibaryon pairs. A signal from B baryons is seen as an excess in the lepton-baryon sample.

---

[2] In these analyses the lepton transverse momentum is measured relative to the jet axis containing the D_s and the lepton, after having removed the lepton to define the jet direction.

With the $\Lambda - \ell$ final states one is sensitive to the production of Λ_b^0 and $\Xi_b^{0,-}$ states whereas using $\Xi - \ell$ correlations one is mainly sensitive to $\Xi_b^{0,-}$, the strange beauty baryons, as explained in Section 5.

4. The B_s^0 meson

4.1. First experimental signals from the B_s^0 meson

As frequent in physics, it is difficult to attribute a discovery to a given person or a given team. The evidence for the B_s^0 has been obtained through a set of experimental results from which I have selected the following:

Results on $B^0 - \bar{B}^0$ oscillations (1986) [15]

The measurements of $B^0 - \bar{B}^0$ oscillations in jets produced at high energy machines are sensitive to B_d^0 and B_s^0 oscillations. A comparison of UA1 results with data registered at the $\Upsilon(4S)$, sensitive only to B_d^0, give evidence for the production of B_s^0 hadrons.

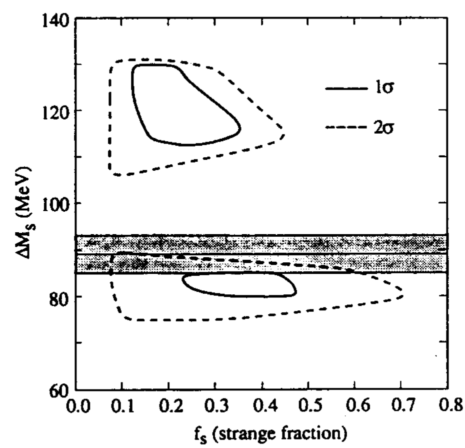

Fig. 5. The 1σ (solid curve) and 2σ (dashed curve) contours in the $(\Delta M_s, f_s)$ plane corresponding to the signal of photons from B_s^* decays. The shaded band gives the present measurement of ΔM_s from the exclusive reconstruction of B_s^0 and B_d^0 decay modes.

CUSB collaboration (1990) [16]

This Collaboration has registered data at the $\Upsilon(5S)$ and observe a signal of monochromatic photons produced in the decays $B^* \to B + \gamma$. The accuracy of the photon energy measurement is better than the width of the photon lines coming from the Doppler effect due to the velocity of the produced B* particles. The B_s meson being heavier than the B_d^0 the Doppler broadening is smaller when these particles are produced. From the shape of the photon energy distribution they find two favoured regions in the plane f_s (probability to produce a $B_s\bar{B}_s$ state), $\Delta M_s = M_{B_s^0} - M_{B_d^0}$. The present value : $\Delta M_s = 89.0 \pm 4.2$ MeV is compatible with one of these regions (Fig. 5).

Isolation of events samples highly enriched in B_s^0 mesons

In the previous signals the content in B_s^0 of the selected events was of the order of 10 %. With the $D_s - \ell$ semileptonic decay channel and the use of vertex detectors at LEP, it has been possible to isolate events samples which contain mainly B_s^0 meson decays ($\gtrsim 90$ % purity). The first signal [17] was shown by DELPHI at LEP meeting, from data registered in 1991 (Fig. 6). Very soon after this presentation ALEPH and OPAL produce similar signals and figure 7 shows distributions which include 1992 data and represent about 1M (million) of hadronic Z^0 decays analyzed by each experiment.

Measurement of the B_s^0 mass

The measurement of the mass of the B_s^0 requires the complete reconstruction of a few unambiguous events. ALEPH [18], with one nice event, $B_s^0 \to \psi'\phi$, has obtained the first and most precise value of the B_s^0 mass.

4.2. Present knowledge of the properties of the B_s^0 meson :

B_s^0 lifetime

From events containing in the same jet a D_s and a lepton, of opposite electric charges, the B_s^0 lifetime has been measured as explained in Section 3. Combining recent LEP measurements one gets [9]:

$$\tau_{B_s^0} = 1.54^{+0.14}_{-0.13} \pm 0.05\, ps\,. \tag{14}$$

Systematic uncertainties are dominated by those on the B_s^0 energy evaluation and on the parametrization of the combinatorial background's lifetime. This measurement is still limited by the statistical uncertainty.

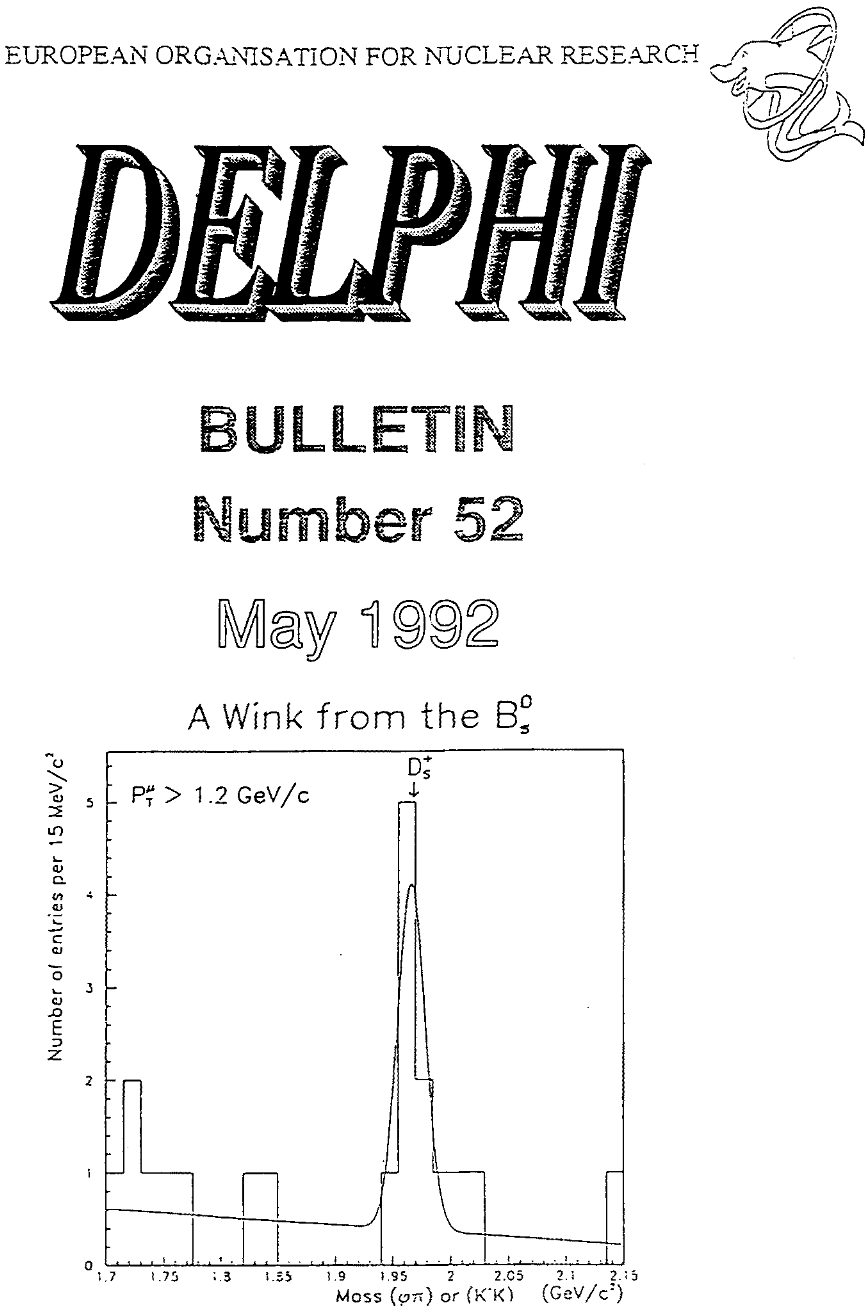

Fig. 6. First signal of D_s mesons coming from B_s^0 meson decays measured by DELPHI and presented at the LEPC (17 February 1992).

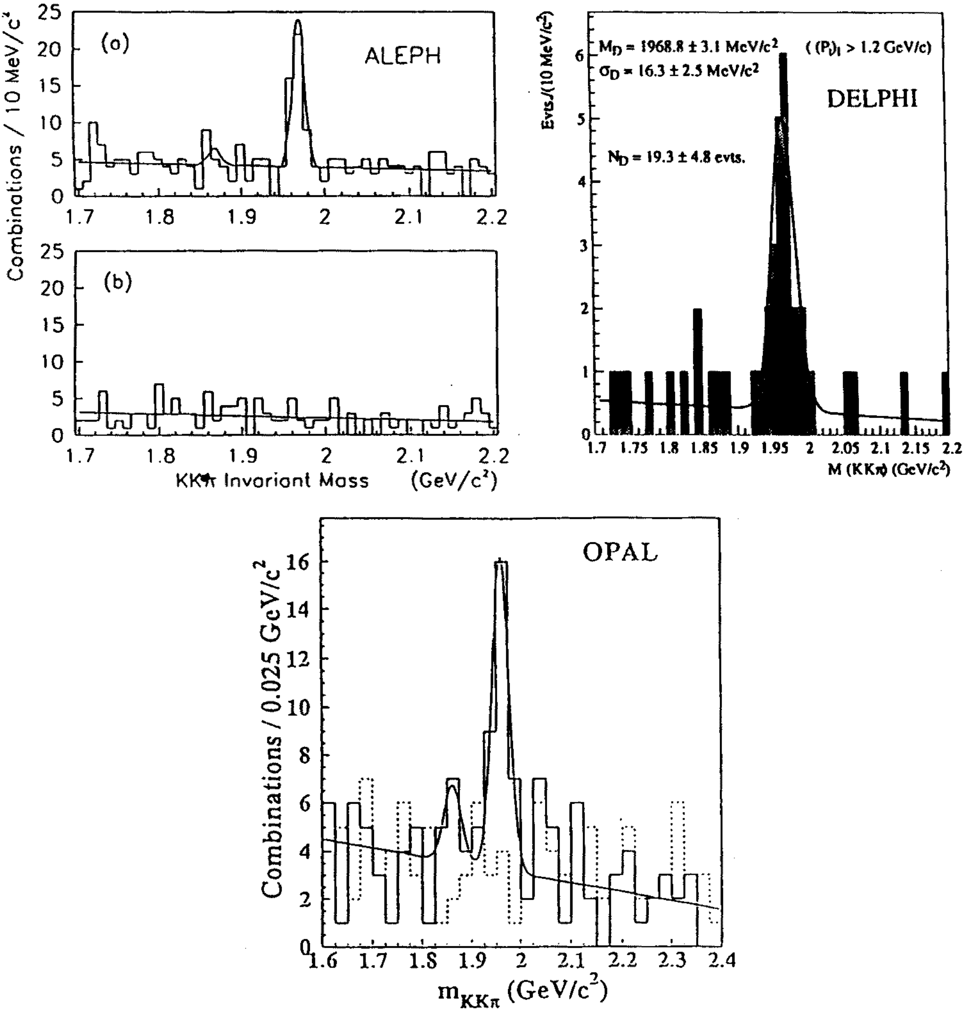

Fig. 7. D_s meson signals from B_s^0 semileptonic decays obtained by ALEPH, DELPHI and OPAL from the analysis of about 1M hadronic Z^0 decays per experiment. The figure b for ALEPH and the dotted histogram for OPAL give the corresponding mass distributions when one selects a D_s and a lepton of same charges.

B_s^0 mass

The mass of the B_s^0 was also obtained in LEP and CDF experiments [9]:

$$M_{B_s^0} = 5368.0 \pm 3.7 \text{ MeV}. \tag{15}$$

This value is in agreement with previous evaluations based on a model independent approach by Martin *et al.* [9]. This prediction was in fact for the B_s^* meson ($m_{B_s^*} = 5409 \pm 1$ MeV) but, using recent CLEO data [20], it is possible to evaluate also the B_s^0 mass. CLEO has precisely measured the mass difference between D^* and D states and found about the same value when the spectator is or not a strange quark :

$$m_{D^{*+}} - m_{D^+} = 140.64 \pm .08 \pm .06 \text{ MeV},$$
$$m_{D_s^{*+}} - m_{D_s^+} = 144.22 \pm .47 \pm .37 \text{ MeV}. \quad (16)$$

As the mass splitting is larger for strange mesons this shows that the increase of the overlap at the origin between the wave functions of the two quarks, due to the larger mass of the strange quark, as compared to u and d quark masses, dominates over the other effect which comes from a decrease of the hyperfine splitting which is due also to the larger strange quark mass:

$$\Delta M_{HF} \sim \frac{|\psi(0)|^2}{m_q m_Q}. \quad (17)$$

For non-strange B mesons, the value $m_{B^*} - m_B = 46.0 \pm .6$ MeV is very close to the expectation from the previous expression which gives:

$$m_{B^*} - m_B \sim \frac{m_c}{m_b} \times (m_{D^*} - m_D). \quad (18)$$

One then expects a mass difference between the strange B_s^* and B_s mesons:

$$m_{B_s^*} - m_{B_s} \sim \frac{m_{D_s^{*+}} - m_{D_s^*}}{m_{D^{*+}} - m_{D^+}} \times (m_{B^*} - m_B),$$
$$m_{B_s^*} - m_{B_s} = 47.0 \pm 1. \text{ MeV}. \quad (19)$$

And then:

$$m_{B_s}^{(\text{theory})} = 5362 \pm 2 \text{ MeV}. \quad (20)$$

x_s measurement

In the Standard Model and using present measurements one expects [12] the following range for x_s values:

$$5.6 \leq x_s \leq 33.2. \quad (21)$$

Recently ALEPH [2] has put a limit on the value of the x_s parameter. It has been obtained, by analyzing events containing a lepton emitted at large P_T:

$$x_s > 9. \quad (22)$$

With more data LEP will push this limit towards higher values and eventually give a measurement if $x_s < 20$.

5. Heavy baryons and first evidence for $\Xi_b^{0,-}$ production

5.1. Weakly decaying heavy baryons

Baryons containing one heavy quark Q (b or c) and decaying by weak interaction are named: $\Lambda_Q(Qud)$, $\Xi_Q(Qsd, Qsu)$ and $\Omega_Q(Qss)$. Masses and lifetimes of the corresponding charmed baryons have been measured, with varying precision. Among the beauty baryon states only the Λ_b^0 lifetime is known and none of their masses is firmly established.

The $\Sigma_Q(Q_{qq})$ baryons have an Isospin 1 and a spin $^1/_2$. They are heavier than the Λ_Q because of the hyperfine interaction:

$$H_{\text{spin spin}} = \frac{c}{2}\sum_{i<j}\frac{\vec{\sigma}_i\cdot\vec{\sigma}_j}{m_i m_j}\delta^3(\vec{r}_{ij}) \quad (i,j=1,3)\,. \tag{23}$$

The mass difference between Σ_Q and Λ_Q states is thus expected to have the following dependence in the effective quark masses:

$$m_{\Sigma_Q} - m_{\Lambda_Q} \propto \frac{1}{m_u}\left(\frac{1}{m_d} - \frac{1}{m_Q}\right)\,. \tag{24}$$

This implies that the splitting increases as the quark Q becomes heavier. Experimentally: $m_\Sigma - m_\Lambda \simeq 75$ MeV, $m_{\Sigma_c} - m_{\Lambda_c} \simeq 168$ MeV. One then expects that $m_{\Sigma_b} - m_{\Lambda_b} > 168 \text{ MeV} > m_\pi$ and that the Σ_b decays by strong interaction.

The excited baryon states containing a strange quark and named $\Xi'_Q(J = {}^1/_2)$ and $\Xi^*_Q(J = {}^3/_2)$ are also expected to decay through electromagnetic or strong interactions.

5.2. Heavy baryons lifetimes

Lifetime differences between heavy hadrons are mainly due to differences in their hadronic decay widths. Several mechanisms, all involving spectator quarks are contributing which can explain the factor of about 3 difference between the Ξ_c^0 and the Ξ_c^+ lifetimes. When two quarks in the final state, have the same flavour, there will be interferences which can be constructive ($\Gamma_{\text{int.cons.}}$) or destructive ($\Gamma_{\text{int.des.}}$) (see Fig. 8) [21]. The other important contribution comes from the exchange of the W ($\Gamma_{\text{exch.}}$) which, contrary to mesons, is not helicity suppressed in case of baryons. Normalizing the partial widths of these processes to the spectator decay width,

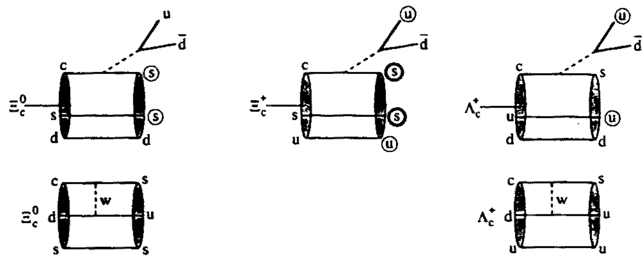

Fig. 8. Illustration of non-spectator mechanisms contributing to nonleptonic decays of charmed baryons.

($\Gamma_{sp.}$) the lifetime differences measured between charmed baryons can be explained using:

$$\Gamma_{exch.}/\Gamma_{sp.} \simeq 2, \ \Gamma_{int.cons}/\Gamma_{sp.} \simeq 1 \ \text{ and } \ \Gamma_{int.des.}/\Gamma_{sp.} \simeq -0.5 \,. \qquad (25)$$

Non-spectator mechanisms are dominant in charmed baryon decays. The typical scale of these processes is given by : $(f_P/m_P)^2$ where f_P and m_P are respectively the decay constant and the mass of the pseudoscalar meson $P = (Q\bar{q})$. One then expects that typical lifetime differences between B hadrons are reduced as compared to charmed hadrons by the ratio : $(m_D/m_B)^2 \sim 0.12$. The hierarchy between B baryons lifetimes can be obtained by considering the different contributing non-spectator mechanisms (Fig. 9). One has then:

$$\underbrace{\tau_{\Xi_b^0} <}_{5\%} \underbrace{\tau_{\Lambda_b^0} < \tau_{\Xi_b^-}}_{20\%} \,. \qquad (26)$$

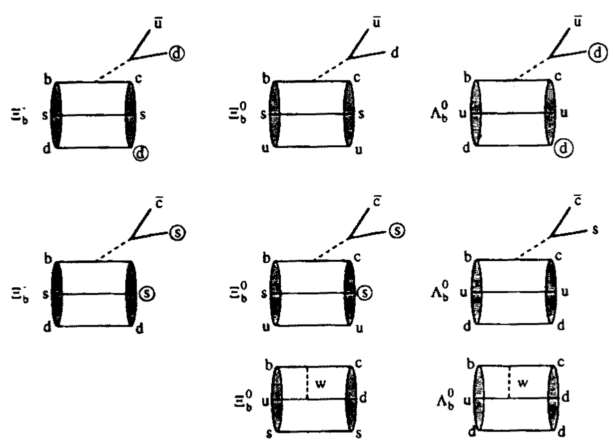

Fig. 9. Spectator and nonspectator mechanisms contributing to nonleptonic decays of B baryons.

5.3. Heavy baryons production rates in jets

The production rate of the Λ_c^+ has been measured by ARGUS and CLEO in e^+e^- annihilation at $\sqrt{s} = 10$ GeV [22]. Recently OPAL [23] has done a similar measurement at the Z^0 energy. If one assumes that : $\mathrm{BR}_{\Lambda_c^+} \to pK^-\pi^+ = 4.0$ % one obtains:

$$P_{c\to\Lambda_c^+} = 9.6 \pm 1.5\ \% \tag{27}$$

(an additional absolute systematic uncertainty of about 2% has to be added to account for the systematic uncertainty on the branching fraction for the decay $\Lambda_c^+ \to pK^-\pi^+$).

At LEP, evidence for Λ_b^0 production has been obtained by measuring the production rates of $\Lambda - \ell$, $\Gamma_c - \ell$, and $p - \ell$ in jets. If one assumes that:

$$\mathrm{BR}(\Lambda_b^0 \to \Lambda_c \ell X) = 10\ \%, \tag{28}$$

the branching fractions for $\Lambda_c \to \Lambda X$, $\Lambda_c \to pK^-\pi^+$ and $\Lambda_c \to pX$ can be used to obtain the following values which correspond to the mean of the results from ALEPH, DELPHI and OPAL experiments, when available:

$P_{b\to\Lambda_b^0}$ (%)	Channel	Reference B.R. [24]
$5.2 \pm 1.1 \pm 0.9$	$\Lambda - \ell$	$\mathrm{BR}(\Lambda_c \to \Lambda X) = 59 \pm 10 \pm 12$ %
$15.4 \pm 2.1 \pm 2.5$	$\Lambda_c - \ell$	$\mathrm{BR}(\Lambda_c \to pK^-\pi^+) = 4.0 \pm 0.3 \pm 0.8$ %
$7.2 \pm 2.0^{+3.1}_{-2.9}$	$p - \ell$	$\mathrm{BR}(\Lambda_c \to pX) = 50 \pm 8 \pm 14$ %

Some inconsistency is present in these values, pointing to an overestimated value for $\mathrm{BR}(\Lambda_c \to \Lambda X)$.

One can conclude, at present, that the production rate of Λ_b^0 in jets is of the order of 10 % with a large systematic uncertainty (±5 %?).

Using a model for baryon production based on diquark (as in JETSET) one expects:

$$P_b \to \Lambda_b = P_c \to \Lambda_c = 7\% \text{ and } P_b \to \Xi_b = 0.9\%. \tag{29}$$

5.4. Evidence for Ξ_b production at LEP (DELPHI) [25]:

Ξ_b baryons containing a strange quark, their production rate is expected to be smaller as compared to Λ_b, thus instead of $\Lambda - \ell$ final states, $\Xi - \ell$ correlations have been studied hoping that they provide a sample of events enriched in Ξ_b semileptonic decays. The analysis which follows is still preliminary and points which deserve more attention are indicated.

Characteristic properties of the channel $\Xi_b \to \Xi^- \ell^- \bar{\nu}_e X$

The purpose of this analysis is to isolate direct semileptonic decays of B hadrons and a few properties of the final state can be exploited:

• the Ξ^- baryon coming from the Ξ_c decay is usually faster than baryons produced in the fragmentation of the remaining light quark-antiquark system (Fig. 10a).

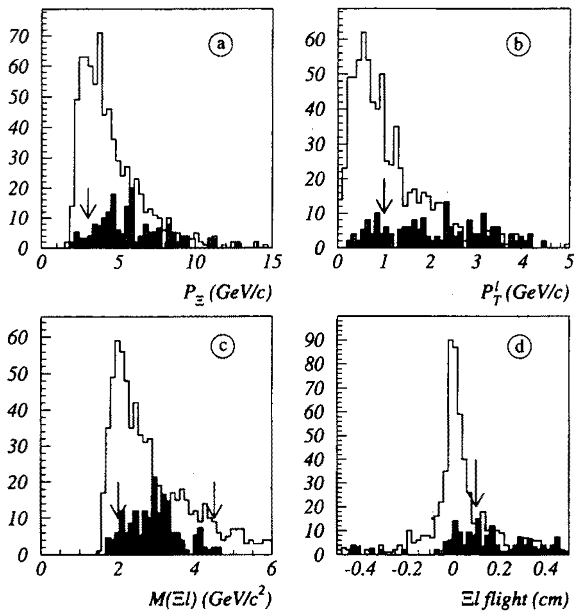

Fig. 10. Results from a Monte-Carlo simulation of events having a Ξ and a lepton in the same jet. The hatched histograms correspond to Ξ_b decays whereas the unshaded ones are for all other channels. (a) — Ξ momentum distribution; (b) — lepton transverse momentum relative to the jet axis; (c) — mass of the $\Xi - \ell$ system; (d) — distance between the $\Xi - \ell$ vertex and the primary vertex.

• the lepton transverse momentum, relative to the jet axis, has a distribution which extends towards larger values than the corresponding distribution from other lepton sources like B hadron cascade or direct charm semileptonic decays (Fig. 10b).

• the mass distribution of the Ξ-lepton system is between 2 and 4.5 GeV/c^2, (Fig. 10c).

• finally if, as expected, the B baryon lifetime is not very different from the lifetime of other B states, the Ξ and the lepton originate from secondary vertices (very close to each other) which can be at a few millimeters from the main vertex of the event and in the jet direction. This property allows to separate the B baryon channel from all other sources of background (Fig. 10d), once the Ξ and the lepton trajectories have been measured in a vertex detector. This has been achieved in DELPHI for Ξ's decaying after the last layer of the silicon vertex detector (Fig. 14).

Other sources of $\Xi - \ell$ pairs in a jet at LEP

Two main classes of events have to be considered depending on the origin of the Ξ baryon.

- the Ξ originates from a secondary vertex (Fig. 11).

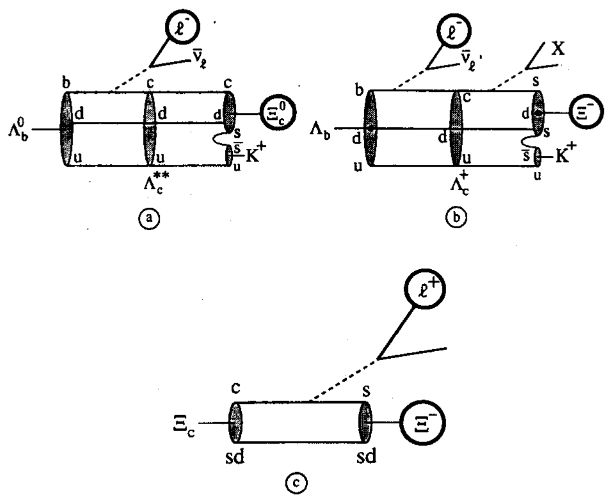

Fig. 11. Schematic description of background mechanisms contributing to the production of $\Xi - \ell$ pairs and in which the Ξ originates from heavy flavour decays. (a) — Λ_b direct semileptonic decay with production of a Ξ_c KX hadronic system; (b) — Λ_b direct semileptonic decay in which the produced Λ_c^+ decays into ΞX; (c) — Ξ_b direct semileptonic decay.

Semileptonic decays of B mesons as :

$$\bar{\mathrm{B}} \to \Xi_c \, \bar{\Lambda} \, \ell^- \, \bar{\nu}_e \, X$$
$$\hookrightarrow \quad \Xi^- X' \qquad (30)$$

are completely negligible because of the very limited available phase space.

Direct semileptonic decays of a Λ_b with a Ξ_c and a kaon produced in the accompanying system (Fig. 11a) are expected also to be negligible (this is a similar situation as the contribution of non-strange B meson decays to the $D_s - \ell$ final state - see section 3.1).

One must pay more attention to direct semileptonic decays of Λ_b^0's where the Λ_c^+ decays into $\Xi^- X$ (Fig. 11b):

$$\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell X$$
$$\hookrightarrow \quad \Xi^- X' . \tag{31}$$

The only decay channel measured up to now is $\Lambda_c^+ \to \Xi^- K^+ \pi^+$ which has a branching fraction of $0.079 \pm 0.013 \pm 0.014$ relative to $\Lambda_c^+ \to p K^- \pi^+$ [26]. It has to be noticed that other channels involving a Ξ^- in a Λ_c^+ decay require the production of at least one additional pion and, because of the masses of the particles involved in the final state, there is not enough available phase space to produce a ρ^+ or a K^*. The inclusive branching fraction $\Lambda_c^+ \to \Xi^- X$ is thus expected to be very close to the exclusive branching fraction for $\Lambda_c^+ \to \Xi^- K^+ \pi^+$ and of the order of 3×10^{-3}.

$\Xi - \ell$ pairs produced in charmed baryon decays contribute only to the opposite sign category (Fig. 11-c).

If a Ξ is produced in a B or D hadron decay and if the lepton is in fact a misidentified hadron one expects rather similar numbers of same-sign and opposite-sign pairs.

• the Ξ originates from the event primary vertex (Fig. 12). The cascade baryon is produced during the hadronization of the jet. This requires the emission of a strange $s - \bar{s}$ quark pair and of a diquark-antidiquark pair containing at least one strange quark. As the selected Ξ baryons are requested to have a minimum momentum (3 GeV/c in this analysis), only those which are close in rapidity to the hadron producing the lepton will be considered in the following qualitative description of the mechanisms. Several mechanisms contribute to the $\Xi - \ell$ final state depending on the origin of the lepton.

— the lepton originates from the direct semileptonic decay of a B baryon (Fig. 12a).
This is a source of opposite $\Xi^\mp - \ell^\pm$ pairs. Its importance and the degree of correlation in rapidity between the Ξ and the lepton depend on the value of the parameter fixing the importance of the popcorn mechanism in the JETSET Monte-Carlo simulation.
The contribution from Λ_b^0 is expected to be similar or even smaller than the one from the Ξ_b states.

— the lepton originates from the direct semileptonic decay of a B meson (Fig. 12b, c and d).
When the lepton comes from a $\bar{B}_s^0$ semileptonic decay, the Ξ^- can share the same $s\bar{s}$ pair with the $\bar{B}_s^0$ meson and then be quite energetic

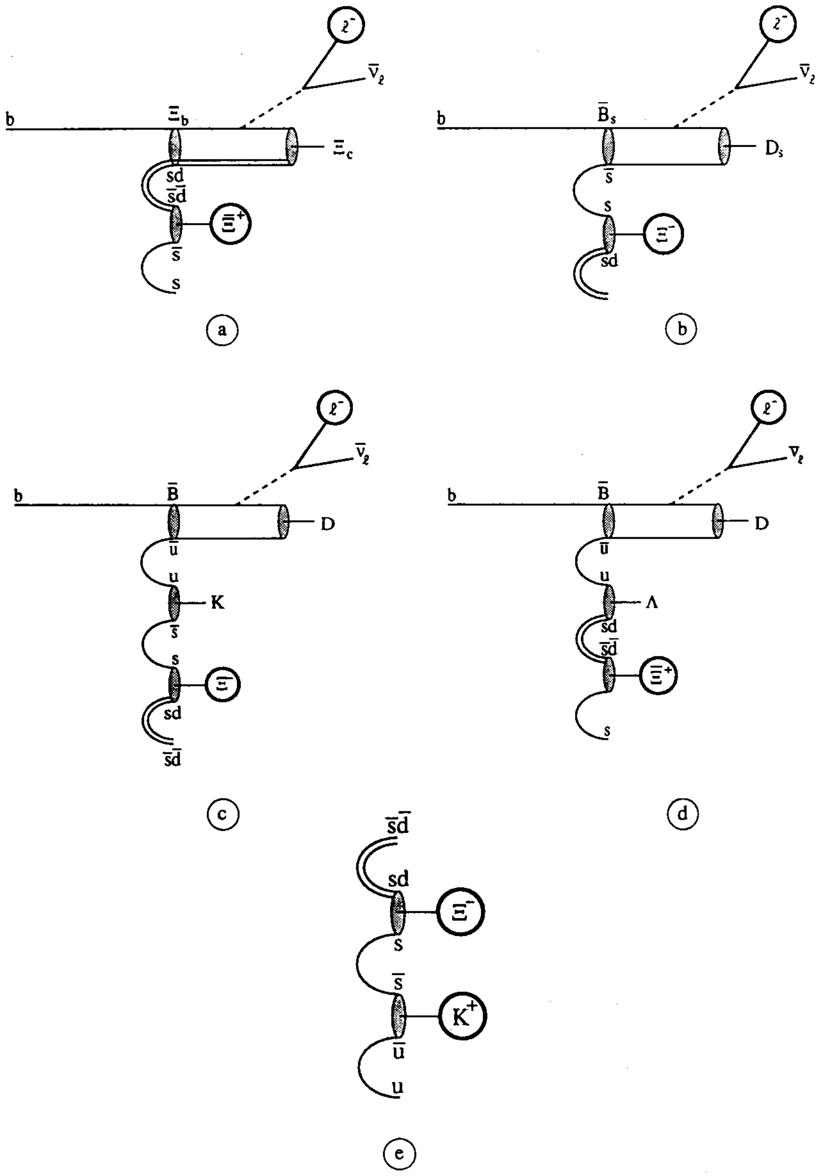

Fig. 12. Schematic description of mechanisms contributing to the production of $\Xi - \ell$ pairs in which the Ξ originates from the event primary vertex. (a) — Ξ_b direct semileptonic decay, with a Ξ emitted during the jet hadronization; (b) — $\bar{B}_s^0$ direct semileptonic decay. Because of $B_s^0 - \bar{B}_s^0$ oscillations there will be as many same-sign and opposite-sign $\Xi - \ell$ pairs produced (c), (d) — $\bar{B}_d^0$ or B^- direct semileptonic decays; (e) — an example of a possible contribution from fake leptons; a K^+ is misidentified as a μ^+ in this case.

(Fig. 12b). As the $\bar{B}^0_s$ meson is expected to oscillate with 50 % probability into a B^0_s meson, similar numbers of same-sign and of opposite-sign $\Xi - \ell$ pairs are expected.
If the lepton comes from a non-strange anti-B semi-leptonic decay it is expected that $\Xi^\mp$ baryons be less energetic because they have to be produced more deeply along the hadronization chain. The contributions to same sign and opposite sign pairs should also be rather symmetric in this case (Fig. 12c and d).

— the lepton originates from a charmed hadron decay.
If this hadron is produced in a B hadron decay the previously quoted mechanisms have to be considered but the sign of the lepton is reversed and its transverse momentum relative to the jet axis will be usually smaller.
If the charmed hadron comes from the fragmentation of a primary charm quark, in case of D_s semi-leptonic decays there will be an excess of opposite-sign $\Xi^\mp - \ell^\pm$ pairs.

— contribution from fake leptons
Because of the strangeness content of the Ξ baryon it will be more probable to get a $\Xi^\mp$ accompanied by a kaon of opposite charge which can be signed as a muon because of the smaller cross section for kaons to interact in the hadronic calorimeter before hitting the muon chambers, as compared to other hadrons. More candidates are then expected from opposite-sign $\Xi^\mp - \mu^\pm$ pairs (Fig. 12e).

As a conclusion, all mechanisms in which the Ξ is produced during the jet hadronization and is accompanied by a lepton emitted at large transverse momentum contribute in a rather similar way to same-sign and to opposite-sign $\Xi - \ell$ pairs with an excess expected in the second category.

Data analysis

As we have noticed, sources of $\Xi - \ell$ pairs in a jet are numerous but, in the absence of B baryon decays one expects to measure an excess of opposite-sign as compared to same sign pairs.

One cannot trust a priori the expectations from the Monte-Carlo simulation because of the great variety of decay channels and production mechanisms which are involved.

As $\Xi - \ell$ pairs from B baryons have characteristic kinematical properties, one can select a sample of events in which their contribution is expected to be marginal and do a comparison with the Monte-Carlo simulation to measure an uncertainty on the rate of all other processes. One finds that data and Monte-Carlo agree inside the statistical uncertainties, at the 25 % level.

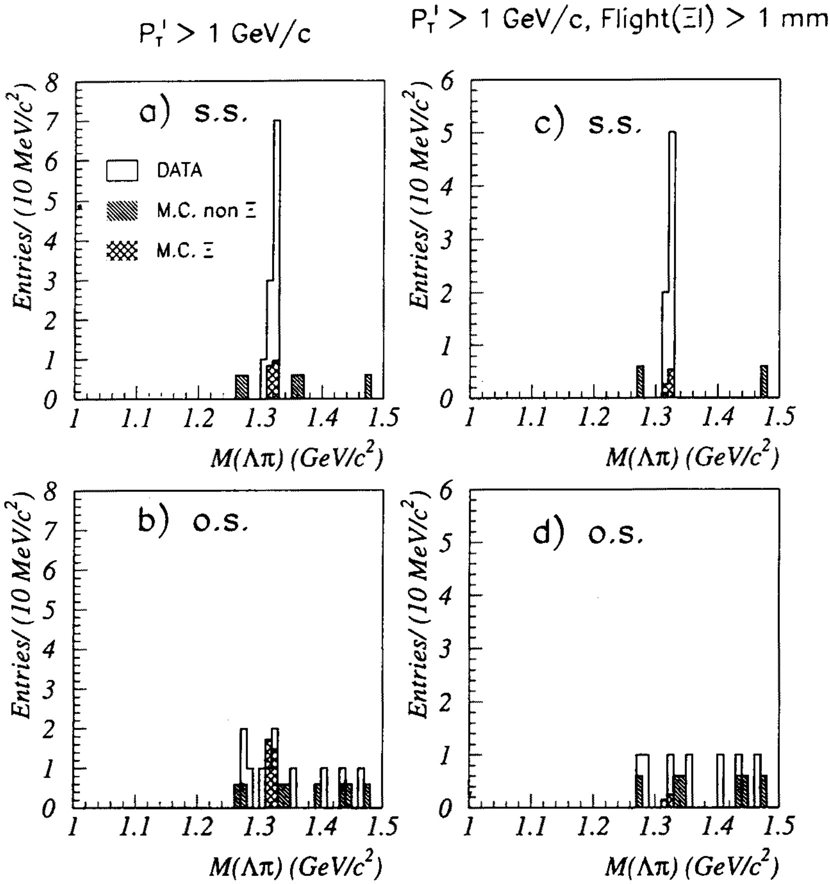

Fig. 13. $\Lambda\pi$ mass distributions for same-sign (a,c) and opposite-sign (b,d) $\Xi - \ell$ pairs. The real Ξ decays expected in the Monte-Carlo simulation, from all process, but B baryons decays, are shown in cross-hatched histograms. (a), (b) — the lepton transverse momentum is larger than 1 GeV/c (c), (d) — in addition the distance between the $\Xi - \ell$ vertex and the primary vertex is larger than 1 mm.

Using selection criteria to isolate events expected to be enriched in B baryon decays one can do a similar comparison. Results are shown in Fig. 13 where a lepton with transverse momentum larger than 1 GeV/c is selected (13a, b) and also a positive decay distance larger than 1 mm is requested (13c, d). For opposite-sign $\Xi - \ell$ pairs the data and the Monte-Carlo are in agreement whereas a clear excess of events is visible in the data for same-sign $\Xi - \ell$ pairs. In the simulation, all mechanisms have been incorporated but B baryon decays. From Fig. 13c one obtains a probability $\lesssim 10^{-4}$ that a background fluctuation explains the data.

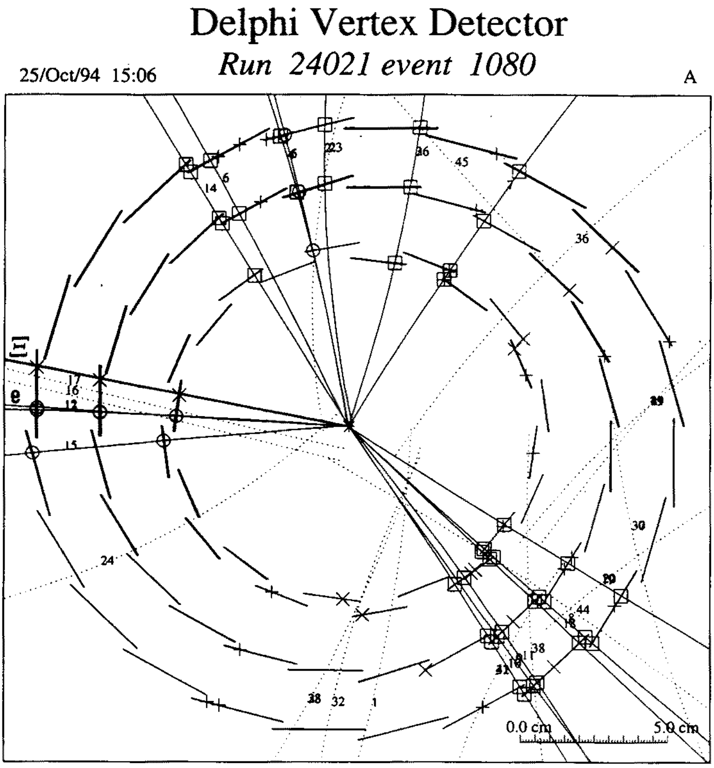

Fig. 14. Example of one event with a Ξ and an electron of same electric charges. The Ξ trajectory has been measured in the silicon vertex detector. The distance between the secondary and primary vertices is 3 mm and is measured with 300 μ accuracy.

A display of one of these candidates is shown in Fig. 14.

Ξ_b production rate in jets

If one assumes that BR$(\Lambda_c^+ \to \Xi^- X) = 0.3$ % the contribution from Λ_b semi-leptonic decays to the measured signal is of the order of 5 % (a probability of 8 % has been used for the production of a Λ_b in a b jet).

The signal of same-sign $\Xi - \ell$ pairs in thus originating mainly from Ξ_b semi-leptonic decays and one measures:

$$P(b \to \Xi_b) \times \mathrm{BR}(\Xi_b \to \Xi^- \ell^- X) = (5.9 \pm 2.1 \pm 1.0)10^{-4} \qquad (32)$$

(this number is valid for the branching fractions into electrons and muons separately).

This value can be combined with a similar measurement obtained by ALEPH [27] ($(3.4 \pm 2.0)10^{-4}$) to give:

$$P(b \to \Xi_b) \times \mathrm{BR}(\Xi_b \to \Xi^- X) = (4.6 \pm 1.5 \pm 1.0)10^{-4}. \qquad (33)$$

If one compares with the Monte-Carlo expectations:

$$\begin{aligned} P(b \to \Xi_b \to \Xi^- \ell^- X) &= P(b \to \Xi_b) && (1\% \text{ for } \Xi_b^0 + \Xi_b^- \text{ states}) \\ &\times P(\Xi_b \to \Xi_c \ell^- X) && (10\% \text{ for } \ell = e \text{ or } \mu) \\ &\times P(\Xi_c \to \Xi^- X) && (17\% \text{ in average for } \\ & && \Xi_c^0 \text{ and } \Xi_c^+ \text{ states}) \\ &= 1.7 \times 10^{-4} && \end{aligned} \quad (34)$$

one finds that the Monte-Carlo underestimates this final state by about a factor 3. However the experimental uncertainties in Ξ^- inclusive production in Ξ_c decays are such that (no measurement exists yet) one cannot tell if the Ξ_b production rate is really larger than expected.

6. Conclusions

Heavy hadrons are good probes to study hadronization mechanisms in jets at high energy because they contain always the primary quark. From data registered in 1991, LEP has obtained a direct evidence for B_s^0 and Λ_b production and more recently also for Ξ_b states. Because of the reduced accuracy in the knowledge of D_s, Λ_c and Ξ_c charmed hadrons decay properties it is not yet possible to measure the production rate of these B hadron states with an accuracy better than 30 to 50%.

Once the effects from hadronic interactions are understood this allows to exploit the full potential of accurate measurements of B hadrons decay properties. As an example, it appears that the most accurate value for the B_d^0 lifetime can be obtained from the measurement of the inclusive B lifetime. Another example is the use of an accurate measurement of the x_d parameter [28]. Its value is sensitive not only to the t quark mass but also to the presence of other heavy particles, but these effects can be detected only if non perturbative QCD contributions are under control.

With more statistics registered at LEP it is hoped to obtain a measurement of the time oscillation period of the $B_s^0 - \bar{B}_s^0$ system, or a limit if it is shorter than 0.5 ps. ($x_s > 20$).

REFERENCES

[1] B. Anderson *et al.*, *Z. Phys.* **C1**, 105 (1979); T. Sjöstrand, *Comp. Phys. Commun.* **28**, 229 (1983); T. Sjöstrand, Pythia 5.6 and JETSET 7.3, CERN-TH 6488/92.
[2] R. Forty, plenary talk at the IHEP 94 Conference, Glasgow 1994.

[3] A. Le Yaouanc, L. Oliver, O. Pene, J.C. Raynal, *Hadron Transitions in the Quark Model*, Gordon and Breach, 1988.
[4] M. Anselmino *et al.*, *Rev. Mod. Phys.* **65**, 1199 (1993).
[5] B. Anderson, G. Gustafson, T. Sjöstrand, *Nucl. Phys.* **B197**, 4 (1982).
[6] A. Casher, H. Neuberger, S. Nussinov, *Phys. Rev.* **D20**, 199 (1979).
[7] J. Ellis, H. Kowalski, DESY 88-103 ; CERN-TH-5120/88.
[8] S. Flek, B. Silvestre-Brac, J.M. Richard, *Phys. Rev.* **D38**, 1519 (1988).
[9] P. Roudeau, plenary talk at the IHEP 94 Conference, Glasgow 1994.
[10] B. Block, M. Shifman, talk at the third Workshop on the Tau-Charm Factory, June 1993, Marbella, Spain. Editions Frontières, p. 247, (see also Ref.[11]).
[11] J. Bigi, B. Blok, M. Shifman, N. Uraltsev and A. Vainshtein, *Non-Leptonic Decays of Beauty Hadrons — from Phenomenology to Theory*, CERN-TH, 7132/94.
[12] A. Ali, D. London, CERN-TH. 7398/94.
[13] A. Dobrovolskaya, private communication.
[14] E. Golowich, A. Le Yaouanc, L. Oliver, O. Pene, J.C. Raynal, *Z. Phys.* **C48**, 89 (1990).
[15] C. Albajar *et al.*, (UA1 Coll.), *Phys. Lett.* **B18**, 247 (1987).
[16] CUSB Collaboration, *Phys. Rev. Lett.* **65**, 2947 (1990).
[17] A. Stocchi, *Mesures de la production et de la durée de vie du méson B_s^0 avec le détecteur DELPHI à LEP*, thèse de l'Université Paris XI Orsay, Mai 1993, LAL 93-10.
[18] D. Buskulic *et al.*, (ALEPH Collaboration), *Phys. Lett.* **B311**, 425 (1993).
[19] W. Kwong, J.L. Rosner, *Phys. Rev.* **D44**, 212 (1991), and references therein.
[20] CLEO Collaboration, CLNS 94/1271, CLEO94-6.
[21] B. Guberina, R. Rückl, J. Trampetic, *Z. Phys.* **C33**, 297 (1986).
[22] H. Albrecht *et al.*, ARGUS Collaboration, *Z. Phys.* **C56**, 1 (1992), and references therein; P. Avery *et al.*, CLEO Collaboration, *Phys. Rev.* **D43**, 3599 (1991); *Phys. Rev. Lett.* **65**, 2842 (1990).
[23] OPAL Collaboration, A measurement of Λ_c^+ production in Z^0 decays, International Conference on High Energy Physics, Glasgow 1994, ref. GLSO511.
[24] G. Crawford *et al.*, (CLEO Collaboration), *Phys. Rev.* **D45**, 752 (1992).
[25] Stephane Plaszczynski, *Etude de la production des hyperons à LEP (DELPHI) et recherche de baryons beaux étranges*, Thèse de l'Université Paris VII, LAL 94-17, 1994.
[26] A. Avery *et al.*, (CLEO Collaboration), *Phys. Rev. Lett.* **71**, 2391 (1993).
[27] ALEPH Collaboration, Search for strange b baryons through $\Xi^{\mp}$ lepton correlations, ICHEP 94, ref. GLSO590.
[28] G.C. Branco *et al.*, CERN-TH. 7345/94.