

Masses and Production of B hadrons at LEP¹

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31 march 1995

Abstract

A summary is given of the LEP measurements on the production and masses of B hadrons. It covers the production of B hadrons, evidence for Ξ_b^+ production and limits on B_c^+ production. Further, the precise measurements of the B_s^0 and Λ_b masses are discussed. The LEP results for B^* production, the B^* mass and properties are summarized. Finally, the latest evidence is shown for B^{**} production, and the results for the B^{**} and B_s^{**} masses are presented.

¹Contributed talk to the LISHEP95 Conference, 20-22 february 1995. Rio de Janeiro, Brazil.

1 Introduction

The aim of this talk is to summarize the present knowledge on the production and masses of B hadrons based on the results of the four experiments ALEPH, DELPHI, L3 and OPAL at the Large Electron Positron collider (LEP). At LEP a pair of $b\bar{b}$ quarks is produced in approx. 21% of the hadronic Z^0 decays. The b quark hadronizes and forms different sorts of B hadrons. The B hadrons can be divided into three categories: pseudo-scalar mesons ($B^+ = \bar{b}u, B_d^0 = \bar{b}d, B_s^0 = \bar{b}s, B_c^+ = \bar{b}c$) and baryons ($\Lambda_b = \bar{b}ud, \Sigma_b^- = \bar{b}uu, \Xi_b^+ = \bar{b}sd$, etc.), the vector mesons with total spin $S=1$ ($B^{*+}, B_d^{*0}, B_s^{*0}$), and the tensor particles with total angular momentum $L=1$ ($B^{**+}, B_d^{**0}, B_s^{**0}$). The LEP experiments perform precise measurements on the production and masses of pseudo-scalar particles, quite recently also measurements on vector mesons and tensor particles became available.

This contribution will review:

- The production of B^+, B_d^0, B_s^0 and Λ_b particles, the evidence for Ξ_b^+ production and limits on B_c^+ production.
- Exclusive B decays: the measurement of the B_s^0 and Λ_b masses.
- B^* production, its mass and properties.
- Evidence for B^{**} production, the measurement of the B^{**} and B_s^{**} masses.

The total data set per LEP experiment until 1993 is approx. 1.7 million hadronic Z^0 events or 0.71 million B hadrons. In 1994 LEP was running very well and 1.5 million hadronic Z^0 events or 0.63 million B hadrons were taken. In most of the analyses the 1994 data was not yet included.

2 The Production of B hadrons at LEP

A full theory that explains the production of different types of B hadrons does not exist yet. There exist only phenomenological models like the JETSET string model that describes the fragmentation process [1]. The different fractions of particles are e.g. obtained by assigning a probability to pull out of the vacuum a pair of $u\bar{u}, d\bar{d}, s\bar{s}$, etc. quarks for meson production, or pairs of $uu\bar{u}\bar{u}, ud\bar{u}\bar{d}$ etc. quarks for the formation of baryons. The fraction of B_u mesons is defined as $f_u = N(B_u)/N(b)$. In the same way f_d, f_s and f_{Λ_b} are defined. Isospin symmetry requires that $f_u = f_d$.

The fractions of produced B hadrons are measured at LEP in the following ways. The fraction f_{Λ_b} is derived from the measurement of three branching ratios: $B(Z_h \rightarrow \Lambda_b \rightarrow \Lambda_c l\nu)$, $B(Z_h \rightarrow \Lambda_b \rightarrow \Lambda l\nu X)$, and $B(Z_h \rightarrow \Lambda_b \rightarrow pl\nu X)$. For this purpose various measured branching ratios are used (e.g. $B(\Lambda_b \rightarrow \Lambda_c l\nu)$), which have rather large uncertainties. The result is $f_{\Lambda_b} = 0.10 \pm 0.04$ [2]. In a similar way $f_s = 0.12 \pm 0.04$ is a commonly used number [3], derived from the branching ratio $B(Z_h \rightarrow B_s \rightarrow D_s l\nu X)$. And finally, $f_u = f_d = 0.40 \pm 0.04$ is derived from the branching ratio $B(Z_h \rightarrow B \rightarrow D^{(*)} l\nu)$. All the fractions have rather large systematic uncertainties.

The fraction f_s can be determined in an alternative way. Using the measured values for the mixing parameters: $\bar{\chi} = f_d\chi_d + f_s\chi_s = 0.122 \pm 0.008$, $\chi_d = 0.183 \pm 0.017$, and the limit on $x_s > 8.5$ [3] or $\chi_s > 0.49$ one obtains the most precise value for $f_s = 0.10 \pm 0.025$.

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2.1 Evidence for Ξ_b

Evidence for Ξ_b production is obtained by the ALEPH and DELPHI experiments by studying Ξ^- -lepton correlations [4], [5].

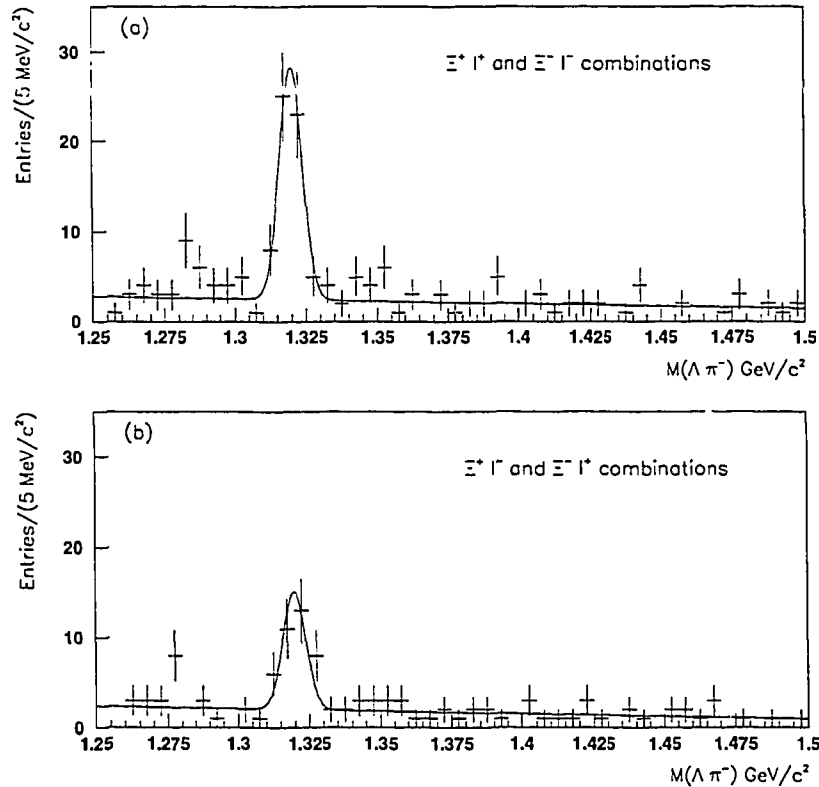


Figure 1: Invariant mass distribution for (a) like sign Ξ^\pm -lepton pairs and (b) unlike sign Ξ^\pm -lepton pairs from ALEPH.

The signal is given by $\Xi_b^- \rightarrow \Xi_c^0 l^- \nu$, where $\Xi_c^0 \rightarrow \Xi^- X$ and the charged Ξ^- is reconstructed in the $\Lambda\pi^-$ channel where $\Lambda \rightarrow p\pi$. The Λ_b baryon can also give the same final state in the decay: $\Lambda_b \rightarrow \Lambda_c^+ l^- \nu$, if $\Lambda_c^+ \rightarrow \Xi^- X$. The last branching ratio has been measured to be $3 \cdot 10^{-3}$. If one assumes a value for $f_{\Xi_b} = 0.01$ based on JETSET, then a signal branching ratio $B(Z_h \rightarrow \Xi^- l^- X) = 1.7 \cdot 10^{-4}$, is obtained with a negligible Λ_b background with a branching ratio of $B = 2.3 \cdot 10^{-5}$ [5].

Additional physics backgrounds come from the processes $B \rightarrow \Xi^- l^- X$ and $\Xi_c^0 \rightarrow \Xi^- l^+ X$, the latter one gives unlike sign Ξ -lepton pairs. Other backgrounds arise from misidentified leptons or combinatorial background below the Ξ^\pm invariant mass distribution. The cuts in the analysis are optimised to suppress both the physics and other backgrounds. They involve cuts on the flight distance and momentum of the Ξ^\pm of $3 \text{ GeV}/c$, the invariant mass of the $\Xi - \text{lepton}$ pair $m > 2$ and $m < 4.5 \text{ GeV}/c^2$ and the transverse momentum of the lepton w.r.t the jet axis of $p_t > 1 \text{ GeV}/c$.

In the DELPHI data a total number of like sign $\Xi - \text{lepton}$ pairs of 28.4 ± 6.1 and unlike sign pairs of 15.2 ± 5.2 are observed. After subtraction of the various backgrounds an excess of three standard deviations is observed.

ALEPH observes a total number of like sign $\Xi - \text{lepton}$ pairs of 51.2 ± 11 and unlike sign

pairs of 26.0 ± 6.6 are observed. After background subtraction a 1.8σ signal is obtained (see figure 1).

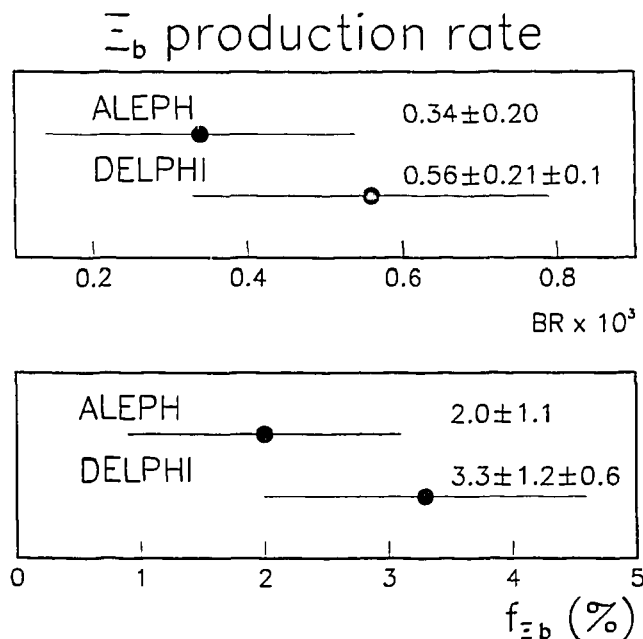


Figure 2: Measurements of (a) the branching ratio $BXSI$ (defined in the text) or (b) f_{Ξ_b}

The product branching ratio of $BXSI = f_{\Xi_b} B(\Xi_b \rightarrow \Xi_c l \nu) B(\Xi_c \rightarrow \Xi X)$ is shown in figure 2a. Assuming that the product of the last two branching ratios equals $1.7 \cdot 10^{-2}$ [5], the fraction f_{Ξ_b} in figure 2b is obtained. The average value of both experiments $f_{\Xi_b} = 0.026 \pm 0.009$ (*statonly*), is rather high if it is compared to the measured Λ_b baryon production fraction of 0.10 ± 0.04 . However, the measured fraction is also compatible with the Ξ_b production rate of around 0.01 predicted by JETSET.

2.2 A Limit on B_c Production

ALEPH studied B_c production in the following two channels (a) $B_c \rightarrow J/\psi \pi$ and (b) $B_c \rightarrow J/\psi l \nu$, where the J/ψ is reconstructed in its decay into two electrons or two muons [6]. In the first channel no events were found in the mass window of $100 \text{ MeV}/c^2$ around the expected B_c mass of $6250 \text{ MeV}/c^2$. The estimated backgrounds is 0.2 ± 0.1 events. In the second channel no events were found in the mass interval from $4500\text{-}6300 \text{ MeV}/c^2$, with an estimated background of 0.6 ± 0.15 events. This results in the following 90 % C.L. upper limits on branching ratios: $B(b \rightarrow B_c \rightarrow J/\psi \pi) < 4.2 \cdot 10^{-4}$ and $B(b \rightarrow B_c \rightarrow J/\psi l \nu) < 3.4 \cdot 10^{-4}$. Assuming the branching ratios $B_c \rightarrow J/\psi \pi = 0.2 - 0.4 \cdot 10^{-3}$, and $B_c \rightarrow J/\psi l \nu = 1 - 3 \cdot 10^{-2}$ the upper limits on f_{B_c} in channel (a) 0.11-0.21 and (b) 0.01-0.03 are derived. More statistics is needed to approach the highest predictions for f_{B_c} of around a few per mille.

3 Masses in exclusive Decays

The results from LEP on the mass of the B_s meson are all published [7]. In figure 3 the mass measurements are listed. The events are reconstructed in the following channels: $B_s \rightarrow \psi'\phi$ (1 event ALEPH), $B_s \rightarrow J/\psi\phi$ (1 event DELPHI and 1 event OPAL), $B_s \rightarrow D_s a_1$ (1 event DELPHI), and $B_s \rightarrow D_s \pi$ (1 event ALEPH and 1 event DELPHI). The latter two channels have the largest error on the mass, firstly because of the rather low intermediate D_s mass and secondly because the B_s meson could be partially reconstructed. In that case the D_s results from a $D_s^* \rightarrow D_s \gamma$ decay, in which the photon is not reconstructed. The first two channels do not suffer from this effect. The most precise measurement is obtained with the $\psi'\phi$ event, because of the ψ' mass constraint. To improve the present mass measurements more $\psi'\phi$ events are needed, since the systematic error on the measurement is negligible.

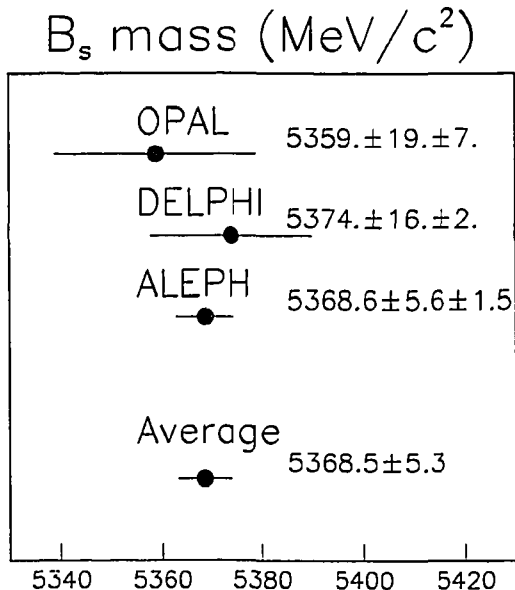


Figure 3: Overview of the B_s mass measurements at LEP.

For the Λ_b baryon the situation is different. The LEP experiments have analysed their data up to 1993 and looked in the gold plated channel: $\Lambda_b \rightarrow J/\psi\Lambda$. On the basis of the measured UA1 branching ratio ($B(\Lambda_b \rightarrow J/\psi\Lambda) = 1.8 \pm 1\%$) one would expect around 10 events, while none were found.

The mass of the Λ_b baryon is important to measure because it provides a precise test of Heavy Quark Effective Theory that predicts a mass of $5625 \pm 5 \text{ MeV}/c^2$ [8], while other models give predictions in the range of $5600 - 5900 \text{ MeV}/c^2$ [9]. DELPHI did a preliminary analysis of the 1992 data and reconstructed one event in the channel $\Lambda_b \rightarrow \Lambda_c \pi$ and one event in the decay $\Lambda_b \rightarrow D^0 p \pi$ with an expected total background of 0.3 ± 0.3 events [10]. The measured mass is $5635^{+38}_{-29} \pm 4 \text{ MeV}/c^2$. It is clear that more statistics is needed. The reconstruction of the Λ_b in these channels, has a larger background than the similar channel for the B_s , because only one (Λ_c) mass constraint is present, instead of two (D_s and ϕ or K^*) in the latter case. For this reason particle identification is crucial. The DELPHI experiment is in a good position to reconstruct these decays identifying the proton and kaon in the RICH and TPC. Here we have to wait for the analysis of the 1994 data.

4 B^* Mass and Properties

The B^* mesons decay electromagnetically by the emission of a photon, because the mass difference between the B^* and B is less than the π mass. The baryons, however, e.g. the Σ_b^* , do not decay electromagnetically but are expected to decay strongly into $\Lambda_b\pi$, like the charmed baryons.

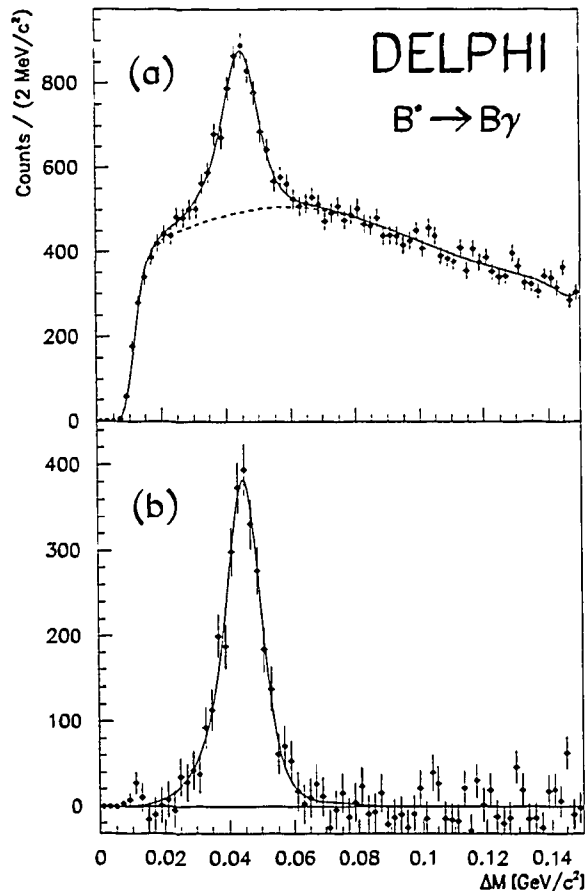


Figure 4: $B^* - B$ mass difference distribution. (a) The data are represented by points with the smoothed simulation background (dashed) and fit (solid) superimposed. (b) The $\Delta M(B^* - B)$ signal after background subtraction.

The L3 experiment has measured the B^* production rate in the following way [11]. B events are selected by requiring a muon at high transverse momentum. The B momentum direction is estimated from the tracks and neutral particles and the total momentum fixed at $35 \text{ GeV}/c$. To this system a photon is added, which is detected in the BGO electromagnetic calorimeter. The gaussian sigma of the $B^* - B$ mass difference is around $10 \text{ MeV}/c^2$. No mass measurement is given because of the systematic uncertainties in the calibration of the electromagnetic calorimeter. From the height of the B^* signal the B^* production rate is measured (see figure 5b).

The ALEPH and DELPHI experiments follow a similar approach [12], [13]. Here the details of the DELPHI analysis are given. B events are selected using the microvertex detector. A probability is calculated that all the tracks come from the primary vertex. By selecting events with a probability less than 0.01, an efficiency for B events of $64 \pm 3\%$ and a purity of

$84 \pm 4\%$ are obtained. A rapidity algorithm is used to select B decay products. If a track or neutral particle has a rapidity $|\eta|$ larger than 1.5 it is classified as a B decay product. The total momentum vector and mass are calculated assuming the pion (or for a neutral particle the photon) mass. The total B momentum is required to be above $20 \text{ GeV}/c$, the mass within $2.5 \text{ GeV}/c^2$ of the B mass. The hemisphere energy should lie within 0.6 and 1.2 times the beam energy. Using the Monte Carlo the estimated B energy is corrected for the dependence with the measured B mass and hemisphere energy. The B energy resolution is 7% for 75% of the events, the angular resolution is 15 mrad for 60% of the events.

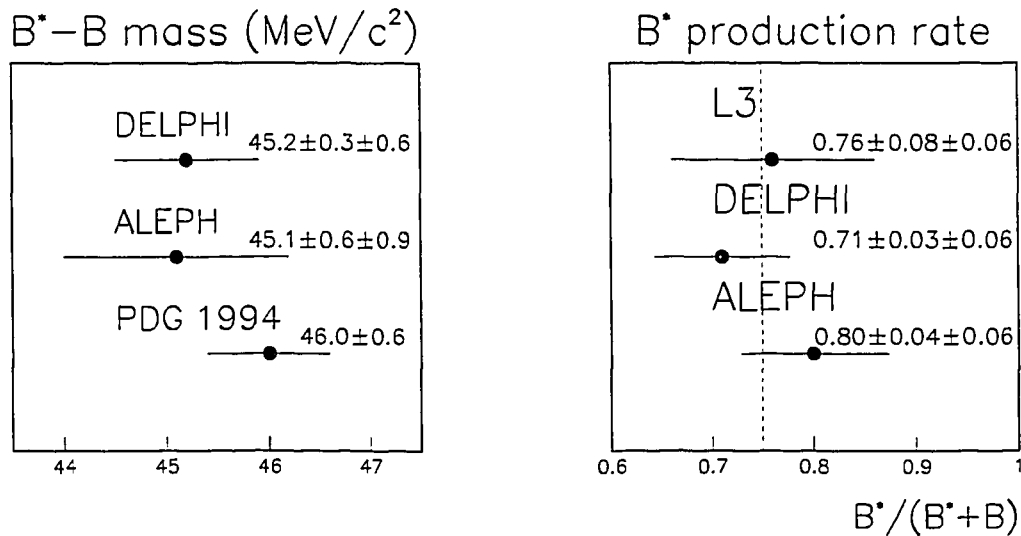


Figure 5: Summary of (a) the B^*-B mass difference measurements and (b) the B^* production rate. The dashed line represents the expectation based on spin counting.

The photons are measured after conversion $\gamma \rightarrow e^+e^-$. The energy of the photon has a resolution of 1% with an angular resolution in the azimuthal and polar angles of 1.5 mrad. The reconstruction of the direction and energy of the photon is cross-checked with neutral pions in the decay $\pi^0 \rightarrow \gamma\gamma$. DELPHI obtains a B^* signal with a gaussian width of $5.5 \text{ MeV}/c^2$ (see figure 4), while ALEPH obtains a width of around $9 \text{ MeV}/c^2$. A summary of the $B^* - B$ mass difference measurements is given in figure 5a. The values measured at LEP are comparable in precision and magnitude with the result of the PDG 1994 [14].

From the amplitude of the B^* signal the production fraction $N(B^*)/(N(B) + N(B^*))$, after correcting for the B baryon production rate f_{Λ_b} , is obtained (see figure 5b). The result is compatible with a simple spin counting model yielding 0.75 (i.e. $3/(3+1)$).

The B^* polarisation is measured fitting the angular distribution of the photon in the B^* rest frame ($\cos\theta^*$). The two longitudinal states (+1,-1) have an angular distribution proportional to $1 + \cos^2\theta^*$, while the transverse (0) is proportional to $\sin^2\theta^*$. In figure 6a the fit to the ALEPH data is shown. The results of the LEP experiments for the fraction $\sigma_l/(\sigma_l + \sigma_t)$ are given in figure 6b. The results of the LEP experiments are compatible with the expectation of a state counting model which gives 0.33 (i.e. $1/(1+2)$).

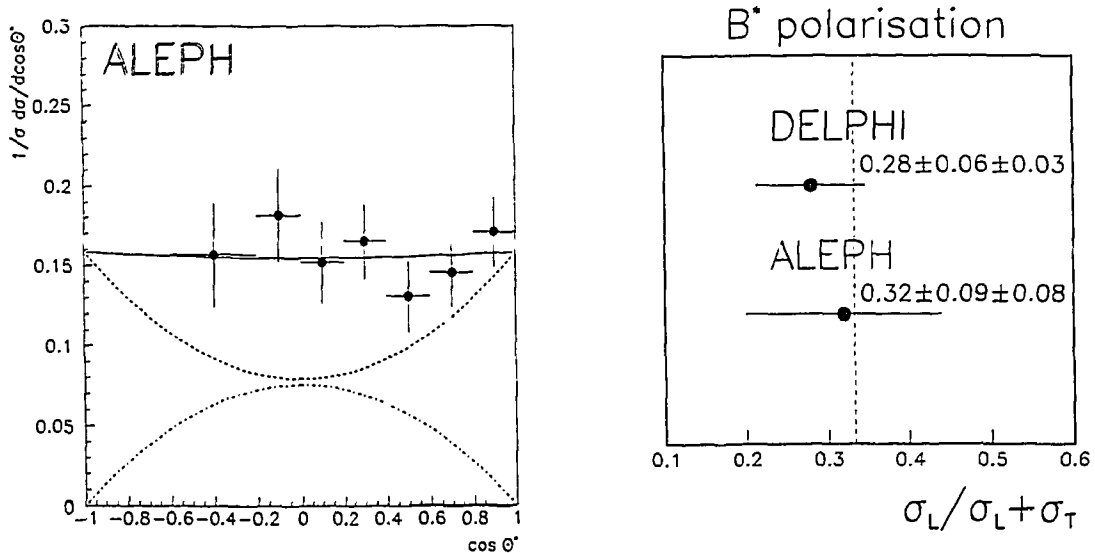


Figure 6: (a) Fit to the $\cos\theta^*$ distribution by ALEPH. The dashed and dotted curves are the contributions from the longitudinal and transverse states. (b) LEP measurements of the fraction of longitudinal states. The dashed line is the expectation based on state counting.

5 B^{**} Production and Mass

Orbitally excited B or B^{**} particles have a total angular momentum of one ($L=1$). Like for the charm sector one expects two narrow particles B_1 (in Lund notation $S=0, J=1$) and B_2^* ($S=1, J=2$) and two broad states B_0^* ($S=1, J=0$) and B_1^* ($S=1, J=1$). All the particles decay strongly: the B_1 and B_0^* mainly in $B^*\pi$; the B_1^* in $B\pi$; and B_2^* both $B^*\pi$ and $B\pi$.

In the charm sector the narrow states D_1 and D_2^* have been measured. For the broad states no experimental evidence exists yet. The production rate of $c \rightarrow D_1$ is measured to be $2.2 \pm 0.3\%$ and of $c \rightarrow D_2^*$ is measured to be $2.8 \pm 0.4\%$ [15]. These are rather large numbers. The theoretical expectation, based on Heavy Quark Effective Theory, for the B_1 mass is $5755 \text{ MeV}/c^2$ and the B_2^* mass $5767 \text{ MeV}/c^2$ with a full width $\Gamma = 20 \text{ MeV}/c^2$ [16].

Both OPAL and DELPHI have claimed evidence for B^{**} production [17], [18]. The OPAL analysis starts from a secondary vertex. The B charge is determined from the charge of the tracks giving them a weight

$$W = R(dsec/\sigma)/(R(dsec/\sigma) + R(dprim/\sigma)),$$

where R is the resolution function, $dsec$ ($dprim$) is the distance to the secondary (primary) vertex and σ is the error. The azimuthal direction of the B hadron is determined from the positions of primary vertex and B decay vertex, the polar angle from total momentum vector of tracks and neutral particles in the hemisphere. The momentum is corrected for the energy in the jet and event. Pions coming from the primary vertex are selected and like and unlike sign $B - \pi$ pairs are combined and the invariant mass is calculated. In the unlike sign distribution an excess of events is observed corresponding to 9 standard deviations [17].

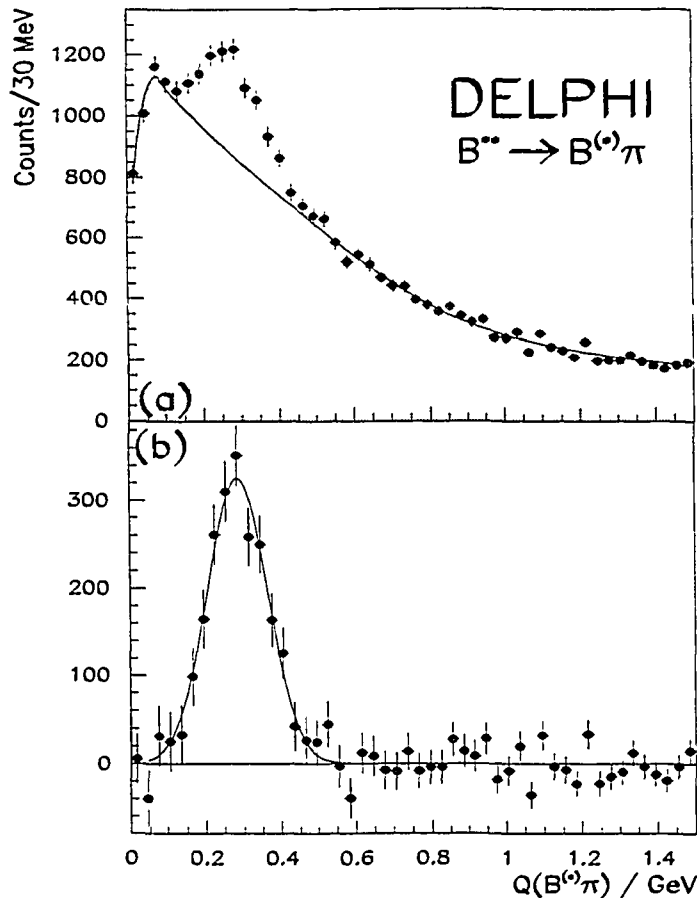


Figure 7: (a) Distribution of the Q-value of $B^{(*)}\pi$ pairs (data points) along with the Monte Carlo expectation without B^{**} production (shaded area). (b) Background subtracted $B^{(*)}\pi$ pair Q-value distribution. The fit is a simple Gaussian.

In the DELPHI analysis the rapidity algorithm, described in the previous section, is used. In addition, a vertex algorithm is developed to reconstruct one primary vertex and two B vertices. Selecting pions coming from the primary vertex - in events having three vertices - gives an excess of events above Monte Carlo corresponding to 18 standard deviations (see figure 7). An overview of the measured Q values, defined as $Q = m_{B^{**}} - m_{B^{(*)}} - m_{\pi}$, is given in figure 8a.

The following interpretation can be given to this signal. The gaussian resolution of the OPAL and DELPHI experiments is around $35 - 38 \text{ MeV}/c^2$. If the distribution is fitted with a Breit-Wigner resonance taking into account the experimental resolution one obtains a full width of 116 ± 24 (OPAL) or $145 \pm 28 \text{ MeV}/c^2$ (DELPHI). This clearly shows that the signal is not due to one single narrow resonance. The observed excess can be described by two narrow resonances (e.g. B_2^* and B_1) if they are splitted by $80 \text{ MeV}/c^2$. This scenario is possible but rather unlikely because the mass splitting in the charm system is already less than $25 \text{ MeV}/c^2$. On the other hand, the signal can be described by the sum of two broad and two narrow resonances. If the prediction of Eichten et al. is lowered for the broad states w.r.t. narrow ones by $50 \text{ MeV}/c^2$, a good description is obtained. A good fit is also obtained if two broad and two narrow states are given the same mass.

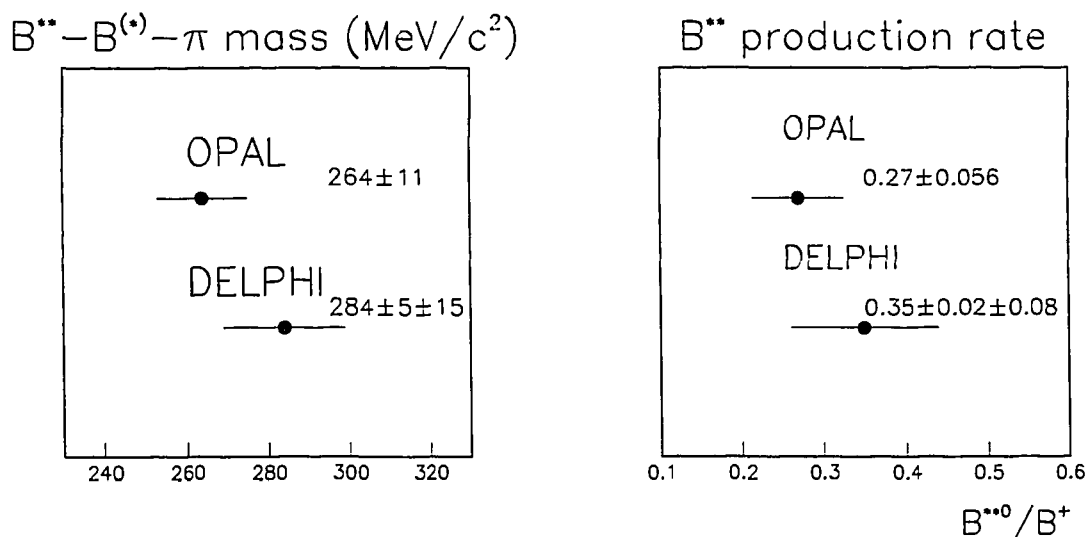


Figure 8: (a) Summary of the Q value measurements for the B^{**} and (b) the B^{**} production rate

It is difficult to give a precise mass estimate for the average of the four B^{**} states, because it depends on the decay modes. Assuming that the B^{**} branching ratio into $B^*\pi$: $B\pi = 2 : 1$, a mass shift of $30 \text{ MeV}/c^2$ is expected. This gives $m_{B^{**}} = 5711 \pm 11 \pm 13$ (OPAL) and $5732 \pm 5 \pm 20$ (DELPHI), where an additional $13 \text{ MeV}/c^2$ systematic error is assumed varying the B^{**} branching ratios.

The production rate $\sigma(B^{**0})/\sigma(B^+)$ can be calculated assuming $B(B^{**0} \rightarrow B^{(*)-}\pi^+) = 2/3$ and $\sigma(B^{**0}) = \sigma(B^{**+})$ based on isospin symmetry. The result is a very high rate of around 30% as shown in figure 8b. If the broad states are not included in the fitted signal, the production rate is only a lower limit! This high rate was not expected by theory.

6 B_s^{**} Production and Mass

For the B_s^{**} one expects, as for the B^{**} , two broad and two narrow resonances. The two narrow states are B_{s2}^* and B_{s1} with expected masses of 5834 and $5846 \text{ MeV}/c^2$ and a width of less than $2 \text{ MeV}/c^2$ [16]. The B_{s1} decays into B^*K and the B_{s2}^* into BK and B^*K . This means that an excited strange B meson decays strongly into a non-strange B meson. This has important consequences for B_s meson production. The OPAL analysis uses identified kaons above $2 \text{ GeV}/c$ based on the measured energy loss dE/dx [17]. Comparing the unlike-sign and like-sign distributions an excess of events is found (see figure 9). The signal corresponds to 5 standard deviations. The measured Q value is $81 \pm 15 \text{ MeV}/c^2$.

After fitting a Breit-Wigner resonance, taking into account the experimental resolution (gaussian width of $30 \text{ MeV}/c^2$), the intrinsic full width is $\Gamma = 47 \pm 22 \text{ MeV}/c^2$. This is compatible with a signal coming from only narrow states but also with the presence of broad states with a full width up to $75 \text{ MeV}/c^2$. Assuming that the B_s^{**} decays into B^*K and BK in a ratio of $2 : 1$, a mass of $m_{B_s^{**}} = 5883 \pm 15 \pm 13 \text{ MeV}/c^2$ is obtained. For the production rate

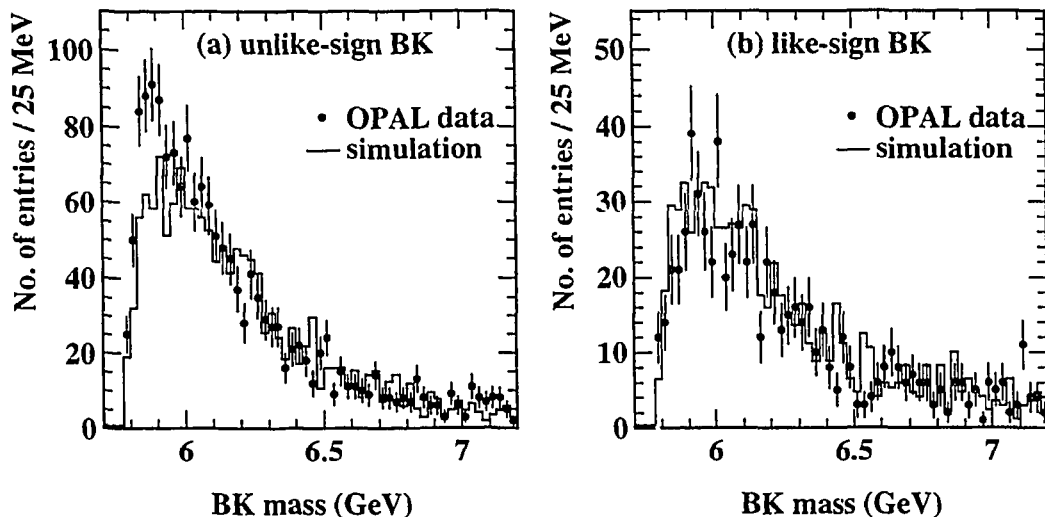


Figure 9: Invariant mass distribution for (a) unlike sign BK pairs and (b) like sign BK pairs.

$\sigma(B_s^{*0})/\sigma(B_s)$ it is assumed that $f_s = 0.12$ and $B(B^+K^-) : B(B^0K^0) = 1 : 1$. One obtains a production rate of 0.175 ± 0.052 , which is rather large. This implies that 17.5% of the produced $b - \bar{s}$ quark pairs do not lead to a B_s meson in the final state.

7 Conclusions

B physics at LEP is an exciting field. Precise mass measurements are performed on the B_s and B^* mesons. Also the properties of the B^* are measured in detail. Furthermore new particles are found: the Ξ_b , the B^{**} and B_s^{**} and their mass and/or production rates are measured. With the data taken in 1994 and the data that will be taken in 1995, it is likely that one will measure the Λ_b mass, discover new particles like the Σ_b and improve on the existing measurements. One thing which is lacking is a theory that explains from basic principles the production of charm and beauty particles and in particular the large production rates of B^{**} mesons.

Finally, the author wants to thank the organizers for the stimulating conference and their willingness to show their beautiful country.

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