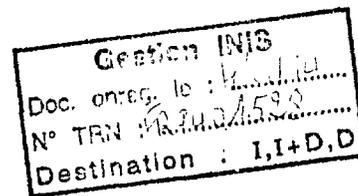


# Laboratoire de l'Accélérateur Linéaire

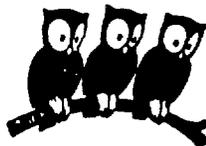
## LEP MEASUREMENTS ON PRODUCTION, MASS, LIFETIME OF BEAUTY PARTICLES

Guy Wormser



*Presented at "Hadron 93"  
Como, Italy, June 21-25, 1993*

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# LEP MEASUREMENTS ON PRODUCTION, MASS, LIFETIME OF BEAUTY PARTICLES

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## Abstract

This report details the present knowledge about the individual properties of the different beauty particles using the results of the LEP experiments. Individual lifetimes for  $B_d^0$  and  $B^+$  are found to be equal within 10% whilst a 15% precision is reached for  $B_s^0$  and  $\Lambda_b$ . The  $\Lambda_b$  lifetime is found to be smaller than  $\tau_{B^+}$  with a  $2.7 \sigma$  significance. The production rate of each of these particles is measured at the 20% level. Preliminary evidence for  $\Xi_b$  production has been reported. Finally, the  $B_s^0$  meson mass has been measured to be  $5373 \pm 4 \text{ MeV}/c^2$ .

## Introduction

This report details the present knowledge about the individual properties of the different beauty particles using the results of the LEP experiments. Precise lifetime information will measure the validity of the spectator model approximation in B weak decays. In such a framework, all different species of B particles should have the same lifetime. This approximation is not valid for charmed particles where the  $D^+$  lifetime is 2.5 times larger than the  $D^0$  one and the  $\Lambda_c$  lifetime is two times smaller than the  $D^0$  one. The first effect is commonly believed to be due to the presence of two identical  $\bar{d}$  quark in the final state which leads to a destructive interference. In  $B^+$  decays, the same effect will occur but with a reduced strength because of the larger available phase space and should lead to a discrepancy between  $\tau_{B^+}$  and  $\tau_{B^0}$  smaller than 10%. For the baryon case, the  $\Lambda_c$  short lifetime is due to the presence of annihilation diagrams which are not helicity suppressed. These diagrams should also occur in the beauty case, leading to a somewhat shorter  $\Lambda_b$  lifetime.

The measurement of the production rate of the different B mesons, i.e the probability for a b quark to hadronize in each species will be especially useful when interpreting average mixing results to extract  $B_d^0$  and  $B_s^0$  oscillation frequencies.

With the present statistics, the field of the complete exclusive reconstruction of  $B_s^0$  and  $\Lambda_b$  is opening up. A precise mass measurement of these states will give useful insight on heavy quark dynamics, for instance by comparing the  $SU_3$  symmetry breaking in the beauty case to the one in the charm case. This report is thus organized as follows : Section 1 contains the description of the lifetime measurements for each beauty species, Section 2 deals with production rates and the exclusive reconstruction is detailed in Section 3.

### 1. Specific lifetime measurements

The usual method to perform the lifetime measurement of a given particle is of course to perform a complete exclusive reconstruction of that particle. This method has been applied at LEP (see below) but is not yet the method of choice because the sample of completely reconstructed B particles is too small, typically a few tens of  $B_d^0$ ,  $B^+$  per experiment. To overcome this problem, specific B states can be partially reconstructed in semileptonic decays which offer much larger branching fractions and still allow a good distinction of each B particle through the reconstruction of the charm particle in the final state. This correlation is made possible by the smallness of non spectator effects in semileptonic decays. A  $\bar{B}_s^0$  decay will then be tagged by a  $D_s^+$  -lepton correlation, a beauty baryon decay by a  $\Lambda_c$  -lepton correlation. Since  $D_s^+$  and  $\Lambda_c$  also lead to specific decay products, namely  $\phi, \Lambda$  and protons, it will also be possible to tag  $B_s^0$  and  $\Lambda_b$  by  $\phi$ -lepton and  $\Lambda$ -lepton (or proton-lepton) respectively.  $\bar{B}_d^0$  and  $B^-$  lead to  $D^+(D^*)$ -lepton and  $D^0$  -lepton correlation but some mixing is to be expected because of the production of  $D^{**}$  -lepton events where the initial D-lepton correlation can be lost in the  $D^{**}$  decay and due to the inefficiency to identify  $D^0$  coming from a  $D^*$  decay as such. As a result, the  $D_s^+$  -lepton samples correspond to  $\bar{B}_s^0$  decays in more than 90% of the cases, while a  $D^0$  -lepton sample contains typically 75%  $B^-$  decays and 25%  $\bar{B}_d^0$  decays.

### 1.1 $B_d^0$ and $B^+$ lifetimes

Fig. 1-a shows the  $K\pi$  mass spectrum obtained in correlation with an high  $p_t$  lepton in ALEPH[1] where a clear  $D^0$  signal can be seen for  $D^0$  coming from  $D^*$  decays. Similar signals are obtained for the  $D^*$  -lepton correlation using  $K\pi\pi\pi$  as  $D^0$  decay mode (Fig. 1-b), direct  $D^0$  -lepton in the  $K\pi$  decay mode (Fig. 1-c) and for the  $D^+$  -lepton correlation in the  $K\pi\pi$  decay mode (Fig. 1-d) as measured by DELPHI[3]. The OPAL collaboration[2] reported similar results. The proper time is extracted from the D-lepton event in a straightforward manner : the D-lepton vertex provides the B decay length while the B energy is usually obtained through a parametrization of the observed D-lepton energy with a precision of 15%. DELPHI has taken advantage that since in  $B^+ \rightarrow D^0$  -lepton X decay, the neutrino is the only unmeasured B fragment, a measurement of the jet visible energy allows a precise measurement (8%) of the B energy to measure from the  $D^0$  -lepton in a event-by-event basis.

Counting the number of charged tracks at the B secondary vertex also allows to distinguish between neutral and charged B decays. This method has been used in bubble chamber or emulsion experiments and has been applied to DELPHI recently[4]. In that case, events where tracks can be unambiguously attributed to a primary and a secondary vertex are selected. The number of wrong charge measurements at the secondary vertex is monitored through the amount of unphysical doubly charged vertices which is compared to the results of Monte-Carlo simulation program. This program is also used to correct for the bias towards long lived events introduced by the selection procedure. The charged sample is almost pure in  $B^+$  whereas the neutral sample contains a mixture of  $B_s^0$ ,  $B_d^0$  and  $\Lambda_b$  mesons. Recent measurements of  $B_s^0$  and  $\Lambda_b$  lifetimes and production rates were used to extract the  $B_d^0$  lifetime from the neutral sample.

Method	$B_d^0$	$B^+$	
Exclusive	$1.19^{+0.42}_{-0.29} \pm 0.14$	$1.77^{+0.45}_{-0.34} \pm 0.14$	ALEPH
$D\ell$	$1.52^{+0.2}_{-0.18} \pm 0.07$ $1.17^{+0.29}_{-0.23} \pm 0.15 \pm 0.5$ $1.51^{+0.24+0.12}_{-0.23-0.14}$	$1.47^{+0.22}_{-0.19} \pm 0.15$ $1.3^{+0.33}_{-0.23} \pm 0.15 \pm .05$ $1.51^{+0.3+0.12}_{-0.28-0.14}$	ALEPH DELPHI OPAL
Charge counting	$1.56 \pm 0.25 \pm 0.17 \pm 0.07$	$1.56 \pm 0.19 \pm 0.13$	DELPHI
Total	$1.43 \pm 0.14$	$1.51 \pm 0.13$	LEP

Table 1 :  $B_d^0$  and  $B^+$  Lifetime (in ps)

Table 1 summarizes the different measurements presented at the conference by the three LEP experiments including the preliminary measurements performed by ALEPH[5] using the exclusively reconstructed  $B_d^0$  and  $B^+$  samples (see Fig. 8). The average  $B_d^0$  and  $B^+$  lifetimes are found to be consistent with each other with a relative precision slightly better than 10%, an impressive achievement. The quality of this measurement should rapidly improve with the addition of data collected in 1992 and a better handle on  $D^{**}$  production that will follow from the direct observation of  $D^{**}$ -lepton correlation.

### 1.2 $B_s^0$ lifetime

The method of choice is as explained above to use  $D_s^+$ -lepton correlations.  $D_s^+$  are reconstructed through the  $\phi\pi$  and  $K^*K$  decay modes. Fig. 2 shows as an example the preliminary DELPHI result[6] including 1992 data where 20  $D_s^+$  events can be clearly found over a negligible background. In addition to similar results from ALEPH[7] and OPAL[8], DELPHI[9] has reported two other measurements based on  $\phi$ -lepton correlations and inclusive  $D_s^+$  production which is also sensitive to  $B_s^0$  production to a lesser extent. The results are summarized on Table 2. The LEP average has a relative precision of 15% and is not significantly different from the  $B_d^0$  and  $B^+$  measurements reported above.

	$1.13^{+0.35}_{-0.26} \pm .09$	OPAL
$D_s$ -lepton	$2.26^{+0.66}_{-0.48} \pm 0.12$	ALEPH
	$1.35 \pm 0.45$	DELPHI
$\phi$ -lepton	$1.24^{+0.61}_{-0.52} \pm 0.2$	DELPHI
Inclusive $D_s$	$0.80^{+0.46}_{-0.30} \pm 0.24$	DELPHI
Total	$1.25 \pm 0.20$	LEP

Table 2 :  $B_s^0$  Lifetime (in ps)

### 1.3 $\Lambda_b$ lifetime

In the following,  $\Lambda_b$  will be used as the generic name for all B baryons which produce either a  $\Lambda_c$  or a  $\Lambda$  in their semileptonic decay since the experiments do not have access to exact nature of the initial beauty baryon. The first set of results concern the observation of  $\Lambda$  lepton correlations reported by the three LEP experiments and illustrated by the OPAL[10] results shown in Fig. 3. Because of the long decay distance of the  $\Lambda$ , its trajectory cannot be reconstructed with the microvertex detectors and therefore

the  $\Lambda_b$  vertex cannot be reconstructed as precisely as in the  $B_s^0$  case. The three experiments have chosen three different methods : ALEPH[11] uses the lepton impact parameter distribution, OPAL uses nevertheless the intersection of the lepton and the  $\Lambda$  while DELPHI[12] looks for an extra pion coming from the  $\Lambda_c$  decay to get a precise  $\Lambda_b$  vertex. The first two methods suffer some dilution from the poor determination of the  $\Lambda_b$  vertex and the third has a lower efficiency.

These results are complemented by the clean observation of fully reconstructed  $\Lambda_c$  in correlation with high  $p_t$  leptons, illustrated by the ALEPH[13] result on Fig. 4. The  $\Lambda_c$  baryon is reconstructed in the  $pK\pi$  mode and proton identification based on  $dE/dx$  for ALEPH and OPAL[14] or on the RICH in the DELPHI[12] case is used to avoid any kinematic reflexion from  $D^+$  or  $D_s^+$  decays. Table 3 summarizes all these results. The average  $\Lambda_b$  lifetime  $\tau_{\Lambda_b} = 1.00 \pm 0.14$  ps is beginning to be significantly lower than the beauty mesons' one. Compared to the largest one, the  $B^+$  lifetime, ( $\tau_{B^+} = 1.51 \pm 0.13$  ps), the statistical significance is 2.7 standard deviation. While awaiting for more data to confirm this expected effect, some more information could be brought by the observation of proton-lepton correlations. Good particle identification is of course required and encouraging results from DELPHI have been submitted to the conference.

$\Lambda - \ell$	$1.12_{-0.24}^{+0.32} \pm 0.16$	ALEPH (Lepton)
	$1.01_{e-0.18}^{+0.2} \pm 0.08$	OPAL ( $\Lambda \ell \nu$ )
	$0.68_{-0.25}^{+0.36} \pm 0.12$	DELPHI ( $\Lambda \pi \ell$ )
$\Lambda_c - \ell$	$1.16_{-0.32}^{+0.42} \pm 0.07$	ALEPH
	$1.1_{-0.6}^{+0.5}$	DELPHI
Total	$1.00 \pm 0.14$ ps	LEP

Table 3 :  $\Lambda_b$  lifetime (in ps)

#### 1.4 Lifetime summary

Table 5 summarizes the results described above on the four individual lifetimes. The precision with which they are measured is comprised between 10% and 15%, a remarkable achievement.  $B_d^0$  and  $B^+$  lifetimes are found to be equal at the 10% level, in striking contrast with the charm case. On the other hand, the  $\Lambda_b$  lifetime is beginning to be significantly smaller, with a  $2.7 \sigma$  effect compared to the  $B^+$  meson. It is now highly probable that the precise hierarchy of the B lifetime will be measured in a year from now.

## 2. B particle production rates

It is highly desirable in order to interpret meaningfully the average mixing results to know the probability with which a b quark will fragment into a  $B_d^0$  meson,  $f_d$ , and a  $B_s^0$  meson,  $f_s$ . The DELPHI collaboration[15] has compared the amount of D mesons coming from a b quark to the D mesons rate coming from  $B_d^0$  or  $B^+$  mesons at the  $\Upsilon(4S)$ . The underlying assumption is that the probability for a c quark to hadronize as a  $D^0$  meson does not change from 10 to 91 GeV. The result is  $f_d = 0.38 \pm 0.06$  which leads to  $f_s + f_{baryon} = 0.24 \pm 0.12$ .

The  $B_s^0$  meson production rate  $f_s$  is measured using the  $D_s^+$  -lepton correlation. Assuming a 2.8% branching ratio for the  $D_s^+ \rightarrow \phi\pi$  branching ratio and 11% for the semileptonic branching fraction, the average over the three LEP experiments give  $f_s = 0.15 \pm 0.03 \pm 0.03$ [16]. For the  $\Lambda_b$ , the average  $f_{baryon} \cdot BR(\Lambda_b \rightarrow \Lambda_c l\nu) \cdot BR(\Lambda_c \rightarrow \Lambda X)$  is  $(0.34 \pm 0.06)\%$ . Using  $27\% \pm 9\%$  as the inclusive branching fraction of  $\Lambda$  in  $\Lambda_c$  decays and  $8\% \pm 2\%$  for the semileptonic  $\Lambda_b$  branching ratio (this branching ratio has to be smaller than the average semileptonic BR since the  $\Lambda_b$  lifetime is lower than the average b lifetime),  $f_{baryon}$  is measured to be  $0.16 \pm 0.07$ . Using now the  $\Lambda_c$  -lepton correlation,  $f_{baryon} \cdot BR(\Lambda_b \rightarrow \Lambda_c l\nu) \cdot BR(\Lambda_c \rightarrow pK\pi) = 7.7 \pm 1.6 \cdot 10^{-4}$  with  $4\% \pm 1\%$  branching ratio for  $\Lambda_c$  into  $pK\pi$ ,  $f_{baryon}$  is  $0.24 \pm 0.10$ . The combined result is thus  $f_{baryon} = 0.19 \pm 0.06$ , a somewhat large result but with a large error too.

The DELPHI collaboration[17] reported the evidence of a  $\Xi$ -lepton correlation which would indicate the production of a  $\Xi_b$  baryon. Fig. 5-a shows the  $\Lambda\pi$  invariant for right sign correlation with a lepton of  $p_t$  above 1.2 GeV/c. Nine candidates are found while at most one event is found in wrong sign combination (Fig. 5-b)

To conclude this section, let us mention that the L3 collaboration[18] reported evidence on the production of  $B^*$  mesons. Low momenta photons were searched for in events containing a high  $p_t$  lepton and boosted back in a approximate B rest frame to obtain the photon energy distribution in the B center of mass displayed on Fig. 6. A clear excess is visible at 50 MeV corresponding to a ratio  $N_{B^*}/N_B = 0.82 \pm 0.08 \pm 0.12$  in good agreement with the value 0.75 expected from spin counting.

## 3. $B_s^0$ mass measurement

Up to now, evidence from  $B_s^0$  production at LEP came from semileptonic decays and therefore no mass determination was possible. The only information available so far was an indirect CUSB measurement[19] based on the inclusive photon spectrum at the  $\Upsilon(5S)$  which gave two solutions for the  $B_s^0$  - $B_d^0$  mass difference of  $82 \pm 2.5$  MeV/ $c^2$  or  $121 \pm 10$  MeV/ $c^2$ . The OPAL[8] collaboration had also published the observation of a  $J/\psi \phi$  event attributed to a  $B_s^0$  decay with a invariant mass of  $5360 \pm 70$  MeV/ $c^2$ , with an unfortunately very large mass error. ALEPH[21] and DELPHI[22] have reported at this conference precise mass determinations, as well as the CDF experiment[23]. These experiments have focused on the few hadronic decay modes which offer a good visibility, a negligible combinatoric background and, above all, a small reflection probability from the more abundantly produced  $B_d^0$  meson. A strong protection against such a problem lies in the requirement of a  $\phi$  meson in the  $B_s^0$  or daughter  $D_s^+$  decay. The DELPHI experiment takes also advantage of its good Kaon identification provided by its RICH Cerenkov counter[20]. The selected modes are (i)  $J/\psi \phi$ , (ii)  $\psi' \phi$  and (iii)  $D_s^+ \pi$  where the  $D_s^+$  decays into  $\phi\pi$  for the ALEPH collaboration, whereas DELPHI considers in addition

(iv) the  $K^* K$  decay of the  $D_s^+$  in the  $D_s^+ \pi$  mode and (v) the  $D_s^+ a_1(1260)$  mode with the  $D_s^+$  into  $\phi\pi$ . ALEPH has found one candidate in modes (ii) and (iii) and DELPHI one in modes (i), (iii), (iv) and (v). The invariant mass spectrum of the DELPHI candidates can be found on Fig. 7. Table 4 summarizes the properties of the 7  $B_s^0$  events unambiguously reconstructed at LEP so far. The individual mass errors are the result of the kinematic constrained fit imposing the correct vertex topology and the PDG value for intermediate resonances (except for the OPAL event). The main systematic error source comes from the uncertainty in the absolute mass scale. This is controlled by the observed deviation from the PDG value of reconstructed  $B_d^0$  and  $B^+$  signals using similar channels and fitting procedures as those described above. Fig. 8 shows the reference peak used by ALEPH group[5]. The 1993 average for the  $B_s^0$  mass including the CDF measurement is thus  $5373 \pm 4 \text{ MeV}/c^2$ . The  $B_d^0 - B_s^0$  mass difference ( $94.5 \pm 4.6$ ) turns therefore to be quite close to the  $D_s^+ - D^+$  one ( $99.5 \pm 0.6 \text{ MeV}/c^2$ ), as expected in the heavy quark limit.

A more inclusive analysis based to strict Kaon identification was performed by DELPHI[24] looking for  $KK\pi\pi$  and  $KK4\pi$  final states. The corresponding mass distribution is shown on Fig. 9, where  $17 \pm 7 B_s^0$  events are observed.

Decay mode	$B_s^0$ mass (MeV)	E(GeV)	Flight (nm)	Expt.
$D_s^-(\phi\pi)\pi$	$5333 \pm 27$	28.0	4.5	DELPHI
$D_s^-(K^0 K)\pi$	$5340 \pm 30$	27.8	0.1	
$D_s^-(\phi\pi)a_1$	$5341 \pm 23$	26.8	1.2	
$J/\psi\phi$	$5387 \pm 19$	36.7	2.4	
average	$5357 \pm 12 \pm 6$			
$D_s^-(\phi\pi)\pi$	$5401 \pm 77$	40.9	1.6	ALEPH
$\psi'\phi$	$5368.4 \pm 5.6$	41.7	4.5	
average	$5368.4 \pm 5.6 \pm 1.5$			
$J/\psi\phi$	$5360 \pm 70$	35		OPAL
$14.0 \pm 4.7 J/\psi\phi$ 's	$5383.3 \pm 4.5 \pm 5.0$			CDF
Overall average	$5373.1 \pm 4.2$			

Table 4 :  $B_s$  mass in  $\text{MeV}/c^2$

#### 4. Conclusion

The table 5 summarizes the present knowledge concerning the B particles mostly given by the recent results from LEP experiments. The achievement is already impressive and some areas will soon be improved : the production rates of the different particles will probably reach the 10% precision level and concerning  $\Lambda_b$  exclusive reconstruction, although no results were reported at this conference, it is expected that a few events will allow to pin down the  $\Lambda_b$  mass to 10 MeV in a near future. The beauty lifetime hierarchy is now reasonably well established and in good agreement with expectations : non spectator effects are only important in  $\Lambda_b$  decays. The  $B_s^0$  mass has been precisely measured

using the “gold plated” decay modes. In the future, the general pattern of  $B_s^0$  decays will become accessible. LEP experiments are in this respect quite complementary to  $\Upsilon(4S)$  experiments.

LEP 93	Mass	Lifetime	Prod. Rate	$\Sigma$ BR seen
$B_d^0$	$5278.7 \pm 2.1$	$1.43 \pm 0.14$	$f_d = 0.38 \pm 0.06$	0.3
$B^+$	$5278.6 \pm 2$	$1.51 \pm 0.13$	$f_d = 0.38 \pm 0.06$	0.21
$B_s^0$	$5366 \pm 6$	$1.25 \pm 0.20$	$f_s = 0.25 \pm 0.08$ $\pm 0.09$	$\psi\phi, \psi'\phi$ $D_s\pi, D_s a_1$
$\Lambda_b$	$5641 \pm 50$	$1.00 \pm 0.14$	$f_\Lambda \gtrsim 0.10$ (?)	?
Others baryons	$\Xi_b$ seen	?		$\Xi\ell\nu$

Table 5 : Summary of B particle properties

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### Figure Captions

**Figure 1 :** (a)  $K\pi$  mass spectrum for D candidates coming from  $D^*$  decays in correlation with a high  $p_t$  lepton (from ALEPH)

(b)  $K\pi\pi\pi$  mass spectrum for D candidates coming from  $D^*$  decays in correlation with a high  $p_t$  lepton (from ALEPH)

(c)  $K\pi$  mass spectrum in correlation with a high  $p_t$  lepton (from ALEPH)

(d)  $K\pi\pi$  mass spectrum in correlation with a high  $p_t$  lepton (from DELPHI)

**Figure 2 :**  $KK\pi$  mass spectrum in correlation with high  $p_t$  lepton (from DELPHI)

**Figure 3 :** Proton  $\pi$  mass spectrum in correlation with a high  $p_t$  lepton (from OPAL). The shaded histogram corresponds to wrong sign correlations.

**Figure 4 :** (a)  $pK^-\pi^+$  mass spectrum in correlation with a right sign ( $l^-$ ) high  $p_t$  lepton (from ALEPH).

(b)  $pK^-\pi^+$  mass spectrum in correlation with a wrong sign ( $l^+$ ) high  $p_t$  lepton.

**Figure 5 :** (a)  $\Lambda\pi^-$  mass spectrum in correlation with a right sign ( $l^-$ ) high  $p_t$  lepton (from DELPHI)

(b)  $\Lambda\pi^-$  mass spectrum in correlation with a wrong sign ( $l^+$ ) high  $p_t$  lepton.

**Figure 6 :** Photon energy spectrum in the approximate B rest frame for events containing a high  $p_t$  lepton (from L3). The shaded histogram corresponds to a simulation without  $B^*$  production.

**Figure 7 :** (a)  $KK\pi\pi$  mass spectrum in the  $D_s^+ \pi$  channel and  $D_s^+ \rightarrow \phi\pi$

(b)  $KK\pi\pi$  mass spectrum in the  $D_s^+ \pi$  channel and  $D_s^+ \rightarrow K^* K$

(c)  $KK4\pi$  in the  $D_s^+ a_1(1260)$  channel. The dotted line in these three histograms shows the expected contribution from  $B_s^0 \rightarrow D_s^* \pi$  and  $D_s^* a_1(1260)$ , normalized to the number of observed  $B_s^0$  candidates.

(d)  $J/\psi \phi$  mass spectrum

**Figure 8 :**  $K\pi\pi$  mass spectrum for exclusive  $B_d^0$  and  $B^+$  reconstruction (from ALEPH)

**Figure 9 :**  $KK\pi$  and  $KK4\pi$  mass spectrum with two RICH identified kaons (from DELPHI)

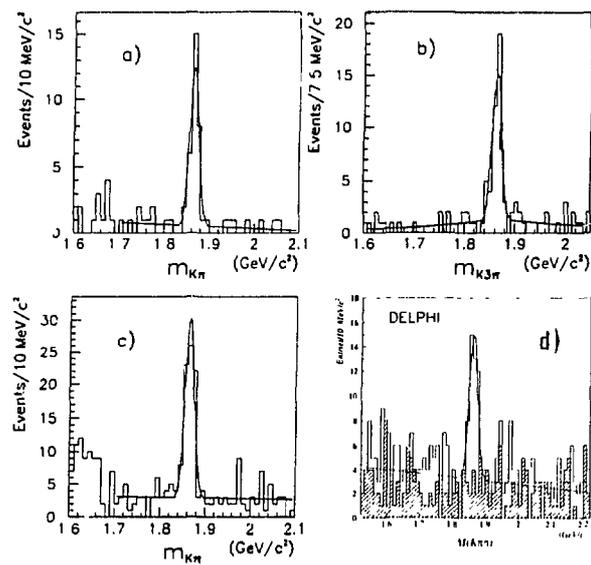


Fig. 1

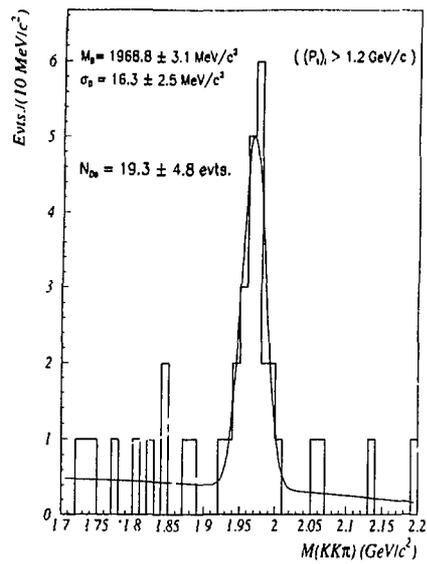


Fig. 2

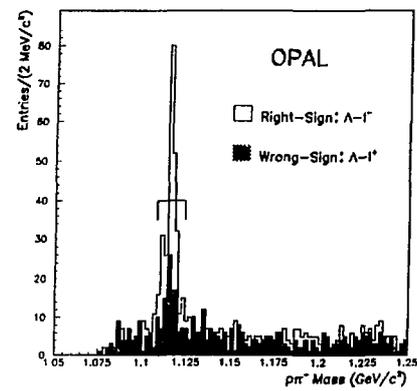


Fig. 3

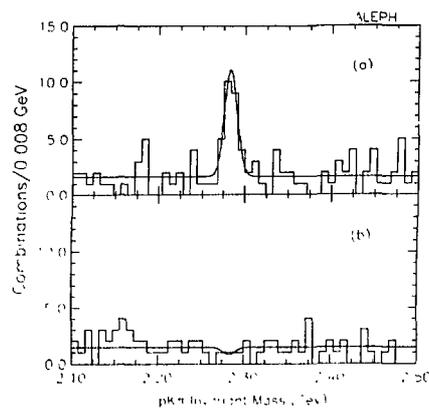


Fig. 4

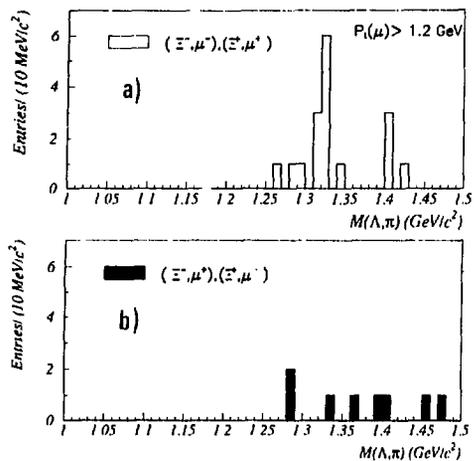


Fig. 5

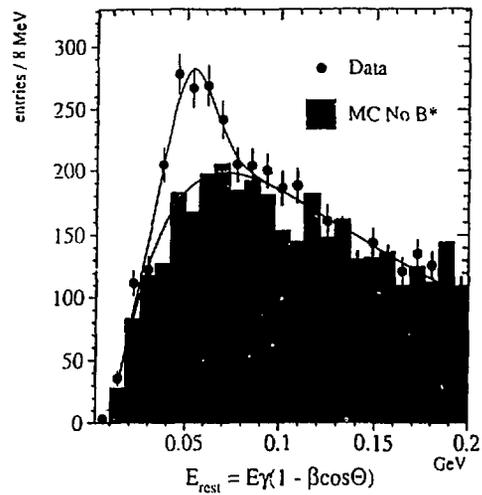


Fig. 6

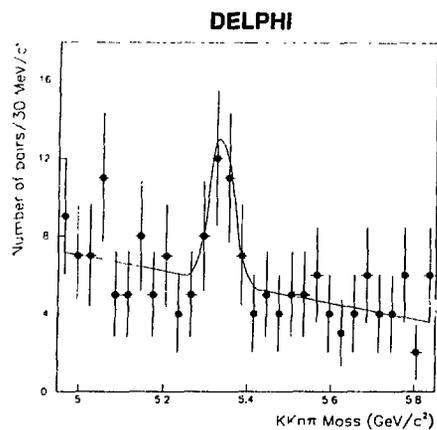


Fig. 7

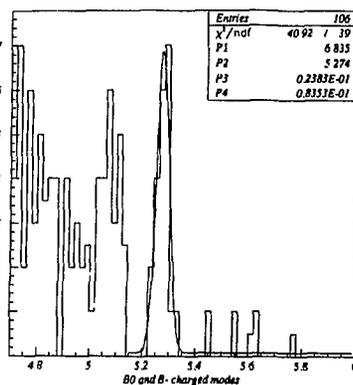


Fig. 8

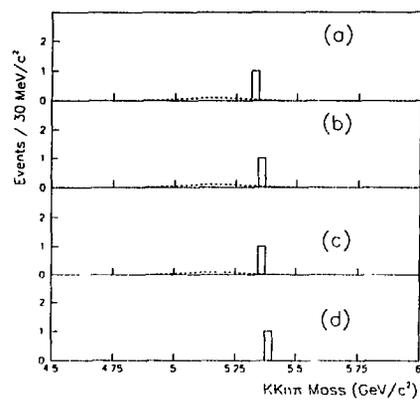


Fig. 9