EPS95 Ref. 0410
Submitted to Pa-05 Pa-14
Pl-05

July 7, 1995

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

Time dependent B_s mixing from lepton-kaon correlations with the ALEPH detector

The ALEPH Collaboration

Abstract

Lower limits have been set on the B_s^0 meson mixing parameter Δm_s using data collected from 1991 to 1994 by the ALEPH detector. First a new method is presented where the time dependent charge asymmetry is measured in lepton-kaon correlations. Events containing a high p, p_T lepton and a fragmentation kaon are selected. The kaon charge, associated with the jet charge in the opposite hemisphere, tags the b quark charge at production while the lepton tags the B_s at decay. Topological vertexing is used to define the B vertex from which the decay time is measured. 4436 lepton-kaon correlations are selected, in which the B_s mistag fraction is 19%. Two methods are used to search for the B_s^0 mixing: the well known log-likelihood difference method and a new method, the fitted amplitude method, proposed to allow an easy combination of various results. They give identical limits. A lower limit of $\Delta m_s > 4.0\ ps^{-1}$ (95% C.L.) is set. An update of the dilepton analysis has also been performed using the same data sample and gives a 95% C.L. level lower limit of $\Delta m_s > 5.6\ ps^{-1}$. Both these limits assume the B_s fraction to be $(12 \pm 3)\%$.

Contribution to the International Europhysics Conference on High Energy Physics,
Brussels, Belgium, July 1995

1 Introduction

Like neutral kaons, neutral B^0 oscillate. Consequently if a B^0 is produced at time t=0, the probability to have a B^0 at time t is:

$$P_{B^0 \to B^0} = \frac{1 + cos\Delta mt}{2} \cdot e^{-\frac{t}{\tau}}$$

where τ is the B^0 lifetime and Δm is the mass difference between the two mass eigenstates B^0 and $\overline{B^0}$. In the standard model mixing, through box diagrams computations involving top quark and W exchange, Δm_d and Δm_s depend on the Cabibbo Kobayashi Maskawa (CKM) matrix elements V_{td} and V_{ts} [1] but also on the top mass and on poorly known strong interaction parameters. Most of these uncertainties cancel in the ratio $\Delta m_s/\Delta m_d$, thus the measurement of both B_d and B_s mixing should provide strong constraint on the CKM matrix element's ratio V_{ts}/V_{td}.

Various lower limits (95% C.L.) have been set on Δm_s, first with dilepton analyses by ALEPH at 3.9 ps^{-1} [2] and OPAL at 2.2 ps^{-1} [3]. The ALEPH lepton-jet charge method recently published [4], has raised this limit to $\Delta m_s > 6.1 ps^{-1}$ using f_s= 12% where f_s is the the fraction of b hadrons that are produced as B_s.

The present paper first reports on a new search for the time dependent B_s mixing using a high p_T lepton for tagging the b quark charge at decay time and a combination of the fragmentation kaon charge with the jet charge in the opposite hemisphere for tagging the charge at production time. The charge asymmetry of the lepton-kaon system is observed as a function of the reconstructed B_s proper time. To set a limit on Δm_s, a new method has been used. For any given Δm_s, a B_s oscillation amplitude $\mathcal{A}$ is fitted by adjusting the observed charge asymmetry time dependence to the expected one in which the B_s oscillation is rescaled by a factor $\mathcal{A}$. The fitted value of $\mathcal{A}$ is therefore compared to either 0 (no mixing is observed) or 1 (the mixing is observed for this value of Δm_s). This method allows a combination of mixing results originating from various analyses and experiments.

Finally an update is reported of the dilepton analysis [2] used to derive a limit on the B_s^0 mixing.

2 Event selection, proper time determination and initial flavor tagging

2.1 Event selection

The ALEPH detector has been described in detail elsewhere [5] with its performance [6]. The present analysis is based on about 3 million hadronic Z^0decays recorded during the 1991-1994 data runs.

Events containing one high momentum ($p >$ 3 GeV/c) and high transverse momentum ($p_T >$ 1.25 GeV/c) lepton are selected, giving a high probability that they originate from a primary semileptonic b decay.

Large simulated samples of hadronic events (3.7 million $q\bar{q}$ and 0.57 million $b\bar{b}$) have been analyzed. The Monte Carlo generator is based on JETSET 7.3.

2.2 Proper time determination

The proper time of a b hadron decay is determined from its decay length and momentum as in the dilepton analysis [2]. Excluding the lepton track, topological vertexing is used to define a 'charm' vertex. Then the charm track is vertexed with the lepton track to give the B decay point. In the Monte Carlo simulation one can compare the measured distance d_{reco} to the generated one d_{true} as a function of the true time t_{true} ($t_{true} = g_{true} d_{true}$ with $g_{true} = m_b / p_B \cdot c$). It is found that the decay length resolution depends on the true time. It displays a negative tail corresponding to fragmentation tracks wrongly assigned to the secondary vertex. To minimize this bias, it is required that the distance of the charm vertex to the primary vertex exceeds $300 \mu m$. After this cut, these distributions have a core containing 83% of the events centered around 0 with an rms of $0.26 ps$, the rest being the negative tail.

The b hadron momentum p_B results from the sum of three contributions obtained from charged particles, missing neutrino momentum and part of the neutral energy of the lepton jet. The distribution of $\Delta p_B / p_B$ is centered at zero with a rms of 17%. The cut on the charm distance creates a time dependence of the selection efficiency with t_{true} which is parametrized from the simulation and used later in the fit.

The determination of the time resolution (decay length and boost) and of the selection efficiency has been done independently for cascade and primary b leptons.

2.3 b charge tagging at production time

From strangeness conservation, the B_s meson hadronizes in association with the production of a fast strange hadron. While the lepton tags the b charge at decay time, the fragmentation kaon allows to tag the b charge at production time and enriches the sample in B_s. Charged tracks of momentum greater than 1.5 GeV are identified as kaons if the sum of the two values of the dE/dx estimator, assuming first the particle to be a kaon and then to be a pion, is negative. The fragmentation kaon is taken as the most energetic kaon at the primary vertex. In these conditions, 22% of the lepton hemispheres contain such a kaon.

To enrich the secondary vertex with D_s, it is required that this vertex has either 0 or 2 kaons or if it has only one kaon, its charge must be opposite to the lepton charge.

To reduce the mistag rate the product of the kaon charge by the b charge in the opposite hemisphere is required to be negative. This opposite hemisphere charge is the lepton charge for dileptons events or the jet charge for single lepton events (calculated with momentum weighting to a power $\kappa = 0.5$).

From the Monte Carlo simulations, the fraction of B_s is determined to be 0.165 ± 0.005 while the input production fraction is 0.122. The kaon selection enriches the B_s sample by a factor 1.35 ± 0.04 while the B_d fraction is only changed by a factor 1.01 ± 0.02. As it will be shown in more detail in section 3, the mistag fraction achieved in B_s events is $19.0 \pm 1.3\%$. With this selection, 4436 lepton-kaon correlations have been measured in the 91-94 data. The sample composition is given in table 1.

Table 1: Sample composition: f_b is the fraction of B events in the total sample, f_{bc} is the fraction of events where a cascade lepton is selected, f_s and f_d are the fractions of B_s and B_d in the primary B lepton sample

source	fraction
f_b	0.921
f_{bc}	0.098
f_s	0.165
f_d	0.385

3 Likelihood fit

3.1 Formalism

A l^-K^- or l^+K^+ correlation is called good sign (G) and tags an unmixed event. A l^-K^+ or l^+K^- pair is called wrong sign (W) and tags a mixed event. The log-likelihood is the sum $\ln L = \ln L_G + \ln Lw$ on these two classes. Summing the contributions of the measured proper time bins, one can write $\ln L_{G,W} = -\sum N_i^{G,W} \ln D_i^{G,W}$ where $N_i^{G,W}$ are the measured rates and $D_i^{G,W}$ are the expected time distribution probabilities:

$$D_i^{G,W} = f_b[(1-f_{bc})P_{b\to l}^{G,W}(t^i) + f_{bc}C_{b\to c\to l}^{G,W}] + (1-f_b)P_{bkg}(t^i)$$

which explicits three components, primary and cascade b decay leptons and non b (called background). All the steps of the computation of these expected time distributions are explained in detail in [7]. Illustrating the formalism in the case of the primary leptonic decay, the $(b \to l)$ probabilities are written as the sum of 3 components:

$$P_{b\to l}^{G,W} = f_d P_{B_d}^{G,W} + f_s P_{B_s}^{G,W} + (1-f_d-f_s)P_{B_u}^{G,W}$$

where the label B_u means the sum of the B_u meson and b baryon contributions. The time dependence of the charge correlation is given, respectively for B_d^0 and B_s^0 mesons (index f = d and s) and B_u, by the expressions:

$$P_f^{G,W}(t) = \frac{1 \pm A_f cos(\Delta m_f t)}{2} \cdot e^{-\frac{t}{\tau_f}}$$

$$P_u^{G,W}(t) = \frac{1 \pm A_u}{2} \cdot e^{-\frac{t}{\tau_f}}$$

The coefficients A are the amplitudes of the asymmetries induced by the charge correlation. For B_u which don't mix the charge correlation is time independent. For B_d^0 and B_s^0 mesons which mix, the corresponding parameters A_d and A_s give the amplitude of the time oscillating charge correlation.

In terms of the corresponding mistag fraction, η, which are frequently used in such studies, we have $A = 1 - 2 \cdot \eta$.

3.2 Monte Carlo values of the parameters

These parameters have been determined from large Monte-Carlo samples (0.57 million of $b\bar{b}$) to be $A_u = 0.285 \pm 0.014$, $A_d = 0.356 \pm 0.043$ and $A_s = 0.600 \pm 0.055$

where the errors come from M.C. statistics. Lepton-kaon charge correlations are induced in several ways. While the lepton charge is linked to the b charge after mixing, the kaon charge is correlated to the b quark charge at production time. This correlation has two origins. For B_u or B_d mesons the production time tagging is provided only by the opposite hemisphere charge requirement. For B_s mesons the tagging sensitivity is enlarged (larger A_s parameter) by the leading fragmentation kaon produced to compensate the strangeness of the B_s meson (we call it the B_s-Kpartner). From MC history, it has been seen in B_s events that $(47 \pm 4)\%$ of the selected kaons are B_s-Kpartner. For them the charge correlation is perfect. For the remaining B_s event kaons, the charge asymmetry, created by the opposite jet-charge selection, is found to be $(26 \pm 4)\%$, consistent with the value of the A_u and A_d parameters.

The detailed parametrization of the background (non b) is given in [7] and taken from the simulation. The list and values of the parameters is given in table 2.

3.3 Data distributions and chosen parameters

To check the sample composition and the time resolution functions of this analysis, a fit to the proper time distribution of the 4436 data events has been performed. The average B lifetime fitted on data is 1.55 ± 0.03 (statistical error only), which has to be compared to the world average value: 1.538 ± 0.022 [8].

For the data, the charge asymmetry:

$$Q^i_{asy} = \frac{N_i^G - N_i^W}{N_i^G + N_i^W}$$

is computed in each time bin i. Figure 1 displays Q_{asy} versus time. The time averaged charge asymmetry can be fitted on the data. Assuming $\Delta m_s = \infty$, and fixing the A_d parameter to the M.C. value and $\Delta m_d = 0.49$ [11], the fit gives: $A_u = 0.22 \pm 0.05$ close to the Monte Carlo value. The χ^2 of the fit is 27.2 for 23 degrees of freedom.

The value of the A_d parameter can be checked on the data. It should not depend on the kaon requirement. Relaxing the kaon selection, 50635 lepton-jet events are selected in the data. The good and wrong sign assignment is done from the lepton and jet-charge alone. The previous analysis is repeated with the same fitting function. The sample composition, charge asymmetries of charm and background are taken from the ALEPH lepton-jet analysis [9]. The fit, where A_d is imposed to be equal to A_u, gives $A_d = 0.29 \pm 0.01$ and $\Delta m_d = (0.428 \pm 0.038)\ ps^{-1}(stat.)$ in fair agreement with the Monte Carlo value given before and with [9].

The parameter values used in the present analysis are listed in table 2 together with the assumed systematic errors. The B lifetimes and Δm_d values and their errors are winter conference averages [10, 11]. The value of the B_d and B_s fractions at the hadronization level (f_d and f_s) are measured values [12]. It should be noticed that they are the fractions of B_d and B_s after occurence of strong decays of the type $B_s^{**} \rightarrow B_d K$, which take place before the weak mixing. These values are rescaled by the enrichment factor obtained by Monte Carlo. All other parameters are taken from Monte Carlo (see previous section) except the value of A_u fitted on the data. The parameters A_d and A_u are given their MC values with large systematics errors. In particular the consistency of the value taken for A_s (0.60 ± 0.12) with the value of $A_d = A_u = 0.29 \pm 0.01$, charge asymmetry due to the jet-charge tagging alone as measured on the data (see above), corresponds to a fraction of B_s-Kpartner contained in the selected kaon sample equal to $44 \pm 17\%$. This 40% relative uncertainty shows that the assumed systematic error on B_s is conservative. All background parameters are also given large errors.

Table 2: Best estimated value and assumed systematic uncertainty of each parameter. $A_{background} = A_{no.pr.} = A_{mis.id.}$. The B_s and B_d fractions, f_s and f_d, are the product of the fractions at production and the selection enrichment factor. The values of these two quantities are given separately in two consecutive lines. The last column gives, for a value of $\Delta m_s = 4ps^{-1}$, the ratio systematic/statistical of the errors on either likelihood or amplitude (see section 4).

parameter	value	uncertainty	Syst / Stat %
$\tau_b(ps)$	1.54	±0.02	0.4
τ_{Bd}/τ_b	1.013	±0.047	0.8
$\tau_{Bs}(ps)$	1.56	±0.12	5.6
Δm_d	0.49	±0.03	0.4
f_d	0.382 ×	±0.026	0.8
	1.01	±0.05	
f_s	0.122 ×	±0.032	35.0
	1.35	±0.09	
f_b	0.921	±0.042	13.1
f_{bc}	0.098	±0.015	3.1
$f_{c\bar{c}}$	0.36	±0.07	3.3
$f_{no.pr.}$	0.42	±0.08	2.8
$A_{c\bar{c}}$	0.35	±0.10	5.3
$A_{background}$	0.0	±0.15	11.1
B_d	0.35	±0.10	2.2
B_s	0.60	±0.12	28.5
A_u	0.22	±0.05	4.0
Total			49.2

4 Setting a Δm_s limit

Two methods have been used to search for the presence of the B_s^0 mixing: A likelihood difference method and a new amplitude fit method.

4.1 Likelihood difference method

This is performed by calculating the difference in the log-likelihood values calculated for any Δm_s and for $\Delta m_s = \infty$. It is given by:

$$\Delta\mathcal{L}(\Delta m_s) = -\sum_{i=1} N_i \ln[\frac{D_i(\Delta m_s, \alpha^0)}{D_i(\infty, \alpha^0)}]$$

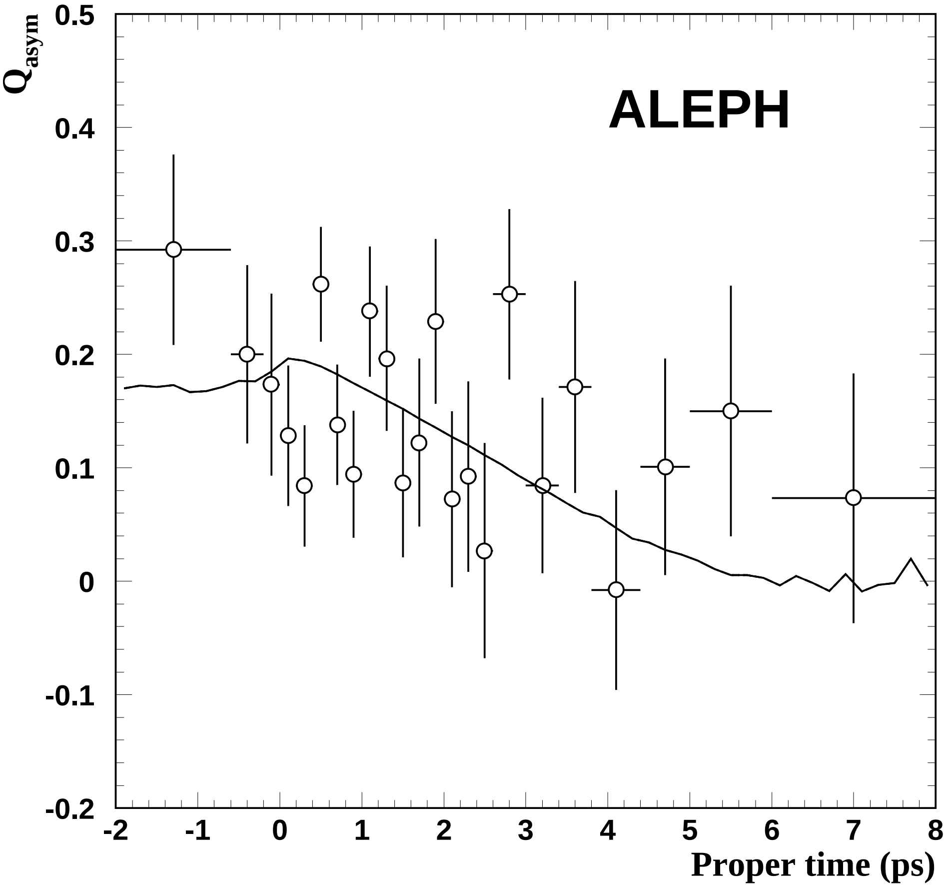

Figure 1: The lepton-kaon charge asymmetry as a function of reconstructed proper time, with the result of the fit shown superimposed, assuming $\Delta m_s = \infty$.

where N_i is the measured rate in time bin i and where D_i is the expected time distribution probability (given in section 3). α^0 denotes the best estimate of all parameters, as listed in table 2, on which depend the charge correlation.

A fast toy Monte Carlo, as described in [2], is used to generate simulated distributions (with a number of events equal to the present data statistics) for any value of Δm_s and of the parameters α. They are used to determine what is the expected distribution of $\Delta\mathcal{L}$ as a function of Δm_s. From it the 95% confidence level upper value of $\Delta\mathcal{L}$ allowed if the B_s^0 mixing has occured with this Δm_s value, can be deduced. Depending if the parameters α are varied or not in their allowed systematic range of table 2, this 95% limit is the statistical or the total limit.

In figure 2 the log-likelihood difference for the data (full line) and the 95 % confidence level limit obtained with the statistical errors only (open circles) and including the systematic errors added in quadrature (black dots) are displayed, as a function of Δm_s. The limits achieved are $\Delta m_s = 4.35 ps^{-1}$ with statistical errors only and $\Delta m_s = 4.0 ps^{-1}$ when

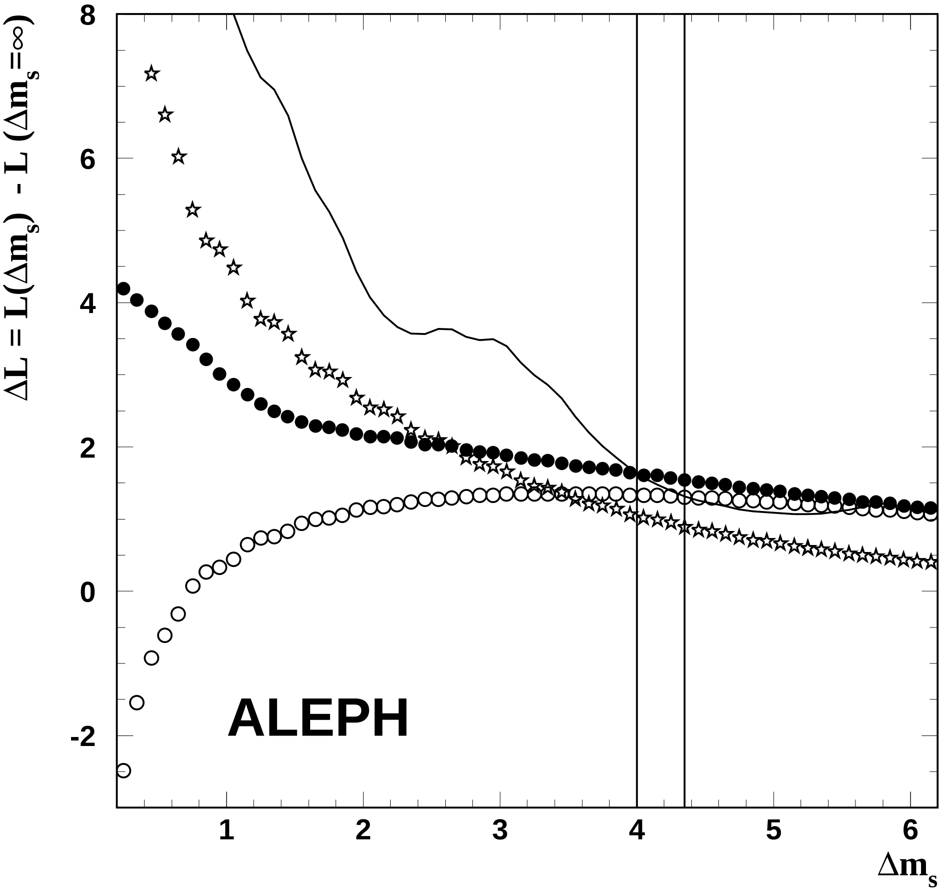

Figure 2: Log likelihood differences versus Δm_s, full curve: data, open circles: $\Delta\mathcal{L}$ 95% C.L. limit (stat. only), dots: $\Delta\mathcal{L}$ 95 % C.L. limit (stat. + syst.) , stars: $\Delta\mathcal{L}$ average on $\Delta m_s = \infty$ samples

the systematics are included.

For each parameter, the ratio of the systematic rms of $\Delta\mathcal{L}$ to the statistical rms, is given in table 2 for $\Delta m_s = 4ps^{-1}$. The contributions of f_s and B_s (oscillation amplitude for B_s mesons) dominate.

The curve giving the variation of the log-likelihood difference $\Delta\mathcal{L}^{\infty}(\Delta m_s)$, averaged for samples generated with $\Delta m_s = \infty$, is displayed on figure 2 (stars). It crosses the 95%C.L. curves at values of Δm_s which represent the averaged potential limits of this analysis. They are $\Delta m_s = 3.45ps^{-1}$ for statistics only and $2.65ps^{-1}$ when including the systematics. The data result is therefore somewhat lucky. To see how lucky it is, 400 toy Monte Carlo samples have been generated with $\Delta m_s = \infty$. In 32% of these samples, the likelihood curve crosses the 95% confidence level limit (with syst.) at a Δm_s value greater than the data limit, $4.0ps^{-1}$.

4.2 Amplitude fit method

To check the validity of the previous limit a new method, the amplitude fit, has been performed.

The log-likelihood formula given at the begining of section 4.1 is modified as follows: the B_s^0 oscillation amplitude (parameter A_s) is rescaled by $\mathcal{A}$, the "fitted amplitude". For any given Δm_s, the amplitude value $\mathcal{A}_0$ which minimizes the log-likelihood and its statistical error $\sigma[\mathcal{A}_0]$ are determined. Figure 3 displays the variation of $\mathcal{A}_0$ with Δm_s. The error on the amplitude is gaussian. Therefore $\mathcal{A}_0 + 1.645 \cdot \sigma[\mathcal{A}_0]$, drawn on figure 3, is the 95% CL limit on the amplitude. The fit result and the limit have to be compared to either 0 (no mixing is observed) or 1 (mixing is observed for this value of Δm_s). This method is more pedagogical to display the mixing visibility and will allow an easy combination of mixing results originating from various analyses and experiments.

In order to determine what systematic errors on the amplitude are induced by the parameter uncertainties, toy Monte Carlo samples including the expected B_s^0 mixing at the value of Δm_s under study are generated. It has been verified that the averaged value of the amplitude $\mathcal{A}$, fitted at this value of Δm_s, is equal to 1. Varying these parameters, one at a time, induces a change in the fitted amplitude used to determine the systematic error on $\mathcal{A}$ due to each parameter, following a procedure described in [7]. The systematic errors are summed quadratically to get the total systematic error $\sigma^{syst}[\mathcal{A}]$ which, at the end, is added to the statistical error:

$$\sigma^{tot} = \sqrt{\sigma_{stat}^2 + \sigma_{syst}^2}$$

The 95% CL limit on the amplitude, including all systematic errors, is $\mathcal{A}_0 + 1.645 \cdot \sigma^{tot}$. It is drawn on figure 3. The 95% CL limits derived on Δm_s are obtained from the crossing of the 95% curves with unity. They are identical to the limits obtained using the log-likelihood difference method of the previous section.

The amplitude fit method offers a unique advantage of making straightforward to combine Δm_s limits originating from various analyses and/or experiments, if they have presented their results according to it. It transforms each search for B_s^0 mixing in the measurement of the same physical quantity, the observed mixing amplitude, which should be the same for all experiments. Combining results means averaging these measurements in the usual way.

The two methods described before give identical results. A linear relationship exists between a log-likelihood difference $\Delta\mathcal{L}$ and an amplitude $\mathcal{A}$ which converts each of the likelihood curves of figure 2 into the corresponding curves of figure 3 [7]. This is true for all curves, so the relationship is not only valid for the central value curves but also for the rms (both statistical and systematic).

5 Conclusion

From the 1991 to 94 data collected by the ALEPH detector a new limit on the B_s^0 mixing has been presented. 4436 lepton-fragmentation kaon-jet correlations have been measured. A new method, the amplitude fit method, is also described. It gives identical results to the log-likelihood difference method, but is more pedagogical and will allow an easy

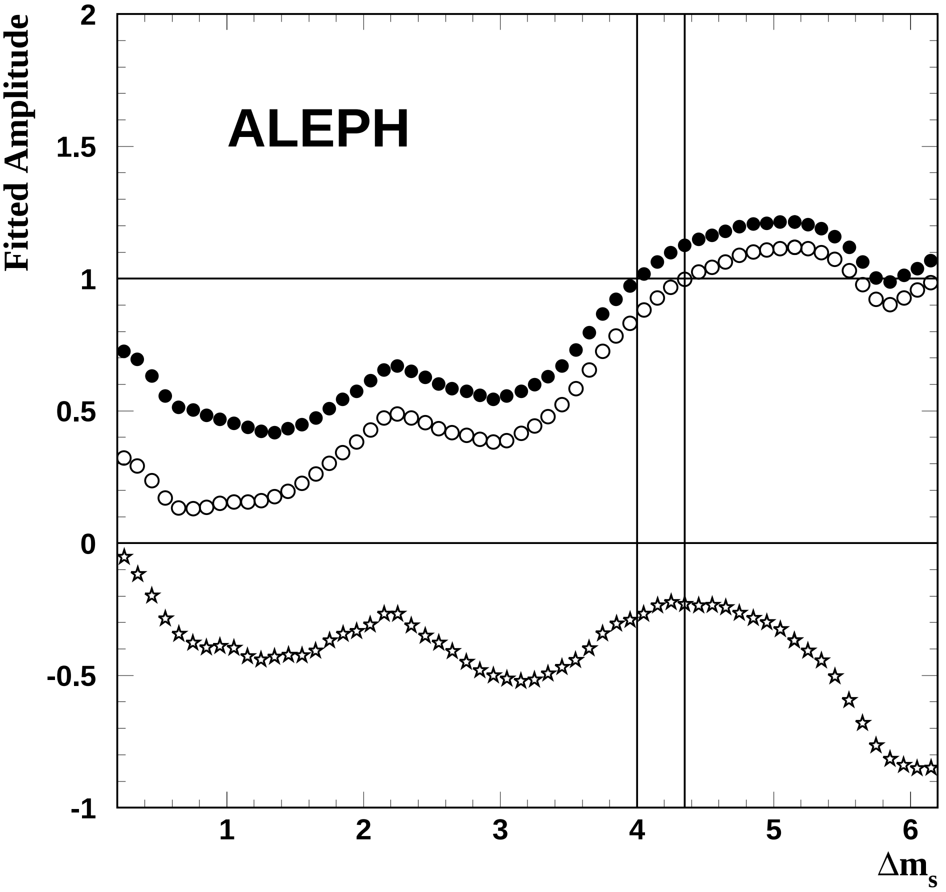

Figure 3: Fitted amplitude $\mathcal{A}$ versus Δm_s, stars: data, open circles: $\mathcal{A}$ 95 % C.L. limit (stat. only), dots: $\mathcal{A}$ 95 % C.L. limit (stat. + syst.). A value of 0 corresponds $\Delta m_s = \infty$ and 1 to full mixing at this value of Δm_s

combination of mixing results originating from various analyses and experiments. From this analysis, a lower limit has been set on the B_s oscillation parameter: $\Delta m_s > 4.0\ ps^{-1}$ at 95% confidence level.

Dilepton events have previously been used [2] to measure the B^0 mixing parameters Δm_d and Δm_s. The same analysis has been updated including the 1994 ALEPH data sample and submitted to this conference [13] in the framework of the report on Δm_d measurements. From 6014 dilepton events a 95% C.L. lower limit on Δm_s of 5.6 ps^{-1} has been set. The average value of the lower limits obtained on a large number of toy Monte Carlo samples generated with maximal mixing is $4.3 ps^{-1}$, and for 24% of them the limit is higher than the data limit.

Both of these limits are derived using the fraction f_s of the b quarks that form B_s to be (12 ± 3)%.

A third limit obtained by ALEPH using the same data sample has already been published [4]. A lower limit (95% confidence level) Δm_s ranging from 5.2 ps^{-1} to 6.5 ps^{-1} had been achieved when f_s is varied from 8% to 16%.

The three limits will be combined using the amplitude method when the statistical and systematic correlations of the measurements will be determined.

References

[1] A. Ali and D. London, Z. Phys. C65 (1995) 431.

[2] D. Buskulic et al. (ALEPH Collaboration), Phys. Lett. B322 (1994) 441, Contributed paper to Int. Conf. on HEP,Glasgow, Scotland (1994), GLS 0584.

[3] R. Akers et al. (OPAL Collaboration), CERN-PPE/95-012.

[4] D. Buskulic et al. (ALEPH Collaboration), CERN-PPE/95-084.

[5] D. Decamp et al. (ALEPH Collaboration), Nucl. Inst Methods A294 (1990) 121.

[6] D. Buskulic et al. (ALEPH Collaboration), CERN-PPE/94-170.

[7] M.-C. Lemaire and A. Roussarie, ALEPH note 95-79, Pysics 95-73.

[8] V. Sharma, Measurement of Beauty Lifetime, 6^{th} International Symposium on Heavy Flavour Physics, Pisa, Italy, June 1995.

[9] S. Emery and W. Kozanecki, Measurement of the $B_d^0 - \overline{B_d^0}$ oscillation frequency using a Jet-Charge Method, ALEPH note Physics 95-030.

[10] M. Jimack, b-physics at LEP, Proc. of XXX Rencontres de Moriond (Les Arcs, Savoie, France), March 1995.

[11] S. Emery, Time Dependent $B^0\overline{B^0}$ oscillation at LEP, Proc. of Rencontres de Moriond QCD (Les Arcs, Savoie, France), March 1995.

[12] D. Buskulic et al. (ALEPH Collaboration), A measurement of $|V_{cb}|$ from $\bar{B}^0 \rightarrow D^{*+}l^-\nu_l$, in preparation.

[13] ALEPH Collab. Measurements of the $B_d^0 - \overline{B_d^0}$ oscillation frequency with the ALEPH detector. Submitted to this conference, EPS95 Ref 0409.