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PRELIMINARY

Investigation of Inclusive CP Asymmetries in Semileptonic B_d^0 Decays

The ALEPH Collaboration

Contact person: Brian Petersen (aagaard@nbi.dk)

Abstract

A search for CP violation in semileptonic B_d^0 decays has been performed using 4 million hadronic Z decays collected by ALEPH between 1991 and 1995. By tagging both the initial and final state of B mesons, the time-dependent asymmetry between B_d^0 and $\overline{B}_d^0$ can be investigated. No CP violation is observed in the data. The CP violating parameter $\mathrm{Re}(\epsilon_B)$ is measured to be -0.013 ± 0.008 (stat.) $\pm$ 0.003 (syst.).

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1 Introduction

CP violation has until now only been observed in the neutral kaon system, but it is predicted [1] to also be present in neutral B mesons. The study of inclusive B^0 samples in existing data is able to constrain CP violation in the B system.

Indirect CP violation in inclusive B^0 samples is expected to be small in the Standard Model. It can be parametrized by the parameter ϵ_B, which is of order 10^{-3} in the Standard Model [2] for B_d^0 and 10^{-4} for B_s^0. In this analysis CP violation in the B_s^0 system has been ignored. The mass eigenstates of the B_d^0 system, when CP violation is allowed and lifetime differences ignored, are given by $|B_{S,L}^0\rangle = \frac{1}{\sqrt{2(1+|\epsilon_B|^2)}}((1+\epsilon_B)|B_d^0\rangle \pm (1-\epsilon_B)|\overline{B}_d^0\rangle)$. From this the probability distribution for a produced B_d^0 to decay as a B_d^0 or a $\overline{B}_d^0$ is given by

$$P(B_d^0 \to B_d^0) = e^{-\Gamma t}\frac{1+\cos\Delta m_d t}{2} \tag{1}$$

$$P(B_d^0 \to \overline{B}_d^0) = e^{-\Gamma t}\frac{1-\cos\Delta m_d t}{2}\cdot(1-4\mathrm{Re}(\epsilon_B)) \tag{2}$$

$$P(\overline{B}_d^0 \to \overline{B}_d^0) = e^{-\Gamma t}\frac{1+\cos\Delta m_d t}{2} \tag{3}$$

$$P(\overline{B}_d^0 \to B_d^0) = e^{-\Gamma t}\frac{1-\cos\Delta m_d t}{2}\cdot(1+4\mathrm{Re}(\epsilon_B)) \tag{4}$$

where t is the proper decay time, Γ the decay width and Δm_d the mass difference between the mass eigenstates. Figure 1 shows the time-dependent asymmetry in the final state for a pure sample of B_d^0. The final state asymmetry is defined as $(N^+(t) - N^-(t))/(N^+(t) + N^-(t))$, where $N^{\pm}(t)$ is the number of events in decaying in final state $B_d^0/\overline{B}_d^0$ at proper time t. The goal is to measure $\mathrm{Re}(\epsilon_B)$ using semileptonic B_d^0 decays. Events where a b-hadron decays semileptonically are selected by requiring a high-p_T lepton and the charge of the lepton is used to identify the final state of the B_d^0. The proper time of the decay is reconstructed and the initial state is identified by the opposite hemisphere jet charge using a discriminating variable as described in Reference [3]. $\mathrm{Re}(\epsilon_B)$ is extracted by a maximum likelihood fit.

2 Event selection

The recently reprocessed data taken from 1991 to 1995 at the Z pole are used and 4.1 million hadronic events are selected using the standard ALEPH selection [4] based on charged tracks. The resolution and background parameterization are extracted from 5.4 million Monte Carlo events.

Each event is divided into two separate hemispheres determined by the thrust axis, and only events satisfying $|\cos\theta_{\text{thrust}}| < 0.85$, where θ_{thrust} is the angle between the thrust and beam axes, are selected. These correspond to events fully contained in ALEPH. Charged and neutral tracks are clustered into jets using the JADE algorithm with $y_{\text{cut}} = 0.002$.

Electrons and muons are selected as explained in Reference [5]. The lepton candidates must have a momentum larger than 3 GeV/c and a transverse momentum larger than 1.25 GeV/c, where the latter is computed with respect to the closest jet with the lepton excluded from the jet. In addition to the wire dE/dx measurement, the pad dE/dx measurement is used in the electron identification. Furthermore, the dE/dx is used to reduce the number

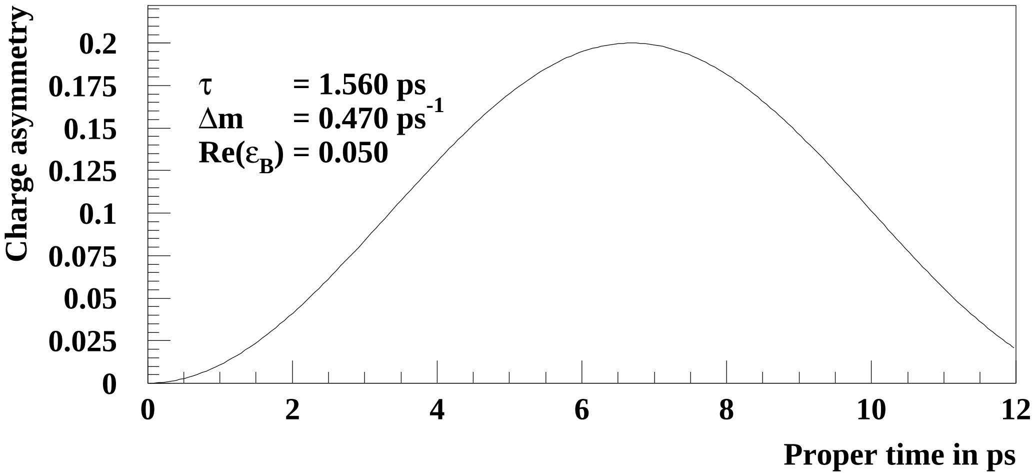

Figure 1: The predicted time-dependent final state asymmetry in a pure sample of B_d^0 decays.

of kaons misidentified as muons. The K^+ and K^- mesons interact differently with matter inducing a charge asymmetry competing with the one we want to measure. The remaining K^+ and K^- amounts have been measured directly from the data by fitting two Gaussians to the dE/dx distribution as shown on Figure 2. The result is $(1.7 \pm 0.6)\%$ K^+ contamination of the positively charged muon candidates and $(1.1 \pm 0.4)\%$ K^- contamination of the negatively charged muon candidates.

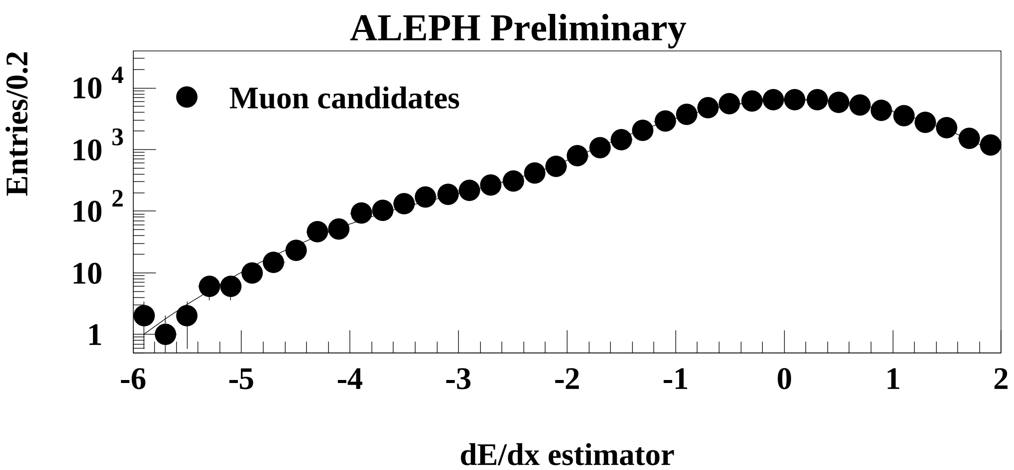

Figure 2: The dE/dx estimator for muon candidates in data after lepton selection. The muons have a mean value of 0, while the kaons have a mean value of -2.2.

The charged lepton is the main part of the decay vertex reconstruction, so accurate spatial information is needed and only leptons with hits in the vertex detector are used. At least one hit in both the $r\phi$ and z views are required.

If several leptons pass these requirements, the lepton with the highest transverse momentum is selected. To suppress 3-jet events where the b-quark pair is not unambiguously separated into the two hemispheres, the angle between the jet closest to the lepton and the thrust axis is required to be less than 35°. A total of 130291 events are selected for this analysis.

The events can be divided into the following mutually exclusive components

1. Semileptonic B_d^0 decays. These are the signal events and include $b \to l^-$, $b \to \tau^- \to l^-$ and $b \to \bar{c} \to l^-$ decays.
2. Other semileptonic b-hadron decays. These are B_s^0, $B^\pm$ and b-baryon decays.
3. Cascade decays ($b \to c \to l^+$). Here the lepton will have the opposite sign of a lepton coming from the direct decay of the b-quark.
4. B decays into two leptons. These are decays where the charge of the lepton is independent of the b quark charge, for instance $B \to J/\psi X, J/\psi \to l^+ l^-$.
5. Charm decays. Leptons from decay of primary produced charm mesons. No CP violation is assumed.
6. Non prompt leptons. Leptons from photon conversion, kaon and pion decay.
7. Fake leptons from B decays. Kaons and pions which do not decay inside the detector, but are misidentified as leptons, mostly as muons.
8. Fake leptons from non-B decays. Same as the previous, but fragmentation particles instead.

The fraction of B_d^0 in the sample is 32%, while the non-B background amounts to 9%.

3 Proper time reconstruction

3.1 Decay length reconstruction

The charged lepton from the semileptonic B decay is known to come from the B decay vertex and the jet closest to the lepton is assumed to point in the direction of the B flight path. The point on the jet axis closest to the lepton track is therefore taken as the B vertex. This procedure has 100% efficiency for finding a vertex, but rather poor resolution. Other methods [3] have better resolution, but at the expense of efficiency losses at large decay lengths where the fit is most sensitive to CP asymmetries in B_d^0 decays. The primary vertex is found on an event-by-event basis as described in Reference [6], but with the lepton excluded. The decay length resolution from the Monte Carlo is shown in Figure 3. The reconstruction efficiency for signal events is found to be independent of the true decay length.

The decay length resolution in data has been studied using tracks which satisfy all selection criteria, except the electron and muon identification. The simulation was checked by comparing the negative tail of the decay length distribution for these tracks in data and Monte Carlo. This showed the resolution to be 2% worse in data compared to Monte Carlo.

3.2 Momentum reconstruction

The neutrino energy, E_ν, is estimated as the missing energy in the hemisphere taking into account the measured mass in both hemispheres [7]. The rest of the energy, $E_{\rm vis}$, of the B meson is estimated by adding charged and neutral tracks from the lepton hemisphere to the lepton with the tracks sorted by decreasing energy. The addition continues until a certain invariant mass cut is reached. The cut is optimized on a Monte Carlo sample as a function of the neutrino energy. From the energy a boost term $b = m/p$ is calculated, where $m = 5.28\mathrm{GeV}/c^2$ and $p = \sqrt{(E_\nu + E_{\rm vis})^2 - m^2}$. The relative boost resolution can be seen in Figure 3.

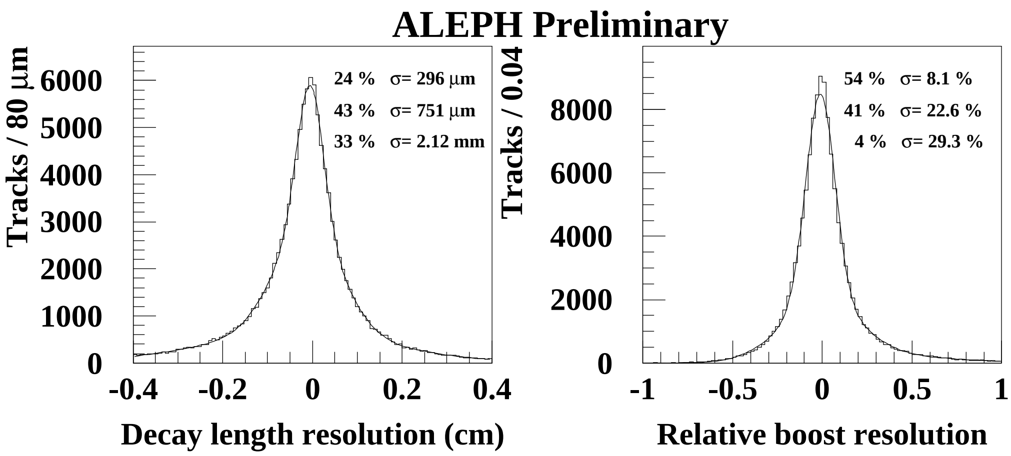

Figure 3: Decay length and relative boost resolution in semileptonic b-hadron decay fitted with three Gaussians.

3.3 Proper time resolution

After the decay length and momentum have been found, the proper time can be calculated. The track uncertainties and badly reconstructed events are taken care of by folding the theoretical proper time distributions with a resolution function. The resolution function is parametrized from Monte Carlo as a sum of four Gaussians with parameters depending linearly on the true proper time. The width is increased by 2% due to the worse decay length resolution in data.

Figure 4 shows the resolution function for several values of the true proper time together with the Monte Carlo. It shows the widening of the resolution as the true proper time increases.

4 Initial and final state tagging

The initial and final state are tagged using a discriminating variable procedure similar to the ones in References [3] and [8].

The final state is tagged by a charged lepton. The $b \to l^-$ and $b \to \bar{c} \to l^-$ decays will have a correct final state tag, while in $b \to c \to l^+$ decays the lepton has the opposite sign

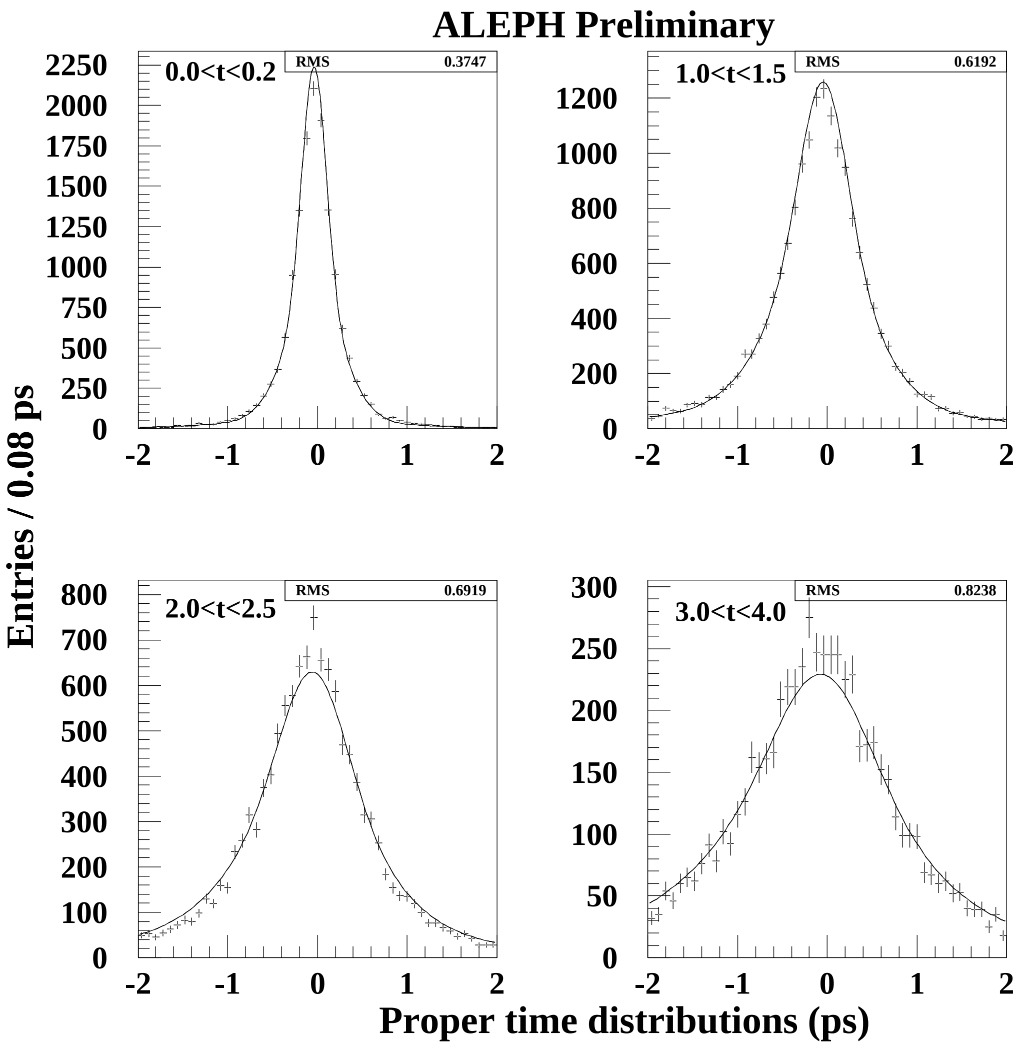

Figure 4: The fitted proper time resolution for different intervals of the true proper time.

of the b quark, corresponding to a 100% mistag. Fake leptons originating from B decays will not always have the correct tag, since a B decay for instance can produce both π^+ and π^-. From Monte Carlo it has been estimated that the final state mistag for fake leptons from B decays is 26%. The different amounts of positive and negative fake leptons are handled by using different composition fractions for positive and negative particles.

The initial state is tagged using jet charge in the opposite hemisphere. The jet charge is the usual jet charge used by ALEPH [9] with $\kappa = 0.5$.

$$Q_o = \frac{\sum_i |\vec{p}_i \cdot \vec{e}_T|^\kappa \cdot q_i}{\sum_i |\vec{p}_i \cdot \vec{e}_T|^\kappa},$$

where $\vec{e}_T$ is the direction of the thrust axis.

The sign of the jet charge is used to tag the initial state, while the absolute value of the jet charge is used in the discriminating variable, x^{eff} [8]. The jet charge distributions for B and $\bar{B}$ should be the same except for a sign, but nuclear interactions introduce a positive offset in the distributions. The offset is taken directly from the data as the average jet charge in all selected events. This assumes that the offset is independent of the flavor and charge of the initial quark. The offset is 0.0030 ± 0.0006 in data while it is 0.0041 ± 0.0005 in the Monte Carlo.

Since the value of the jet charge is also used in the tagging, the distributions (e.g. the mean and width) in data and Monte Carlo need to be compared. This is done using a multi-tag technique, which separates b and $\bar{b}$ hemispheres. The result of this is shown in table 1, where μ is the mean jet charge in a $\bar{b}$ hemisphere and σ is the width. This method also gives an estimate of the offset due to nuclear interactions, although with a larger error. The result is 0.0037 ± 0.0011 compatible with the previous result.

Parameter:	Value:
$\mu_{\text{Data}} - \mu_{\text{MC}}$	0.0023 ± 0.0015
$\sigma_{\text{Data}}/\sigma_{\text{MC}}$	1.007 ± 0.007

Table 1: Differences between the jet charge distributions in data and Monte Carlo.

The effective discriminating variable, x^{eff}, is defined as [8]

$$x^{\text{eff}} = \frac{\eta w(Q_o)}{(1-\eta) r(Q_o) + \eta w(Q_o)}$$

where η is the average initial state mistag probability and $r(Q_o)$, $w(Q_o)$ are the probability distributions for correctly and wrongly tagged B^0_d events. These have been extracted from Monte Carlo and corrected as described above. A small value indicates the tag is most likely correct. The average mistag for B^0_d using only the jet charge sign is $(35.5 \pm 0.5)\%$, but the use of a discriminating variable gives an effective mistag of $(32.7 \pm 0.5)\%$.

5 Fit method

The fit uses the discriminating variable, x^{eff}, to calculate the event-by-event mistag and sample composition. For B-components the proper time distributions are described by the true proper time distributions folded with efficiency and resolution functions taken from Monte Carlo. Non-B components (charm and fake leptons) proper time distributions are taken from Monte Carlo. These are all combined into a likelihood, from which Δm_d and $\mathrm{Re}(\epsilon_B)$ can be measured.

6 Consistency checks

Several checks of the parameterizations used in the fit have been performed. The resolution was checked by fitting the average B lifetime in data. The tagging information was ignored in this fit, and all B mesons are assumed to have the same lifetime, while the b-baryon lifetime was fixed at 1.22 ps. Only events with proper time between -1.0 ps and 8.0 ps were used in the fit. The result, 1.593 ± 0.007 ps, is consistent with the world average of 1.597 ps [1]. The quoted uncertainty is statistical only. A plot of the proper time distribution and background contributions is shown on Figure 5.

The full fit procedure has been tested on a Monte Carlo reweighted according to different values of $\mathrm{Re}(\epsilon_B)$. The result of the fits is reported in Table 2.

Input values		Results	
$\Delta m_d/\mathrm{ps}^{-1}$	$\mathrm{Re}(\epsilon_B)$	$\Delta m_d/\mathrm{ps}^{-1}$	$\mathrm{Re}(\epsilon_B)$
0.470	0.00	0.466 ± 0.018	0.006 ± 0.007
0.470	0.05	0.467 ± 0.018	0.059 ± 0.007
0.470	-0.05	0.467 ± 0.018	-0.049 ± 0.007
0.470	0.10	0.473 ± 0.017	0.111 ± 0.007
0.470	-0.10	0.479 ± 0.018	-0.096 ± 0.007

Table 2: The result of fitting CP violation in reweighted Monte Carlo. The reweighted Monte Carlo samples are statistically correlated.

7 Results

The data are fitted with the b-hadron lifetimes and production fractions fixed to the PDG values shown in Table 3 and $\Delta m_s = 50\ \mathrm{ps}^{-1}$. The result is $\Delta m_d = 0.507 \pm 0.022\ \mathrm{ps}^{-1}$ and $\mathrm{Re}(\epsilon_B) = -0.013 \pm 0.008$, statistical uncertainty only. The result is not changed significantly when only using events with proper time larger than 1.0 ps (this removes some of the background from the fit) or when fitting electrons and muons separately. The result of these fits are shown in Table 4.

Figure 6 shows the B_d^0–$\overline{B}_d^0$ mixing and lack of indirect CP violation. The lepton-signed jet charge is $-Q_o \times q_l$, where Q_o is the jet charge and q_l the lepton charge. This value is on average positive for unmixed decays and negative for mixed decays. The figure clearly shows mixing. The final state asymmetry is $(N^+(t) - N^-(t))/(N^+(t) + N^-(t))$, where $N^{\pm}(t)$ is the number of positive/negative leptons. Indirect CP violation would be seen as a deviation from zero at large proper time and the deviation would be larger for events enriched in mixed events. No CP violation is observed.

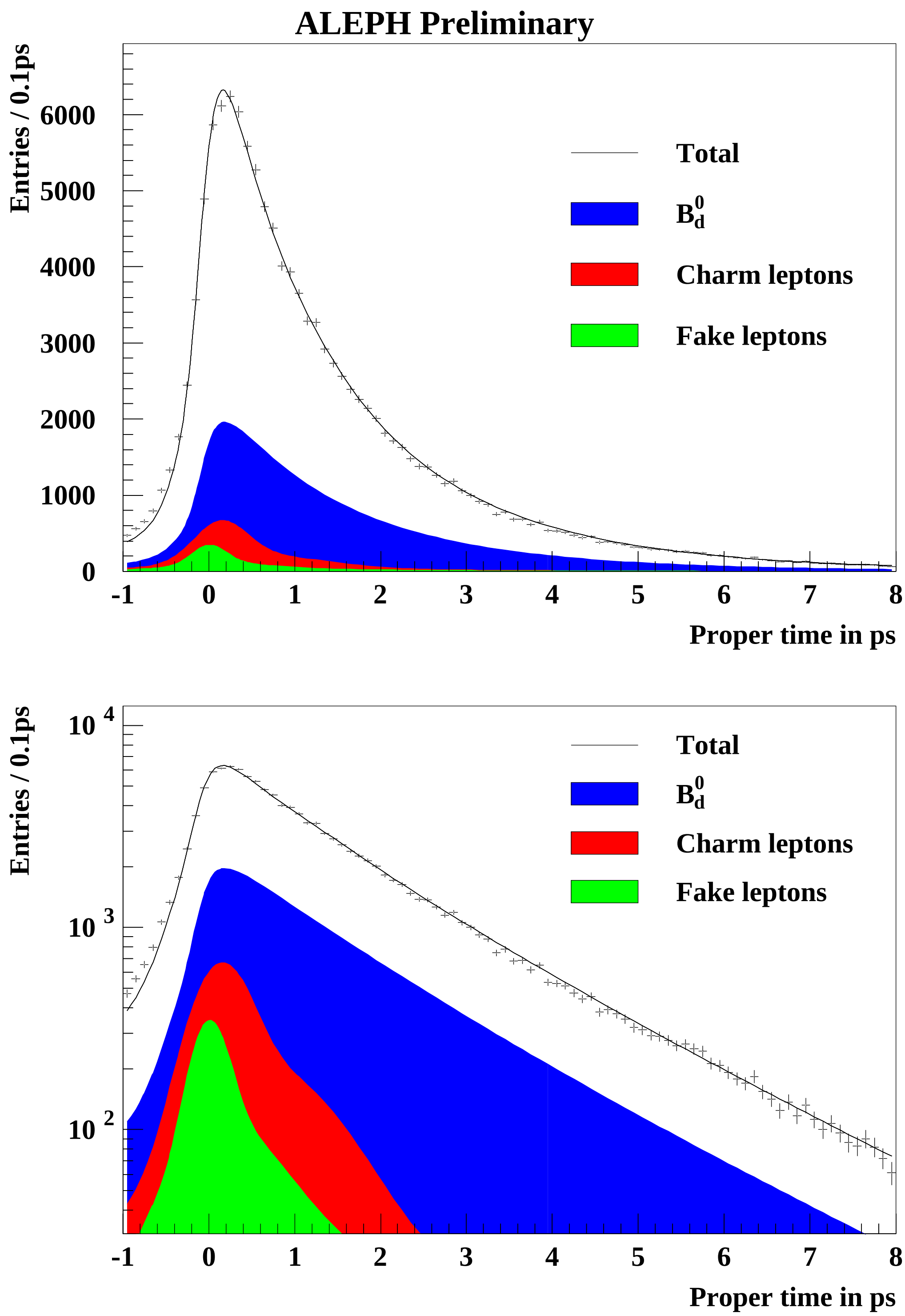

Figure 5: Proper time distribution in the data and the result of the fit. Some of the components are also shown.

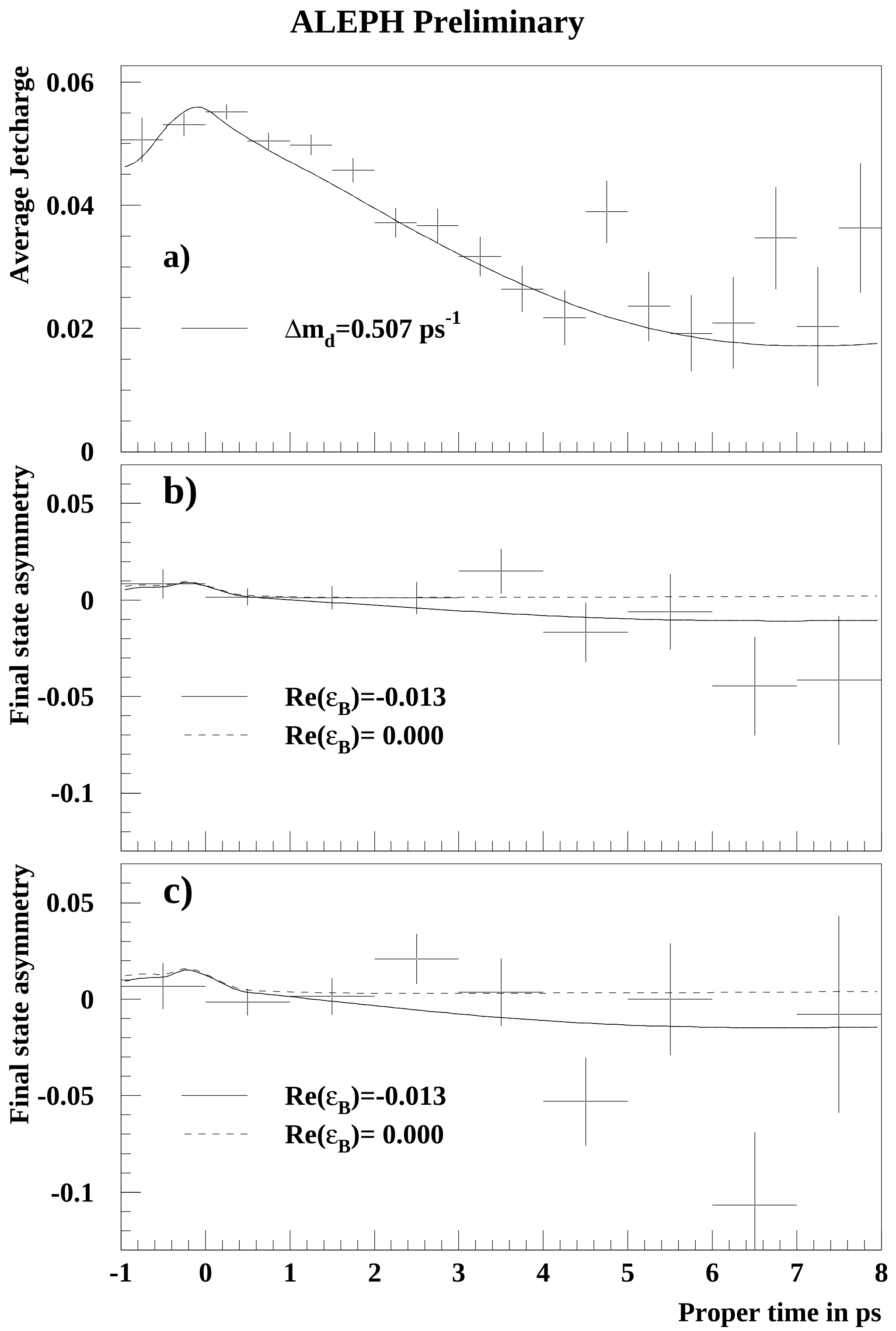

Figure 6: a) The average of the lepton-signed jet charge, which shows the increase of mixed decay at high proper time. b) Final state asymmetry in all events. c) Final state asymmetry in all events tagged as mixed. The deviation from zero on b) and c) at proper time around 0 ps is due to fake leptons. The results of the fit (solid lines) and $\mathrm{Re}(\epsilon_B) = 0$ (dashed lines) has been superimposed.

Hadron:	Lifetime:	Production fraction:
$B^{\pm}$	1.65±0.04 ps	$39.7^{+1.8}_{-2.2}\%$
B^0_d	1.56±0.04 ps	$39.7^{+1.8}_{-2.2}\%$
B^0_s	1.54±0.07 ps	$10.5^{+1.8}_{-1.7}\%$
Λ^0_b	1.20±0.07 ps	$10.1^{+3.9}_{-3.1}\%$

Table 3: World-average b-hadron lifetimes and production fractions from [1].

Sample	$\Delta m_d/\text{ps}^{-1}$	$\text{Re}(\epsilon_B)$
Full	0.507 ± 0.022	-0.013 ± 0.008
$1 < t < 8$ ps	0.499 ± 0.023	-0.014 ± 0.008
Electrons	0.483 ± 0.031	-0.011 ± 0.012
Muons	0.528 ± 0.031	-0.013 ± 0.010

Table 4: Fits are done using the full sample, only events with proper time between 1 and 8 ps, only electrons and only muons. Statistical uncertainties only.

8 Systematics

The systematic uncertainties are reported in Table 5.

Error sources	Δm_d	$\text{Re}(\epsilon_B)$
B lifetimes	±0.012	±0.0003
B composition	±0.026	±0.0008
$b \to c \to l$ fraction	±0.017	±0.0004
Δm_s	±0.000	±0.0000
Charm fraction	±0.008	±0.0003
Light quark fraction	±0.003	±0.0000
Fake leptons	±0.001	±0.0006
Resolution	±0.004	±0.0001
Jet charge correction	±0.025	±0.0015
Jet charge offset	±0.001	±0.0026
Total	±0.042	±0.0032

Table 5: Summary of systematic uncertainties on Δm_d and $\text{Re}(\epsilon_B)$.

- B **lifetimes:** The b-hadron lifetimes are varied separately within the errors on the measured values given in Table 3. Changing the B lifetimes influences the mixing, because the fraction of B^0_d changes at large proper time and therefore the amount of mixed events.
- $\boldsymbol{\Delta m_s}$ The value is varied between 9.1 ps^{-1} and 50 ps^{-1}, but it has little effect on the measurement since the proper time resolution is not good enough to see the fast B^0_s

oscillations.

- B **composition** The fractions of each type of b-hadron are varied separately within the errors on the measured values given in Table 3.
- $\boldsymbol{b \to c \to l^+}$ The amount of these decays are varied by 4%.
- **Charm and light quark fractions** As suggested in [3] the c and uds background fractions are varied with 25%.
- **Fake leptons**

  The amount of kaons identified as muons is varied within the uncertainty quoted Section 2. The main uncertainty is the mean value of dE/dx for kaons used in the extraction of the kaon fractions.
- **Resolution**

  The resolution due to the decay length was varied 5% in addition to the 2% difference observed between data and Monte Carlo. The resolution due to the momentum measurement is varied by 10%.
- **Initial state tagging**

  The initial state is tagged using jet charge and two sources of error are considered: the jet charge offset and the jet charge distribution itself. The jet charge offset was extracted from data and is varied within the statistical uncertainty on the extracted value, 0.0030 ± 0.0006.

  The jet charge distribution is taken from Monte Carlo, but with a correction from data as described in Section 4. The systematic uncertainty is estimated by using the Monte Carlo values without corrections. This changes not only the jet charge distribution, but also the mistag.

9 Conclusion

Using reprocessed 1991–1995 ALEPH data a measurement of $\mathrm{Re}(\epsilon_B)$ has been performed. The measured value is $\mathrm{Re}(\epsilon_B) = -0.013 \pm 0.008$ (stat.) $\pm$ 0.003 (syst.). This result is preliminary. It is consistent with a previous ALEPH result [10], which used totally inclusive decays to get $\mathrm{Re}(\epsilon_B) = -0.002 \pm 0.011$ (stat.) $^{+0.003}_{-0.002}$ (syst.). The two measurements have been combined assuming they are statistically uncorrelated. The result of the combination is $\mathrm{Re}(\epsilon_B) = -0.009 \pm 0.006$ (stat.) $\pm$ 0.003 (syst.) .

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