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The measurement of the time dependence of $B_d^0\bar{B}_d^0$mixing using D^* lepton and D^* Jet Charge Correlations

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Abstract

Mixing in the B_d^0 system was measured by observing the time dependence in its decay distribution to $D^{*-}X$. The decay length was inferred from the subsequent decay of the D^{*-} to $\bar{D}^0\pi^-$. The charge state of the D^{*-} correlated with the initial charge of the B indicates whether the B_d^0 has mixed. This initial charge state was determined by tagging the other B particle in the event, with a decay lepton if present, or otherwise with its jet charge. The observed value for $\Delta m = 0.497 \pm 0.070 \pm^0 .036$.

1 Introduction

The first measurements of the time dependence of B_d^0 mixing, and so the direct measurement of the mass difference between the two B_d^0 states, were presented by ALEPH in [1, 2], a further result has since been published by OPAL [3]. This note reports on an upgraded method following on that described in [1]. In that paper oscillations were observed through the measurement of the charge state and decay distance of the B^0 via its decay to a charged D^*. The initial state of the B^0 was determined by the charge of a lepton from the semileptonic decay of the B on the other side of the event. The published result was: $\Delta m = 0.52^{+0.10}_{-0.11}\ (stat.)^{+0.04}_{-0.03}\ (syst.)\hbar/ps$.

This measurement is clearly limited by statistics. One major limitation is that relatively few events have a B decaying semileptonically on the opposite side of the event. If it were possible to use a larger fraction of available hadronic events an improvement could be possible. In order to do this the jet charge of the opposite hemisphere can be used, although at the expense of a lower probability of correctly extracting the initial state charge (higher mistag).

In the original paper, one of the reasons to choose a lepton tag was of its relatively high probability of giving a correct value of the initial state charge. The signal to noise ratio as a function of the number of events and the mistag is proportional to: $(S/N)^2 \propto \lambda = N(1-2\eta)^2$, where N is the number of events in a sample and η the mistag fraction. From this expression it is clear that the usefulness of an event sample decreases rapidly as the mistag increases, and the reduction of the mistag must play an important part in this analysis.

Here a combination of the two methods is used. In events where a good lepton is found, this with its lower mistag, is used, otherwise the jet charge is used. In other respects the method follows the earlier D^*l analysis.

The paper is organized as follows: First the principles of the measurement are discussed, then the event selection and reconstruction are described. This is followed by a description of the optimization of the charge tagging. The background sources and their determination are enumerated. Finally the fit procedure is described, and the results and systematic errors are presented.

2 Principle of the Measurement

As was mentioned above, in order to measure the oscillation frequency Δm the charge state of the B^0 at its origin and at its decay must be tagged, and the decay length or time must be measured. The original state is tagged by the lepton charge or the jet charge on the opposite side of the event. The decay time state is tagged by the charge of the D^* in the decay $B^0 \rightarrow D^{*-}X$ and $\bar{B}^0 \rightarrow D^{*+}X$. In both the lepton and jet charge cases, the same sign situation reflects an unmixed event whereas opposite signs tag a mixed event. The B^0 decay time is inferred from a convolution of the decay length of the D^0, and the D^* momentum.

There are several complications:

- Mistagging of the initial state charge, leading to a reduction of the amplitude of the oscillation. This can arise:
  - In the lepton case from mixing on that side of the event, or from $b \to c \to l$ decays
  - In the jet charge case from the intrinsic resolution of the jet charge.
- D^* produced directly from charm
- Combinatorial backgrounds, particularly severe in the $D^0 \to K^-\pi^+\pi^0$ mode.
- D^* produced from charged B decays.
- Since the slow pion from the D^* leads to a poorly reconstructed D^* vertex, the D^0 vertex is used instead. This leads to a shift in the decay length distribution.
- The limited vertex resolution smears the decay length.
- The B^0 momentum is not measured. Instead the decay length and the expected B^0 momentum are convoluted in the fit.

To present the data one can use the charge correlation function:

$$QQ = \frac{N^{ss} - N^{os}}{N^{ss} + N^{os}},$$

where N^{ss} are the number of same sign events, and N^{os} the number of opposite sign events, both as a function of D^0 decay length.

For a detailed discussion, including the calculation of the expected decay length distributions see [4].

3 D* Selection

This analysis uses charged D^*'s, which are then observed in their decay to $D^0\pi^+$. Two decay modes of the D^0 are used: $K^-\pi^+$ and $K^-\pi^+\pi^0$. The latter has a high branching ratio, but needs hard cuts to reduce combinatorial background.

Standard multihadronic events are used with the requirements that the detectors needed for heavy flavour analysis, in particular the silicon vertex detector, are in a good working state. Data from 1991, 1992, and 1993 are used providing a sample of about 1.5 million events.

Selection requirements for both D^0 channels are:

- $d_0 < 2\text{cm}$ and $z_0 < 10\text{cm}$
- ≥ 4 TPC hits on each charged track
- $\chi^2/dof < 4$ for the track fit
- ≥ 1 $r - \phi$ VDET hits on the charged tracks from the D^0
- $\chi^2 < 25$ for vertex fit
- Charged track momenta $> 0.2 GeV/c$
- Reject tracks belonging to V0's (K^0, Λ, and converting photons)
- D^* momentum $< 25 GeV/c$ (This removes a large fraction of $c\bar{c}$ events)

For the $D^0 \to K^-\pi^+$ decay the following additional requirements are made:

- $\mid \cos(\theta_{D^0K}) \mid < 0.8$ ie. the decay angle of the K in the D^0 rest frame.
- $7GeV/c < p(D^*) < 25GeV/c$
- $1.845GeV/c^2 < m(D^0) < 1.885GeV/c^2$ (2σ around the D^0 mass)
- $1.845GeV/c^2 < m(D^0) < 1.885GeV/c^2$
- $144MeV/c^2 < m(D^*) - m(D^0) < 147MeV/c^2$

For the $D^0 \to K^-\pi^+\pi^0$ decay the following additional requirements are made:

- π^0 are identified and kinematically fitted $\mid m(\gamma\gamma) - m(\pi^0) \mid < 50MeV/c$
- $p(\pi^0) > 2.0GeV/c$
- $11GeV/c < p(D^*) < 25GeV/c$
- $p(K), p(\pi) > 2.5GeV/c$
- $1.835GeV/c^2 < m(D^0) < 1.895GeV/c^2$
- $144MeV/c^2 < m(D^*) - m(D^0) < 147MeV/c^2$

Note that the requirements for the $K^-\pi^+\pi^0$ channel are more severe as combinatorial backgrounds are high.

The mass difference spectra for these selections are shown in figure 1, and the numbers of events passing these requirements are summarized in table 1. Also quoted therein are the the numbers of events after final lepton and jet charge selection requirements are made (see section 5).

For Monte Carlo studies the standard ALEPH $b\bar{b}$ and $c\bar{c}$ Monte Carlo data is used. Generation is with JETSET.

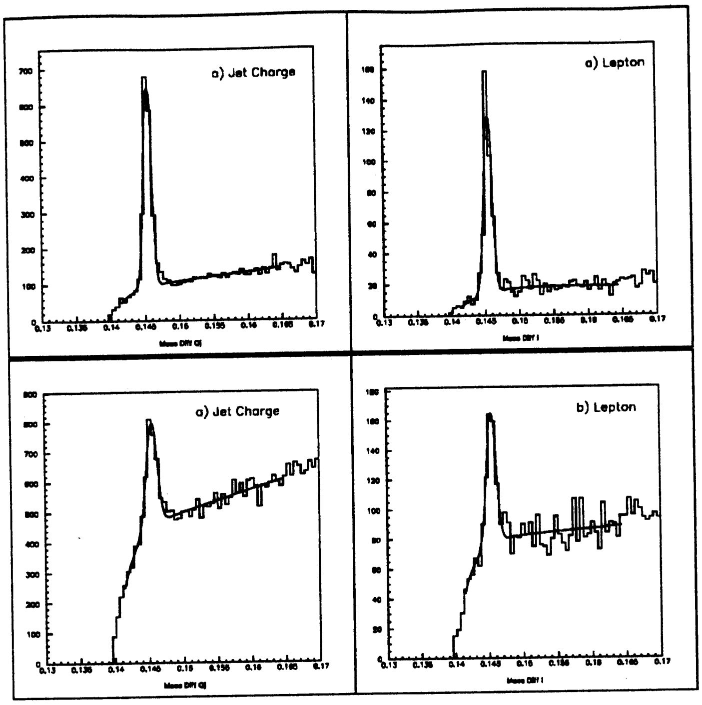

Figure 1: Mass difference spectra for basic D^0 selection, before the application of the lepton and jet charge quality criteria. Upper plots for $D^0 \rightarrow K^-\pi^+$ channel divided into a) for jet charge sample and b) for lepton sample. Lower plots similarly for $D^0 \rightarrow K^-\pi^+\pi^0$

Sub Sample	Events	Final Events	Background
$K\pi$ jet charge	1557 ± 135	432 ± 73	52 ± 7
$K\pi$ lepton	334 ± 30	147 ± 8	19 ± 4
$K\pi\pi^0$ jet charge	580 ± 63	174 ± 17	130 ± 11
$K\pi\pi^0$ lepton	165 ± 25	69 ± 4	46 ± 7

Table 1: Events in different subsamples. The first set of values is the number of events after the basic cuts. The others after all lepton and jet charge quality requirements, and with decay length greater than zero.

4 Decay Length Reconstruction

As was discussed above the time dependence of the B^0 oscillation is determined via the measurement of the decay length of the D^0. To reconstruct this decay length the primary vertex is reconstructed using the primary vertex is reconstructed from the intersection point of the tracks and jets in the event [5], and D^0 decay vertex using the charged decay tracks. The most probable decay length is calculated using:

$$l = \frac{t_i \sigma_{ij}^{-1} x_j}{t_i \sigma_{ij}^{-1} t_j}$$

t_i is the normalized momentum vector of the D^0, x_i the difference between D^0 and primary vertex, and σ_{ij} the sum of the error matrices of the primary and the D^0.

The vertex resolution to be used in the fitting procedure was determined from the data. A set of pseudo D^0 vertices was reconstructed removing combinations containing genuine lifetime, to determine the intrinsic tracking resolution. The following selection requirements were made:

- Track selection in both channels as for real events.
- Reject $b\bar{b}$ and $c\bar{c}$ events using the a lifetime anti-tag [6] procedure accepting only those events with with an event probability of greater than 0.2.
- Reconstruct pseudo D^0 candidates in both channels.
- Reject events within 3σ of the D^0 mass

The separation between the "D^0" and primary vertices was determined as for real events. This distribution was fitted with three gaussians centred at zero. The upper positive tail was excluded from the fit in order to remove any possible residual lifetime particularly from V0's in *uds* events. The fitted data is shown for the $K^-\pi^+$ channel in figure 2. The results are consistent with those expected from Monte Carlo and with those of the previous analysis.

5 Initial State Charge Tagging

To tag the initial state of the B^0 the charge of the opposite side lepton or of the opposite side jet charge are used. In this section the the expectations and optimization of the selection to achieve the highest sensitivity are discussed. There are also implications for the sample composition using the two different charge tag methods. Using leptons the charm content of the sample can be controlled by selecting on the momentum and the p_t of the leptons. Using the jet charge sample this is not possible, instead a cut on the hemisphere lifetime is used on the jet charge side of the event.

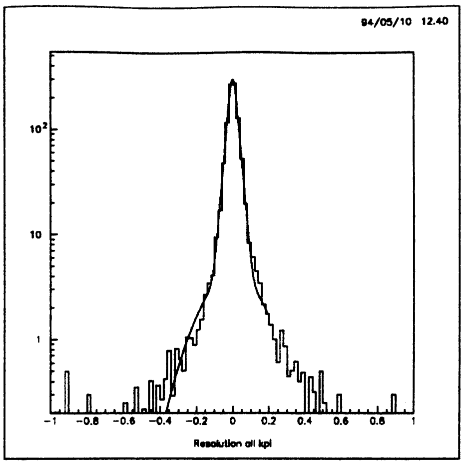

Figure 2: Vertex resolution for the $D^0 \rightarrow K^-\pi^+$ decay channel. The function is fitted with three gaussians. The core gaussian has a resolution of 180μ and contains 70% of the data.

5.1 Leptons

Leptons are identified using the standard ALEPH criteria. Electrons from their shower shape in the electromagnetic calorimeter, and and dE/dx, if available. Muons from their penetration of the hadronic calorimeter and hits in the muon chambers. Converting photons are removed in the same way as for the D^0 charged tracks.

Jets are selected using charged tracks and neutral calorimeter objects, using the missing mass squared algorithm.

To isolate a sample of B events, the lepton momentum, and transverse momentum are first calculated. The lepton p_t is determined with the lepton excluded from its jet. The requirements made are: $p(lepton) > 3.0GeV/c$ and $p_t(lepton) > 0.75GeV/c$. Using the values for the rate of $Z^0 \rightarrow c\bar{c}$ and $Z^0 \rightarrow b\bar{b}$ from reference [7], and Monte Carlo acceptance studies the charm fraction in the sample after these cuts (and the maximum $25GeV/c$ D^* momentum) should be: 6.8 ± 2.1 % for the $K\pi$ subsample.

The expected mistag in the lepton sample can be determined from the various lepton source fractions and from the overall value of $B^0_{d,s}$ mixing. A value of 25 ± 2 % is expected.

5.2 Jet Charge

Where no opposite side lepton is available the original quark charge can still be determined using the jet charge in the opposite hemisphere of the event. The jet

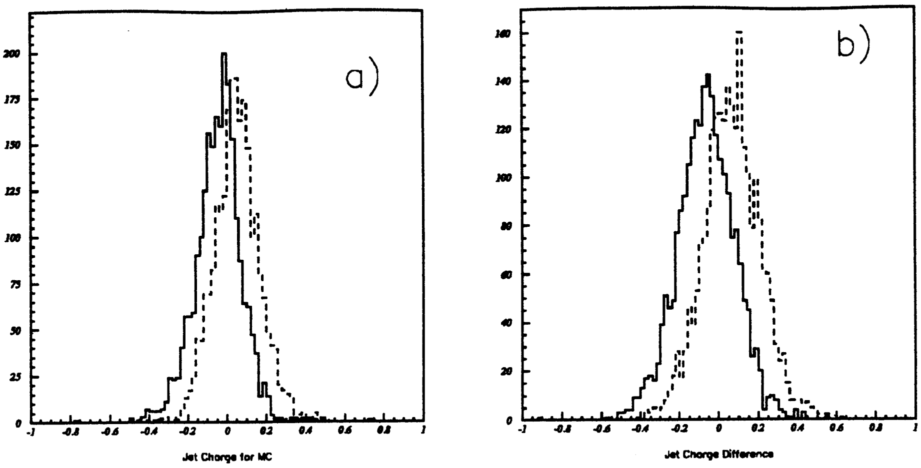

Figure 3: Jet charge distributions from Monte Carlo $b\bar{b}$ data. Figure a) is the jet charge for the jet side of the event and a value of $\kappa = 0.5$. Figure b) shows similarly the difference of the jet charge on the jet side and the mean charge on the D^* side of the event. The better separation is clear.

charge is determined according to:

$$Q_J = \frac{\sum_t q_t p_{\|t}^{\kappa}}{\sum_t p_{\|t}^{\kappa}}.$$

Where the sum is over good charged tracks, $p_{\|}$ is the momentum of the track along the thrust axis of the event, and κ is a weighting factor.

Monte Carlo studies were made on a sample of events to optimise the jet charge selection. The most sensitive value of the parameter κ was found to be 0.5. Figure 3 shows the jet charge distribution for Monte Carlo $b\bar{b}$ events (the sample used in this case is required to have a $D^* \rightarrow D^0\pi \rightarrow K\pi$ on the side opposite to the jet, but the results are consistent with a general $b\bar{b}$ sample).

If the sign of the quark charge is is simply taken as following the sign of the jet charge the mistag is found to be 0.334 ± 0.009. The quality factor λ for this level of mistag (with $N = 1$) is 0.110.

In order to improve this value the charge on the D^* side of the event, can also be considered. Since the charge of a B^0 is identically zero independent of mixing, the mean of the charges (Q_{D^*}) of the tracks on this side of the event should be relatively immune to the state of the B^0. The mean charge is composed mainly of the fragmentation tracks before the b quark has formed a B^0 meson, and thus should reflect the original charge of the quark.

To study this the distribution $Q_J^{\kappa=0.5} - Q_{D^*}$ is examined in Monte Carlo events, see figure 3. The fraction of unmixed events in the Monte Carlo sample where the sign of this distribution incorrectly follows the sign of the original quark is 0.32 ± 0.01, for mixed events, this fraction is 0.30 ± 0.02, confirming the assumption of independence from the mixing state.

The overall mistag using the sign of this distribution as reflecting the sign of the quark is: 0.318 ± 0.008, implying a value of $\lambda = 0.133$. A further improvement may be made if the region centred around zero is removed. Events in this region have a mistag of close to 50%, and so contribute no information. A trade off between lost statistics and lower mistag can be made. Removing events where $\mid Q_J^{\kappa=0.5} - Q_{D^*} \mid < 0.05$ reduces the overall mistag to 0.273 ± 0.009, with an efficiency of 0.74 ± 0.01. The quality factors λ is raised to 0.153 with this rejection. Note that choosing non-optimal values of the selection criteria cannot bias the result, but only reduce the sensitivity of the analysis.

With this selection the charm contamination of this sample is of course much higher than the lepton sample. The simplest method to reduce it is to use a lifetime tag on the jet side of the event. This does not affect the jet charge distributions, as the lifetimes of the B's are quite close. A cut on the lifetime hemisphere probability from QIPBTAG of 0.01 is made. From Monte Carlo studies this leaves a charm fraction of $12.3 \pm 3.7\%$ in the $D^0 \rightarrow K^- \pi^+$ subsample.

6 Background Determinations

The final sample of events originates from several sources. There is of course the process that to be measured, B^0 decaying to D^*, but there are several backgrounds and these must be understood: Combinatorial, where the "D^*" consists of random tracks, D^* produced directly from $Z^0 \rightarrow c\bar{c}$, and D^*'s from the decay of charged B mesons. All of these backgrounds are taken into the fit, for each the charge correlation and the time structure must be accounted for.

The nature of the combinatorial background is studied by looking in the sidebands of the D^0 mass and the mass difference spectrum. The time dependence of the background and its charge structure which is flat is fitted from events taken from the sidebands. The time dependence and charge structure of the combinatorial background is shown in figure 4. The number of background events is taken from a fit to the mass difference spectrum.

The amount of remnant charm background is left as a free parameter in the fit. The time dependence of the distribution is exponential governed by the D^0 lifetime. The charge correlation for the lepton sample is given by the fraction of lepton misassignments for the lepton subsample, and from the jet charge misassignment for that sample. Both of these values are extracted from Monte-Carlo studies. Rather than fitting four different charm fractions for the four event subsamples, one value is used, multiplied by the appropriate ratio of acceptances for each of the subsamples. The expected value of the charm fraction can be determined from the known values [7]

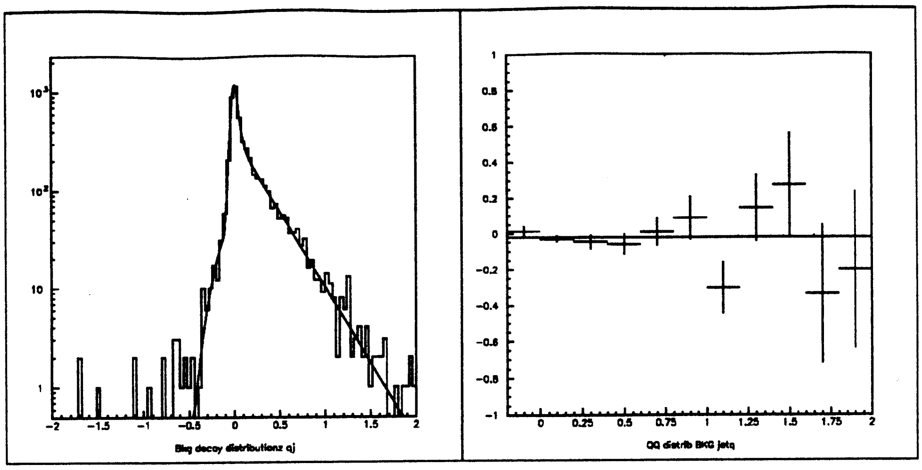

Figure 4: Sideband lifetime and charge correlation distributions for $K\pi$ jet charge events.

for $Z^0 \to c\bar{c}$ and $Z^0 \to b\bar{b}$ and for the rate of D^* production from each of these sources. The fitted free parameter is that for the $K^-\pi^+$ lepton subsample, and the expected fraction is 0.068 ± 0.21

The charged B background is more difficult to treat. No measurement of the inclusive branching ratio of $B^- \to D^{*+}X$ exists, nor is there any experimental evidence for its charge structure. In a spectator model, it should be suppressed over $B^0 \to D^{*-}X$. Evidence for such a suppression is seen in B^- to D^{*+} semileptonic decays [8]. This would imply a charged B fraction of around 15%. In addition there is the question of the charge correlation of the $D^{*\pm}$ with respect to the B^-. In the Montè Carlo the mistag for the $K\pi$ jet charge subsample is 0.48. In the fit the charged B fraction is left as a free parameter.

7 Fitting Procedure

The data are fitted using an unbinned maximum likelihood fit. Like and unlike sign data are each fitted to a function that contains the following terms:

- B^0 term, fitting for Δm. This consists the time dependent oscillation term, and a decay term. These are convoluted with the vertex resolution function and D^* momentum function.
- Direct Charm, exponential convoluted with the vertex resolution function. One parameter is used, that of the $K\pi$ lepton subsample. Other subsamples are fixed to this by the ratio of their acceptances.

- Combinatorial background. The shape and charge correlation is taken from sideband fits. The number of background events is constrained by the number fitted from the mass difference distributions.
- Charged B, consisting of an exponential decay function convoluted with the momentum and resolution functions. The charge correlation is varied over a large range and the fraction is allowed to vary freely in the fit.

The following parameters are fitted: Δm, the number of B^0 events in each subsample, the charm fraction, and the charged B fraction, and the mistag for the lepton and jet charge samples separately.

8 Results and Systematic Errors

The fit gives the following results:

- $\Delta m = 0.497 \pm 0.070$
- $f_c = 0.05 \pm 0.1$ Charm fraction, for the $K\pi$ lepton sample
- $\eta_l = 0.258 \pm 0.052$ Mistag for the lepton sample
- $\eta_Q = 0.341 \pm 0.045$ Mistag for the jet charge sample
- $f_{B^+} = 0.02 \pm 0.49$ Fraction of charge B.

The charm fraction and the mistags for the both sets of data are consistent with Monte Carlo expectations. The charge correlation distribution is shown in 5.

A check was performed by separating the jet charge and the lepton samples and performing the fits independently. The charm fraction and the mistag also allowed to float. In this case it was found that for the lepton sample alone $\Delta m = 0.508 \pm 0.114$ and that for the jet charge sample alone $\Delta m = 0.524 \pm 0.093$. The mistag and charm fractions have much larger errors.

The following sources of systematic error have been examined, and are listed in table 2.

- The charged and neutral B meson lifetimes. First the B^0 lifetime is varied holding the $B^0 - B^+$ lifetime difference constant. Then the lifetime difference is varied within its maximum error ± 0.20. The values used are to be found in reference [9], $\tau_0 = 1.50 \pm 0.10$ and $\tau_+ = 1.62 \pm 0.10$. Variation of the lifetimes has an effect not only on Δm but also on the mistag fractions and on the charged B fraction. To avoid the problems associated with the correlations of these quantities the systematic errors due to lifetime changes have been determined using

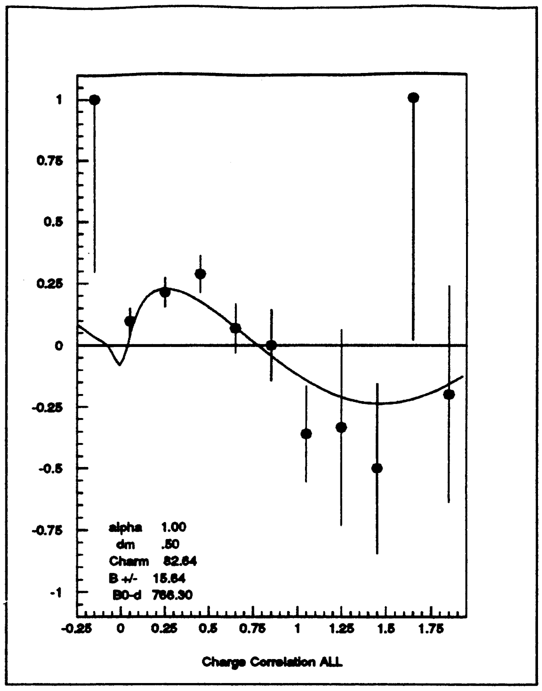

Figure 5: Final charge correlation distribution for all samples combined.

a Monte-Carlo procedure where the input parameters are varied separately. It is found that the charged B lifetime has little effect on Δm, the larger effect comes from varying τ_{B^0}.

- The mistag assumed for charged B events. This is estimated from the Monte Carlo and varied within large limits. For the lepton sample the value is 0.38 ± 0.12 and for the jet charge sample 0.35 ± 0.13.

- The D^0 lifetime.

- Two overall values for the charm fraction is fitted, and the relative fractions of the other subsamples are fixed to values determined from Monte Carlo acceptance studies. This relative acceptance is varied within the statistical errors of the acceptance correction.

- The resolution function for the D^0 decay. The value determined from Monte Carlo studies is used for this.

- The charge correlation of the background. It is varied within the errors found from fitting the charge correlation in the sidebands.

- The D^* momentum spectrum. To perform the fit for Δm the D^0 decay length must be convoluted with the expected momentum distribution of the D^* from

Source	Value and Variation	Variation of Δm
τ_{B^0} holding $\Delta\tau$ constant	1.50 ± 0.10ps	± 0.025
Varying $\Delta\tau$	± 0.20ps	$\pm .01$
Charge B mistag	See text	± 0.002
τ_{D^0}	0.42 ± 0.08	$\pm^{0.016}_{0.014}$
Relative Charm acceptance	$\pm 1\sigma$	± 0.01
Resolution Function	Monte Carlo Values	± 0.005
Background charge correlation	$\pm 1\sigma$	$\pm^{0.004}_{0.006}$
D^0 momentum	13.4 ± 0.7GeV/c	$\pm^{0.006}_{0.005}$
B fragmentation $< x >$	0.714 ± 0.012	± 0.010
Total		± 0.036

Table 2: Sources and values of the systematic errors in this analysis.

B decay. Comparison of the D^0 momentum spectrum between the data and the Monte Carlo shows a difference of about 5%. Varying this in the convolution produces the systematic error shown.

- The B momentum spectrum, also provided from Monte Carlo studies is varied by reweighting events with different values of the fragmentation parameter $< x >$. The value of $< x >= 0.714 \pm 0.012$ was taken from [7]

The final result with all systematic errors summed in quadrature is: $0.497 \pm 0.070 \pm 036$. Converting this into a measurement of $\Delta m/\Gamma$ gives $0.75 \pm 0.11 \pm^{0.05}_{0.06}$

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