Measurement of $B^0-\bar{B}^0$ Mixing at the CERN Sp $\bar{p}$ S collider*UA1 Collaboration, CERN, Geneva, Switzerland*

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ABSTRACT

We report on a new measurement of $B^0\text{--}\bar{B}^0$ mixing at the CERN Sp $\bar{p}$ S collider. Mixing is measured in the non-isolated high mass dimuon sample using data from the 1988–1989 collider runs. The measured value of the mixing parameter, χ , is $0.145 \pm 0.035(\text{stat}) \pm 0.014(\text{syst})$. The average of this measurement and that from our 1984–1985 data is $\chi = 0.148 \pm 0.029(\text{stat}) \pm 0.017(\text{syst})$ assuming fully correlated systematic errors. Using the measurement of χ_d from ARGUS and CLEO, we obtain $\chi_s = 0.50 \pm 0.20$, which gives a limit of $\chi_s > 0.17$ (0.12) at 90% (95%) CL. Including the measurements of χ from the ALEPH and L3 experiments gives $\chi_s = 0.53 \pm 0.15$, and a limit of $\chi_s > 0.27$ (0.23) at 90% (95%) CL.

1. Introduction

In the Standard Model, the flavor quantum numbers are not conserved in weak interactions. The transitions $K^0\text{--}\bar{K}^0$, $D^0\text{--}\bar{D}^0$ and $B^0\text{--}\bar{B}^0$ are therefore allowed by second order weak interactions. Evidence for $B^0\text{--}\bar{B}^0$ mixing was first seen at the UA1 experiment^[1] and was confirmed by the observation of B_d^0 mixing by ARGUS^[2]. Using the increase in statistics in the UA1 analysis and the measurements of B_d^0 from ARGUS^[2] and CLEO^[3], the existence of B_s^0 mixing can be demonstrated. A recent review of the formalism of $B^0\text{--}\bar{B}^0$ mixing is given in Reference [4].

2. Detector and data selection

A detailed description of the UA1 detector can be found elsewhere^[5]. In brief, as particles leave the interaction vertex, they first encounter a large volume drift chamber, the central detector (CD). Here, momenta of charged particles are measured in a 0.7 T dipole magnetic field, with a typical accuracy on $\Delta p/p$ of $0.01 * p$ (GeV/c) for a 1 m long track. These particles then pass through an air gap of 0.5 – 1.0 m in thickness. This gap is the result of removing the electromagnetic calorimeters (Gondolas and Bouchons) in preparation for the envisaged installation of a new uranium–TMP calorimeter. The particles next encounter the hadronic calorimeter and at least 60 cm of additional iron shielding (about 1.5 m in the forward region). Together, the hadronic calorimeter and the shielding wall consist of at least 8 nuclear interaction lengths of material, which almost completely absorb strongly interacting particles. The iron shielding wall is partially instrumented with planes of limited streamer tubes. These tubes measure the position of muons, as they leave the hadronic calorimeter, with a resolution of 1 to 2 mm. Finally, muons are detected in the muon chambers, which surround the experimental apparatus and cover approximately 75% of the solid angle. These muon chambers allow the detection of muons in a pseudorapidity range $|\eta| < 2.3$. Muon trigger processors require tracks in the muon chambers which point back to the interaction region.

These processors permit triggering with $|\eta| < 1.5$ for single high p_T muons, where p_T is the momentum transverse to the beam axis, and with $|\eta| < 2.3$ for muon pairs.

The analysis presented here is based on data collected with the UA1 detector during runs at the CERN $p\bar{p}$ collider from 1988 to 1989, and corresponds to a total integrated luminosity of 4.7 pb^{-1} . Muons are identified as high p_T tracks in the CD, which when extrapolated through the iron shielding have corresponding tracks in the muon chambers. Dimuon events are selected requiring both tracks to come from the primary interaction vertex and to have $p_T > 3 \text{ GeV}/c$. In order to eliminate muons from low mass mesons such as J/ψ and b chain decays ($\bar{b} \rightarrow \mu^+ \nu + \bar{c}$; $\bar{c} \rightarrow \mu^- \bar{\nu} + \bar{s}$) a mass cut of $M(\mu\mu) > 6 \text{ GeV}/c^2$ is applied. The events are also required to have non-isolated muons to remove Drell-Yan and $\Upsilon \rightarrow \mu^+ \mu^-$ decays. We define the isolation variable $S^{[6]}$:

$$S = \sum_{i=1}^2 \left[(\Sigma E_T(\mu_i)/2)^2 + (\Sigma p_T(\mu_i))^2 \right],$$

and require $S > 8 \text{ GeV}^2$, where $\Sigma E_T(\mu_i)$ is the sum of the transverse energy measured in the calorimeter and $\Sigma p_T(\mu_i)$ is the sum of the p_T of charged particles measured in the CD in a cone of $\Delta R < 0.7$ around μ_i . Here, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where η is the pseudorapidity and ϕ is the azimuthal angle.

In addition, each muon is required to have associated jet activity in the CD so that the variable p_T^{rel} , which is the momentum of the muon transverse to the jet axis, can be defined. The jet is required to have at least one track of $p_T > 1 \text{ GeV}/c$ in addition to the muon and the jet axis is required to lie within a cone of $\Delta R < 1.0$ around the muon track. Each muon is also required to have $p_T < 20 \text{ GeV}/c$ to eliminate sign ambiguities and $p_T^{\text{rel}} < 3 \text{ GeV}/c$ since the $b\bar{b}$ contribution is negligible above this value.

There are 889 events left after these cuts, of which 537 are unlike-sign and 352 are like-sign.

3. Method for measuring $B^0-\bar{B}^0$ mixing

We define the mixing parameter $\chi_{s,d}$ by:

$$\chi_{s,d} = \frac{\text{BR}(B_{s,d}^0 \rightarrow \bar{B}_{s,d}^0 \rightarrow \mu^- + \bar{\nu}_\mu + X)}{\text{BR}(B_{s,d}^0 \rightarrow \mu^+ + \nu_\mu + X) + \text{BR}(\bar{B}_{s,d}^0 \rightarrow \mu^- + \bar{\nu}_\mu + X)},$$

which is the probability of a B^0 meson oscillating into a $\bar{B}^0$ meson. In this analysis we assume that CP violation effects are negligible so that the charge conjugate reaction has the same probability. Since B_d^0 and B_s^0 are indistinguishable in the UA1 detector, the measured χ is a mixture of χ_d and χ_s . The separation of χ into χ_d and χ_s is discussed in section 5.

Process	Like-sign	Unlike-sign
1st generation $b\bar{b}$	$2\chi(1-\chi)$	$(1-\chi)^2+\chi^2$
2nd generation $b\bar{b}$	$(1-\chi)^2+\chi^2$	$2\chi(1-\chi)$
$c\bar{c}$		100%
Drell-Yan		100%
Upsilon		100%
Decay Background	50%	50%

Table 1: Like-sign and Unlike-sign fractions of the contributions to the dimuon sample.

The processes which contribute to the dimuon sample are listed in Table 1. The non-isolated dimuon sample is dominated by $b\bar{b}$ and $c\bar{c}$ production^[7]. Dimuons from $b\bar{b}$ contain the information about mixing, these dimuons are predominantly produced in two processes:

- First generation $b\bar{b}$ events where both B mesons decay directly into muons. The charge of the decay muon is correlated with that of the initial quark, i.e. $\bar{b} \rightarrow \mu^+ \nu + \bar{c}$, and $b \rightarrow \mu^- \bar{\nu} + c$. In this case the event will be an unlike-sign dimuon event. If a B^0 meson oscillates into a $\bar{B}^0$ or vice versa, the event will be a like-sign dimuon event.
- Second generation $b\bar{b}$ events where one B^0 meson decays directly into a muon and the other decays into a c-quark, which then decays into a muon. The decay chain is $\bar{b} \rightarrow \mu^+ \nu + \bar{c}$, and $b \rightarrow c + X$; $c \rightarrow \mu^+ \nu + s$, or its charge conjugate. These events result in like-sign dimuons unless one of the B^0 mesons oscillates, in which case the event becomes unlike-sign.

We use the variable p_T^{rel} to distinguish between $b\bar{b}$, decay background of pions and kaons in flight, and $c\bar{c}$ events^[7]. The shape of the p_T^{rel} distribution depends only on the mass of the initial quark and the decay chain. It is independent of the boost of the initial meson as it is defined perpendicular to the boost axis. There are four decay chains that contribute to the dimuon data:

$$\begin{aligned}
b &\rightarrow \mu^- \bar{\nu} + c, \\
b &\rightarrow c + X; c \rightarrow \mu^+ \nu + s, \\
c &\rightarrow \mu^+ \nu + s, \\
u, d, s &\rightarrow \mu^\pm + X \text{ } (\pi, K \text{ decays in flight}).
\end{aligned}$$

The following parameterization is used for the shape of the p_T^{rel} distributions for the above processes:

$$f(p_T^{\text{rel}}) = \frac{A (p_T^{\text{rel}})^\alpha \exp\left[\frac{(p_T^{\text{rel}})^\beta}{\gamma}\right]}{\int (p_T^{\text{rel}})^\alpha \exp\left[\frac{(p_T^{\text{rel}})^\beta}{\gamma}\right] d(p_T^{\text{rel}})}.$$

The integral in the denominator is necessary in order to decouple the normalization variable (A) from the shape variables (α , β , γ). For first generation $b\bar{b}$, the higher p_T and lower p_T muons have the same kind of decay chain and thus have the same p_T^{rel} distributions. The same is true for $c\bar{c}$ events. Therefore, a distribution can be applied to both the higher and lower p_T muons for first generation $b\bar{b}$ and $c\bar{c}$ events. The second generation $b\bar{b}$ events contain both direct and indirect b to muon decays in equal proportion. However, the two decays are not divided equally between the higher and lower p_T muons, therefore, they must be kept separate and a p_T^{rel} distribution used for each.

To estimate the dimuon decay background from pions and kaons, the probability of a decay muon from a pion or kaon being accepted by the reconstruction algorithm is calculated by Monte Carlo simulation. The probability is evaluated as a function of the p_T of the initial hadron and the p_T of the reconstructed muon. Fake dimuon events are constructed using real single muon events. In these events, each CD track (other than the muon track) is consecutively assumed to be a pion or kaon which then decays into a second muon. The event is given a weight based on the probability that the track is a pion or kaon multiplied by the probability that the particle would decay into a muon^[8]. Since the decay background calculation depends on real single muon events, there is a contamination of higher p_T muons coming from b- and c-quark decays. Therefore, the higher and lower p_T distributions must also be kept separate. Since the sign of the muons from decay background are essentially uncorrelated, we assume that there are an equal number of decay background events in the like-sign and unlike-sign data samples.

The shape variables α , β and γ are determined in a chi-squared fit to the Monte Carlo p_T^{rel} distributions. The ISAJET Monte Carlo program [9] was used to produce 50 pb^{-1} of events, which were then passed through the full detector simulation. The Monte Carlo p_T^{rel} distributions with the fitted curves are displayed in Fig. 1. There are too few Upsilon and Drell-Yan events to perform a chi-squared fit. In order to estimate the shape of these processes a histogram is filled and smoothed. This is an acceptable approximation as we estimate only 7 Upsilon decays and 6 Drell-Yan events in our data sample of 889 events.

We perform an event by event log-likelihood fit of the p_T^{rel} distributions of the muons to measure the amount of $b\bar{b}$ in the like-sign and unlike-sign data samples. The p_T^{rel} of the higher p_T and lower p_T muons ($p_T^{\text{rel hi}}$ and $p_T^{\text{rel lo}}$) are fitted independently. The mixing parameter, χ , is varied in the fit until the Monte Carlo prediction for the ratio of like-sign and unlike-sign events agree with that obtained from the data. However, this ratio is also affected by sources of uncertainty both from the shape of the p_T^{rel} distributions and the prediction of the number of events. These sources are allowed to vary in the fit within gaussian constraints. The sources of uncertainties in the number of events are listed in Table 2.

Variable	Central value $\pm 1\sigma$ constraint
mixing parameter (χ)	unconstrained
$\text{BR}(b \rightarrow \mu^\pm + X)$	$(11.4 \pm 1.3)\%$
$\text{BR}(c \rightarrow \mu^\pm + X)$	$(9.0 \pm 0.9)\%$
$c\bar{c}$ fraction of unlike-sign events	$(11.0 \pm 5.5)\%$
Drell-Yan fraction of unlike-sign events	$(1.2 \pm 0.2)\%$
Υ fraction of unlike-sign events	$(1.0 \pm 0.3)\%$
Decay Background fraction of all events	$(37.0 \pm 9.2)\%$

Table 2. Input values and constraints for the variables that are fitted to determine the number of like-sign and unlike-sign events.

The shape parameters are constrained from the chi-squared fit to the Monte Carlo distributions. The branching fraction of $b \rightarrow \mu^\pm + X$ is taken from Mark II measurements [10] at 29 GeV. The error on the $c \rightarrow \mu^\pm + X$ branching fraction is

composed of the uncertainty on the D meson semi-leptonic branching fractions and the uncertainty of the relative production of D mesons in B meson decays. We use the ISAJET prediction of the $c\bar{c}$ fraction assuming a conservatively large error. This prediction is consistent with the UA1 analysis of the 1984–1985 data taking runs ^[1]. The errors on the Υ and Drell–Yan fractions are due to the systematic uncertainty coming from the isolation cut. The error on the decay background comes from the uncertainty in the fraction of pions and kaons produced at the collider.

The absolute number of decay background events is determined from the data with the method outlined before. The absolute number of Υ and Drell–Yan events is determined from the isolated dimuon data sample and extrapolated to the non-isolated sample using the Monte Carlo. The relative number of events from the b- and c-quark processes are also predicted by Monte Carlo but normalized to the number of events in the data after background subtraction. This makes the measurement of χ independent of the b cross-section as mixing only changes the ratio of unlike-sign and like-sign events.

In the like-sign data there are contributions only from $b\bar{b}$ and decay background events. As can be seen in Fig. 1, the $b\bar{b}$ distribution peaks at higher p_T^{rel} than the background. The $b\bar{b}$ contribution is set by the events with high p_T^{rel} and the background contribution by the low p_T^{rel} events. In the unlike-sign events, the $b\bar{b}$ contribution is also determined by the high p_T^{rel} events. However, the low p_T^{rel} events can come from either decay background or $c\bar{c}$. The variable p_T^{rel} separates $b\bar{b}$ events, which contain the mixing information, from background events on a statistical basis, thus reducing the sensitivity of the mixing result to the calculation of the backgrounds.

4. Results

The individual p_T^{rel} distributions along with the data can be seen in Fig. 2. The fitted number of events for each process is given in Table 3.

Process	Like-sign events	Unlike-sign events
1st generation $b\bar{b}$	86.7	263.2
2nd generation $b\bar{b}$	90.7	29.9
$c\bar{c}$	0.0	63.1
Drell–Yan	0.0	4.9
Upsilon	0.0	4.2
Decay Background	173.1	173.1

Table 3. Fitted number of events for each process.

The result of the fit is shown in Fig. 3. We obtain:

$$\chi = 0.145^{+0.040}_{-0.036},$$

where the error is the total of the statistical and systematic errors. The individual systematic errors on χ can be estimated by taking the difference in quadrature of the error on χ , calculated including and excluding a source of uncertainty, to be the contribution of that source of uncertainty to the error. Table 4 shows the estimated systematic error on χ coming from each source of uncertainty.

Source of uncertainty	Systematic error on χ
1st generation $b\bar{b}$ shape	0.0009
2nd generation $b\bar{b}$ shape	0.0044
$BR(b \rightarrow \mu^\pm + X)$	0.0062
$BR(c \rightarrow \mu^\pm + X)$	0.0056
$c\bar{c}$ fraction	0.0104
$c\bar{c}$ shape	0.0060
Υ and Drell–Yan normalization	0.0013
Decay Background normalization	0.0039
Decay Background shape	0.0034

Table 4. Sources of uncertainty and the corresponding systematic errors.

The total systematic error on χ is estimated to be 0.014 from this method. Subtracting this in quadrature from the total error, which is taken to be 0.038, we obtain the statistical error on χ , hence:

$$\chi = 0.145 \pm 0.035 \text{ (stat)} \pm 0.014 \text{ (syst)}.$$

The previous UA1 analysis^[1], using a data sample of 0.7 pb^{-1} , assumed negligible Upsilon and Drell–Yan backgrounds. This was because the muons were required to be non-isolated. However, the non-isolation cut was only 82% efficient in removing these backgrounds. When the residual Upsilon and Drell–Yan events were included, the measurement gave $\chi = 0.158 \pm 0.052 \text{ (stat)} \pm 0.026 \text{ (syst)}$. The previous and new UA1 measurements can be combined in an average weighted by the errors. The systematic errors have an unknown degree of correlation, but since the measurement is dominated by the statistical uncertainty the degree of correlation does not have a large effect on the total uncertainty, i.e.

$\chi = 0.149 \pm 0.029$ (statistical) ± 0.013 (systematic)	no correlation,
$\chi = 0.148 \pm 0.029$ (statistical) ± 0.017 (systematic)	full correlation.

The fully correlated number is used in the calculation of the χ_s limit.

5. Calculation of χ_s limits

As we do not distinguish between B^0_s and B^0_d mesons in this analysis, our measurement is a combination of B^0_s and B^0_d mixing. Assuming that the inclusive muonic decay branching fraction is equal for all b-mesons and b-baryons, the mixing parameter, χ , can be written as:

$$\chi = f_{dd} \chi_d + f_{ss} \chi_s,$$

where f_{dd} and f_{ss} are the quark fragmentation fractions. We use

$$f_{dd} = 0.36 \text{ and } f_{ss} = 0.18,$$

which are estimated using data from the ISR, UA2 and UA5 experiments^[11].

The ARGUS^[2] and CLEO^[3] collaborations have measured χ_d to be (0.170 ± 0.054) and (0.154 ± 0.056) , respectively. The weighted average of these measurements is $\chi_d = 0.162 \pm 0.039$. Fig. 4 shows the new UA1 mixing measurement along with the average ARGUS and CLEO measurement and their $\pm 1\sigma$ bands. The Cabibbo-Kobayashi-Maskawa (CKM) line indicates the upper limit on χ_d as a function of χ_s , which can be derived from existing limits on the CKM matrix elements, assuming the standard model with three families^[12].

In order to calculate the limit on χ_s , the measurement of χ_d must be combined with the two UA1 measurements. To do this a log-likelihood fit of χ_d and χ_s is done taking each measurement as a gaussian constraint. This fit produces a probability density function in the χ_d versus χ_s plane. The measured value of χ_s from the fit is 0.50 ± 0.20 . However, the probability density function extends into non-physical regions ($\chi_{d,s} < 0.0$, $\chi_{d,s} > 0.5$). To take this into account when calculating the limits, the non-physical regions are cut away and the remaining probability density is renormalized to one over the physical region. In Fig. 5a, we show the two dimensional limits at 90% and 95% confidence levels on χ_d versus χ_s derived from the fit. The one dimensional limits for χ_s are:

$$\chi_s > 0.12 \text{ at } 95\% \text{ CL, and}$$

$$\chi_s > 0.17 \text{ at } 90\% \text{ CL.}$$

The above limits do not coincide with the edges of the ellipses in Fig. 5a. This is because the total probability outside of a 90% CL ellipse is 10% and a vertical line

drawn tangent to the ellipse will exclude less than 10%; the one dimensional limit obtained this way will not be at 90% confidence level.

The LEP experiments^[13,14] assume $f_{dd}=0.375$ and $f_{ss}=0.15$ at the Z mass. If we use these values in our analysis, the limits are reduced to $\chi_s > 0.11$ at 95% CL and $\chi_s > 0.16$ at 90% CL. Thus, the limit on χ_s is not very sensitive to variations in this parameter.

In Fig. 5b, we show the two dimensional limits resulting from including the recent mixing measurements from ALEPH^[13] (0.132 ± 0.027) and L3^[14] ($0.178^{+0.049}_{-0.040}$). The error on the L3 value is taken to be 0.045 in order to combine it with the other measurements. The fitted value of χ_s including the LEP measurements is 0.53 ± 0.15 and the limits for χ_s are:

$$\chi_s > 0.23 \text{ at 95\% CL, and}$$

$$\chi_s > 0.27 \text{ at 90\% CL.}$$

6. Conclusions

In an analysis of dimuon events collected in the 1988–1989 collider runs (4.7 pb^{-1}), we measure the mixing parameter $\chi = 0.145 \pm 0.035(\text{stat}) \pm 0.014(\text{syst})$ using the variable p_T^{rel} to separate $b\bar{b}$ events from background and $c\bar{c}$ events. We combine this measurement with the previous UA1 measurement assuming fully correlated systematic errors. The combined value is $\chi = 0.148 \pm 0.029(\text{stat}) \pm 0.017(\text{syst})$. Using the combined UA1 result and the measurements of χ_d from ARGUS and CLEO, we determine $\chi_s = 0.50 \pm 0.20$ (assuming $f_{dd}=0.36$ and $f_{ss}=0.18$). We obtain a limit of $\chi_s > 0.17$ at 90% CL and $\chi_s > 0.12$ at 95% CL. Including the recent LEP results, we obtain $\chi_s = 0.53 \pm 0.15$, and a limit of $\chi_s > 0.27$ at 90% CL and $\chi_s > 0.23$ at 95% CL.

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Figures

1. Distributions of p_T^{rel} for Monte Carlo events. The line is the fitted parameterization of the Monte Carlo distribution. The p_T^{rel} of the higher p_T muon is labelled $p_T^{\text{rel hi}}$; the p_T^{rel} of the lower p_T muon is labelled $p_T^{\text{rel lo}}$.
2. Distributions of p_T^{rel} for the data. The solid line, labelled fit, is the Monte Carlo predicted distribution of p_T^{rel} . The individual Monte Carlo distributions are also shown.
3. Variation of log-likelihood as a function of χ . The levels corresponding to $\pm 1\sigma$ to $\pm 4\sigma$ are shown.
4. Plot of χ_d versus χ_s . The combined UA1 measurement from 1984 – 1989 is drawn as well as dotted lines indicating the $\pm 1\sigma$ bands. The same is shown for the ARGUS and CLEO measurements. The region below the CKM matrix line is allowed by unitarity.
5. Allowed region in the χ_d versus χ_s plane for the combined measurements:
a) UA1 + ARGUS + CLEO; b) UA1 + ARGUS + CLEO + ALEPH + L3.
The limits shown are at 90% and 95% confidence levels.

FIG. 1

FIG.2

FIG. 3

FIG. 4

FIG. 5a

FIG. 5b