Measurement of $B^0\bar{B}^0$ Mixing via Time Evolution

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July 1995

Submitted to the XVII International Symposium on Lepton-Photon Interactions,
Beijing, China, August 10-15, 1995
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Abstract

With the CDF detector at the Tevatron $p\bar{p}$ collider the $B^0$ mixing parameter $x_d$ has been measured via time evolution. From a sample of $\sim 20 \text{ pb}^{-1}$ dimuon data a value of $x_d = 0.64 \pm 0.18 \pm 0.21$ has been obtained.

1 Introduction

Oscillations in the $B^0\overline{B}^0$ meson system were observed by the ARGUS [1] and CLEO collaboration [2] as well as the LEP experiments [3] including time dependent measurements. A determination of the rate of $B^0$, as well as $B^0_s$ mixing is desirable, both to estimate the magnitude of $CP$ violating effects in $B$ meson decay, and to measure the Cabibbo-Kobayashi-Maskawa (CKM) [4] matrix element $|V_{td}|$.

The probability that an initially pure $B^0$ state can be observed as a $\overline{B}^0$ at time $t$ is given by:

$$\text{Prob}(B^0 \rightarrow \overline{B}^0, t) = \frac{1}{2} \cdot \exp^{-\frac{t}{\tau}} \cdot (1 - \cos \Delta m t).$$

If the decay time $t$ cannot be measured the time integrated probability, which is usually referred to as $\chi$, can be obtained as

$$\chi_i = \frac{\text{Prob}(B^0_i \rightarrow \overline{B}^0_i)}{\text{Prob}(B^0_i \rightarrow \overline{B}^0_i) + \text{Prob}(B^0_i \rightarrow B^0_i)} = \frac{x_i^2}{2(1 + x_i^2)}$$

where $i = s, d$. (2)

If both neutral $B$ mesons, $B^0$ and $B^0_s$, are produced, the time integrated and flavour averaged mixing parameter $\overline{\chi}$, which is defined as

$$\overline{\chi} = F_d \chi_d + F_s \chi_s,$$

can be obtained, where $F_d$ and $F_s$ are the fractions of $b$ hadrons that are produced as $B^0_s$ and $B^0$ mesons, respectively. Here the frequently used mixing parameter $x = \Delta m / \Gamma$ has been introduced. It describes the oscillation period relative to the $B$ meson lifetime $\tau_B = \hbar / \Gamma$.

Keeping the time dependence of $Prob(B^0 \rightarrow \bar{B}^0, t)$ the following expression yields:

$$\frac{Prob(B^0 \rightarrow \bar{B}^0, t)}{Prob(B^0 \rightarrow B^0, t) + Prob(B^0 \rightarrow \bar{B}^0, t)} = \frac{1}{2} (1 - \cos \frac{x t}{\tau})$$

In the Standard Model, $B$ mixing occurs via second order box diagrams (Fig. 1). The mass difference $\Delta m_B$ can be calculated and the dominant contribution is due to top quark exchange:

$$\frac{\Delta m_B}{\Gamma} = \frac{\tau_B}{6 \pi^2} G_F^2 m_W^2 m_B (f_B^2 B_B) \eta_{QCD} F(m_t) |V_{tb}|^2 |V_{td}|^2.$$  

Here, $G_F$ is the Fermi coupling constant, $m_B$ the $B$ meson mass, $m_W$ the $W$ boson mass, and $f_B$ the weak $B$ decay constant. $B_B$ is the bag parameter of the $B$ meson and $\eta_{QCD}$ are QCD corrections, which are in the order of 1. $|V_{tb}|$ and $|V_{td}|$ are the two Cabibbo-Kobayashi-Maskawa matrix elements involved, and $F(m_t)$ is a correction depending on the top quark and the $W$ mass.

In general a time dependent mixing measurement requires the knowledge of:

1. the flavour of the $B$ meson at its origin
2. the flavour of the $B$ meson at its decay
3. the proper decay time $t$ of the $B$ meson.
The latter can be obtained from a measurement of the $B$ decay distance $L$ which can be inferred from the vector pointing from the primary interaction vertex, where the $B$ meson is generated, to the secondary vertex, where it decayed. The decay time $t$ is related to the decay distance $L$ by

$$t = \frac{L}{\beta \gamma} = L \cdot \frac{m_B}{p_B}.$$  \hspace{1cm} (6)

This relation is also valid if the decay length is only measured in the transverse plane ($L_{xy}$):

$$t = L_{xy} \cdot \frac{m_t}{p_t}.$$  \hspace{1cm} (7)

If the $B$ meson is not fully reconstructed a so called $\beta \gamma$ correction to scale from the only partially measured $B$ decay momentum $p_t^{cl}$ and mass $m_t^{cl}$ to the unknown $B$ momentum $p_B$ must be applied. This leads to the definition of $c_t$:

$$c_t = L_{xy} \cdot \frac{m_t^{cl}}{p_t^{cl}} \cdot F_{\beta \gamma}(p_t^{cl}, m_t^{cl}).$$  \hspace{1cm} (8)

From Eq. (8) the uncertainty on the decay time can easily be calculated to be (in units of the $B$ lifetime $\tau$):

$$\frac{\sigma_t}{\tau} = \sqrt{\left(\frac{\Delta L_{xy}}{L_{xy}^0}\right)^2 + \left(\frac{t \Delta p_t}{p_t \tau}\right)^2} \text{ where } L_{xy}^0 = \frac{p_t}{m_t} \cdot c_t$$  \hspace{1cm} (9)

From this it is obvious that the proper time resolution $\sigma_t/\tau$ depends on the resolution to infer the decay length from the primary to the $B$ decay vertex (vertexing resolution) as well as on the $B$ momentum resolution ($\beta \gamma$ correction).

In this note we report on the first preliminary measurement of the $B^0 \bar{B}^0$ mixing parameter $x_d$ via time evolution in a hadron collider environment. The flavour of the $B$ meson at its decay is inferred by the charge of the lepton in semi-muonic $B$ decays, while the flavour of the $B$ meson at its creation is obtained using the semi-muonic decay of the other $B$ meson in the event. In section 2 we describe the used dataset as well as the CDF detector while our selection is presented in section 3. The results are given in section 4. We conclude in section 5.

### 2 Detector and Dataset

The CDF detector has been described in detail elsewhere [5]. The detector systems used for this analysis are the silicon vertex detector (SVX), the central tracking chamber (CTC), and
the muon system. The SVX and CTC are located in a 1.4 T solenoidal magnetic field. The SVX consists of 4 layers of silicon-strip detectors with r-\phi readout, including pulse height information [6]. The pitch between readout strips is 60 \mu m and a spatial resolution of 13 \mu m has been obtained. The first measurement plane is located 3.0 cm from the interaction point, leading to an impact parameter resolution of \sim 15 \mu m for tracks with \pt > 5 GeV/c. The CTC is a cylindrical drift chamber containing 84 layers, which are grouped into alternating axial and stereo superlayers containing 12 and 6 layers, respectively. The combined CTC and SVX system has a resolution of \delta \pt/\pt = [(0.0009\pt)^2 + (0.0066)^2]^{1/2} for beam constrained tracks, where \pt is the momentum transverse to the beam direction (measured in GeV/c).

The central muon system consists of three detector elements. The Central Muon Chambers (CMU), located behind \sim 5 absorption lengths of material, provide muon identification over 85% of \phi for the pseudorapidity range |\eta| \leq 0.6, where \eta = -\ln[\tan(\theta/2)]. This \eta region is further instrumented by the Central Muon Upgrade (CMP), located after \sim 8 absorption lengths. The central muon extension (CMX), which covers the pseudorapidity range 0.6 < |\eta| < 1.0, provides muon identification over 67% of the azimuth and is located behind \sim 6 absorption lengths.

The dataset used for this analysis originates from the 1992/93 Tevatron collider run and corresponds to an integrated luminosity of about 20 pb^{-1}. It was collected using di-muon triggers in the CDF three level trigger system. At Level 1, two-muon candidates are selected with a trigger that requires the presence of two charged tracks in the central muon system. The efficiency for finding a muon at Level 1 rises from 50% at \pt = 1.8 GeV/c to 90% for \pt = 3.8 GeV/c. At Level 2, the dimuon trigger requires that at least one of the muon tracks match a charged track in the CTC. This CTC track is found by a Central Fast Track processor (CFT) [7]. The efficiency to find a track in the CFT rises from 50% at 2.7 GeV/c to 90% for \pt = 3.4 GeV/c. At Level 3 the trigger uses online track reconstruction software and selects dimuon candidates by requiring the presence of two oppositely charged muons with invariant mass greater than 4.0 GeV/c^2.

3 Selection

A sample of about half a million of low \pt dimuon triggers is used for this measurement of \x with time evolution. A substantial amount of background is removed by applying \mu quality cuts and requiring the invariant mass of the dimuon system to be larger than 5 GeV/c^2 to reject double semi-leptonic decays of the \B meson. After these cuts the sample reduces to
Figure 2: Comparison of the $p_{t}^{\text{rel}}$ distributions from sequential $b \rightarrow c \rightarrow \mu$ and direct $b \rightarrow \mu$ as obtained from MC (left). The right hand figure shows the normalized integral of these distributions with the cut value at 1.3 GeV/c.

$\sim 100,000$ events. We then apply a secondary vertex $b$-tagging algorithm to select decays of heavy flavours and require the tag to be close to one of the muons. This is a necessary step in this analysis since we need a secondary vertex to measure the $c\tau$ of at least one of the $B$'s. We assign all tracks in the tag, excluding the associated muon, to an inclusive "$D^n$" decay and fit all these tracks to a common vertex. We then define a transverse decay length, $L_{xy}$, as the intersection of the "$D^n$" trajectory with that of the associated $\mu$ projected onto the transverse direction of the $\mu"D^n"$ system. The proper decay length cannot be calculated exactly, since in general we are missing some of the $B$ decay particles. As already mentioned in section 1, we define

$$c\tau = L_{xy} \frac{M_B}{p_t^{D^n}} \cdot F,$$

where $F$ is an average kinematical correction factor to be determined via Monte Carlo.

We also require that the $p_{t}^{\text{rel}}$ of the muon relative to the "$D^n$" direction be larger than 1.3 GeV/c. As can be seen from Fig. 2 this cut reduces significantly the contribution from sequential $b \rightarrow c \rightarrow \ell$ decays, which cause a significant dilution of the effect of mixing. The $p_{t}^{\text{rel}}$ cut additionally reduces dimuon background from direct $c\bar{c}$ production.
Figure 3: Like-sign fraction versus \( c\tau \). The solid line is our fit to the data; the dashed line is our fit after forcing \( x_d=0 \) and the dotted line is a prediction assuming just the sequential decay contribution and both \( x_d \) and \( x_s = 0 \).

## 4 Results

After all cuts we are left with 3873 events (1516 like-sign and 2357 opposite-sign). In Fig. 3 we show the dependence on \( c\tau \) of the like-sign fraction, defined as:

\[
\frac{N_{LS}(c\tau)}{N_{LS}(c\tau) + N_{OS}(c\tau)}.
\]

A clear oscillation signal is observed. The solid line is the fit to the data, while the dashed line is the fit after forcing \( x_d=0 \). The dotted line is a prediction assuming just the sequential decay contribution and both \( x_d \) and \( x_s = 0 \).

To fit the observed oscillation we need an estimate of the background, the \( c\tau \) resolution function and the behaviour of the sequential decay fraction. We find that the combined request of two high quality muons and a b-tag selects an extremely pure \( b\bar{b} \) sample. A three component fit to the muon \( p_T^{\text{rel}} \) distribution on the vertex side, which takes into account direct and sequential \( B \) decays as well as direct charm production, yields a charm background in the order of 1%. A two component fit to the \( \mu \) impact parameter in the away side, taking into account a \( b\bar{b} \) and a fake muon component, estimates a fake fraction of \( (10\pm3.5)\% \).
We then use the Monte Carlo to simulate $b\bar{b}$ events from where the kinematical correction factor $F_{\beta\gamma}$ is calculated. The $L_{xy}$ resolution function is shown in Fig. 4a, and the $1/\beta\gamma$ resolution function in Fig. 4b as obtained from Monte Carlo (see eq. (9)). Overlaid is in both cases a parametrization obtained as a sum of weighted gaussians, which are not necessarily centered at zero. The fraction of $b \to c \to \ell$ decays relative to the total number of $b$ semi-leptonic decays $f_{\text{seq}}$ is also obtained from MC. For this specific analysis we found that the $b$-tagging biases $f_{\text{seq}}$, therefore we calculate an average fraction of $f_{\text{seq}} = (19.4 \pm 0.6)\%$ for the away side and $f_{\text{seq}} = (15.1 \pm 0.6)\%$ for the vertex side. Furthermore, on the vertex side $f_{\text{seq}}$ is parametrized as a function of the measured $c\tau$ value.

Additional inputs to the fit are $\chi_{st}$, which we assume to be saturated at 0.5, and $F_d$ and $F_s$, which are the fractions of $B^0$ and $B_s^0$ contained in our sample. For these we take the values $0.37 \pm 0.03$ and $0.15 \pm 0.04$, respectively. We find that the event selection does not bias these fractions significantly.

The result of the fit to the like-sign fraction plot is:

\[ x_d = 0.64 \pm 0.18 \pm 0.21 \]

\[ \Delta m_d = 0.44 \pm 0.12 \pm 0.14 \text{ ps}^{-1}. \]
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<th>Description</th>
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Table 1: Summary of systematic error on $x_d$.

A compilation of the systematic error on $x_d$ can be found in Table 1. The systematic error is largely dominated by the uncertainty on the overall fraction of sequential decays.

5 Conclusion

In summary we have measured the $B^0$ mixing parameter $x_d$ with the CDF detector at the Fermilab Tevatron in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. From a time evolution analysis a value of $x_d = 0.64 \pm 0.18 \pm 0.21$ has been obtained using a sample of about 20 pb$^{-1}$ highmass dimuon data. The result is consistent with measurements at LEP or CLEO and can serve as a 'proof of principle' that $B$ physics involving both $B$ mesons in the event is feasible in a hadron collider environment.

Acknowledgements

We thank the CDF technical support staff at all CDF institutions for their hard work and dedication. We also thank the Fermilab Accelerator Division for their hard and successful work in commissioning the machine for this physics run. This work was supported by the Department of Energy; the National Science Foundation; the Istituto Nazionale di Fisica Nucleare, Italy; the Ministry of Science, Culture, and Education of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the A. P. Sloan Foundation; and the Alexander von Humboldt-Stiftung.

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