Fermi National Accelerator Laboratory

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

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Abstract

With the CDF detector at the Tevatron $p\overline{p}$ collider the B^0 mixing parameter x_d has been measured via time evolution. From a sample of $\sim$ 20 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_S^0 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:

$$Prob(B^0 \to \overline{B}^0, t) = 1/2 \cdot \exp^{-\Gamma t} \cdot (1 - \cos \Delta m t). \tag{1}$$

If the decay time t cannot be measured the time integrated probability, which is usually refered to as χ, can be obtained as

$$\chi_i = \frac{Prob(B_i^0 \to \overline{B}_i^0)}{Prob(B_i^0 \to \overline{B}_i^0) + Prob(B_i^0 \to B_i^0)} = \frac{x_i^2}{2(1+x_i^2)} \qquad \text{where } i = s, d. \tag{2}$$

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

$$\overline{\chi} = F_d\,\chi_d + F_S\,\chi_S, \tag{3}$$

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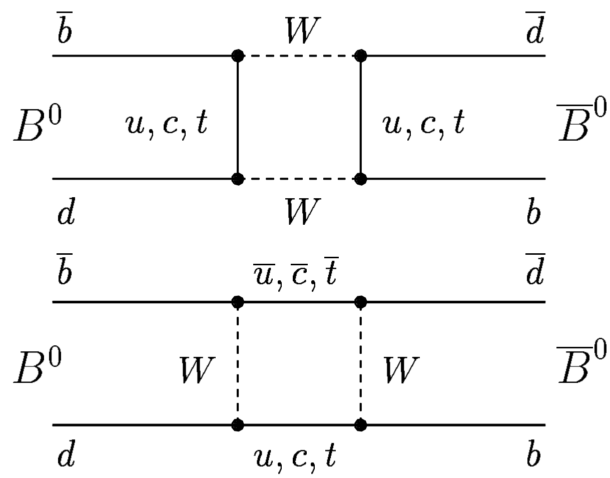

Figure 1: Box diagram describing $B^0\overline{B}^0$ mixing.

can be obtained, where F_d and F_S are the fractions of b hadrons that are produced as B_S^0 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 $Prob(B^0 \to \overline{B}^0, t)$ the following expression yields:

$$\frac{Prob(B^0 \to \overline{B}^0, t)}{Prob(B^0 \to B^0, t) + Prob(B^0 \to \overline{B}^0, t)} = \frac{1}{2}(1 - \cos x\frac{t}{\tau}) \tag{4}$$

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

$$\frac{\Delta m_B}{\Gamma} = \tau_B \frac{\mathrm{G_F^2}}{6\pi^2} m_W^2 \, m_B \, (f_B^2 B_B) \, \eta_{\mathrm{QCD}} \, F(m_t) \, |V_{tb}|^2 |V_{td}|^2. \tag{5}$$

Here, $\mathrm{G_F}$ 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 η_{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 infered 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

$$t = \frac{L}{\beta\gamma} = L \cdot \frac{m_B}{p_B}. \tag{6}$$

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

$$t = L_{\mathrm{xy}} \cdot \frac{m_t}{p_{\mathrm{t}}}. \tag{7}$$

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

$$c\tau = L_{\mathrm{xy}} \cdot \frac{m_t^{\mathrm{cl}}}{p_t^{\mathrm{cl}}} \cdot F_{\beta\gamma}(p_t^{\mathrm{cl}}, m_t^{\mathrm{cl}}). \tag{8}$$

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

$$\frac{\sigma_t}{\tau} = \sqrt{\left(\frac{\Delta L_{\mathrm{xy}}}{L_{\mathrm{xy}}^0}\right)^2 + \left(\frac{t}{\tau}\frac{\Delta p_t}{p_t}\right)^2} \qquad \text{where} \qquad L_{\mathrm{xy}}^0 = \frac{p_t}{m} \cdot c\tau \tag{9}$$

From this it is obvious that the proper time resolution σ_t/τ 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 $B^0\overline{B}^0$ mixing parameter x_d via time evolution in a hadron collider environment. The flavour of the B meson at its decay is infered 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-ϕ readout, including pulse height information [6]. The pitch between readout strips is 60 μm and a spatial resolution of 13 μm has been obtained. The first measurement plane is located 3.0 cm from the interaction point, leading to an impact parameter resolution of ~ 15 μm for tracks with $p_{\mathrm{t}} > 5$ 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 $\delta p_{\mathrm{t}}/p_{\mathrm{t}} = [(0.0009 p_{\mathrm{t}})^2 + (0.0066)^2]^{1/2}$ for beam constrained tracks, where p_{t} 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 ϕ for the pseudorapidity range $|\eta| \leq 0.6$, where $\eta = -\ln[\tan(\theta/2)]$. This η 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 $p_{\mathrm{t}} = 1.8$ GeV/c to 90% for $p_{\mathrm{t}} = 3.8$ 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 $p_{\mathrm{t}} = 3.4$ 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 p_{t} dimuon triggers is used for this measurement of x_d via time evolution. A substantial amount of background is removed by applying μ 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

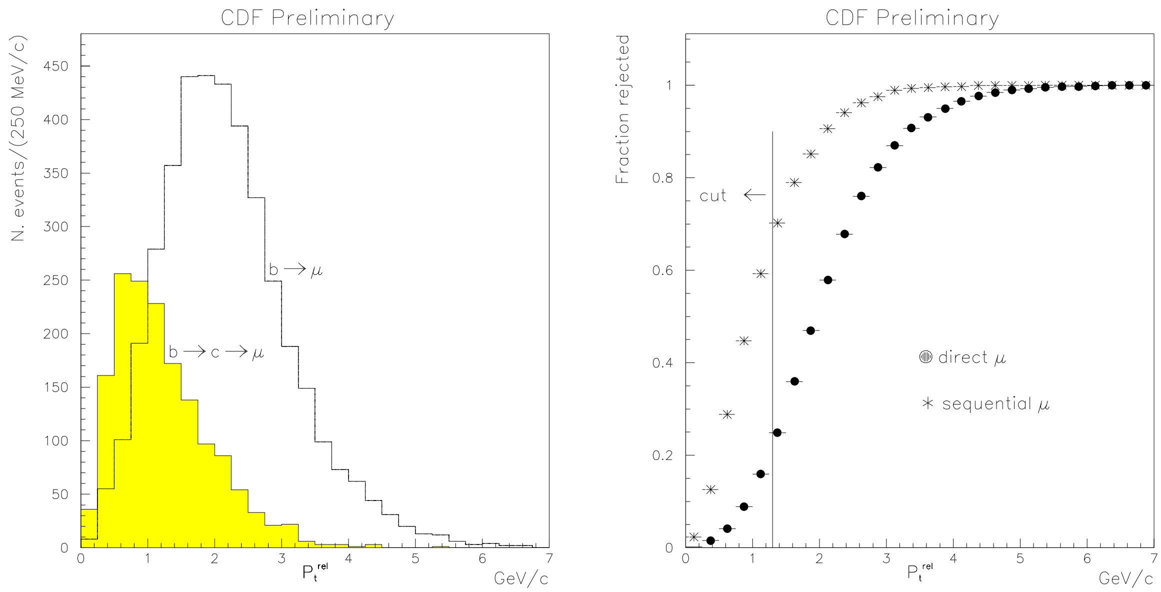

Figure 2: Comparison of the $p_{\mathrm{t}}^{\mathrm{rel}}$ distributions from sequential $b \to c \to \mu$ and direct $b \to \mu$ as obtained from MC (left). The right hand figure shows the normalized integral of these distributions with the cut value at 1.3 $GeV/$c.

$\sim$ 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" 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" trajectory with that of the associated μ projected onto the transverse direction of the μ"D" 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

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

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

We also require that the $p_{\mathrm{t}}^{\mathrm{rel}}$ of the muon relative to the "D" direction be larger than 1.3 $GeV/$c. As can be seen from Fig. 2 this cut reduces significantly the contribution from sequential $b \to c \to \ell$ decays, which cause a significant dilution of the effect of mixing. The $p_{\mathrm{t}}^{\mathrm{rel}}$ cut additionally reduces dimuon background from direct $c\bar{c}$ production.

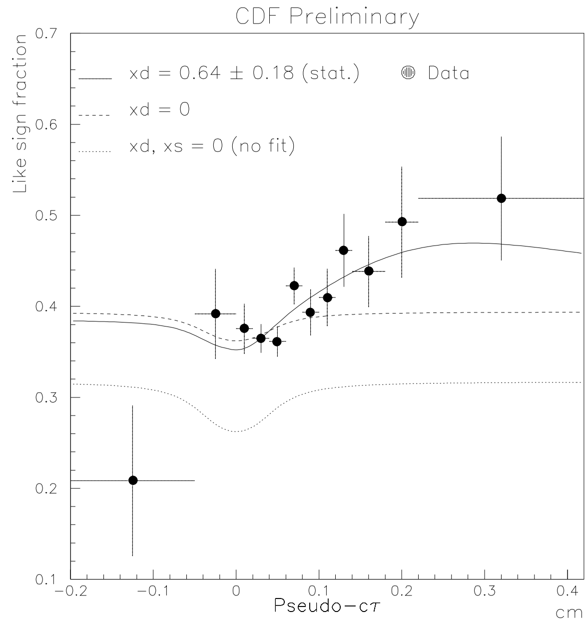

Figure 3: Like-sign fraction versus $c\tau$. The solid line is our fit to the data; the dashed line is our fit after forcing x_d=0 and the dotted line is a prediction assuming just the sequential decay contribution and both x_d and x_s = 0.

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 $p_t^{\rm rel}$ 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 μ impact parameter in the away side, taking into account a $b\bar{b}$ and a fake muon component, estimates a fake fraction of (10±3.5)%.

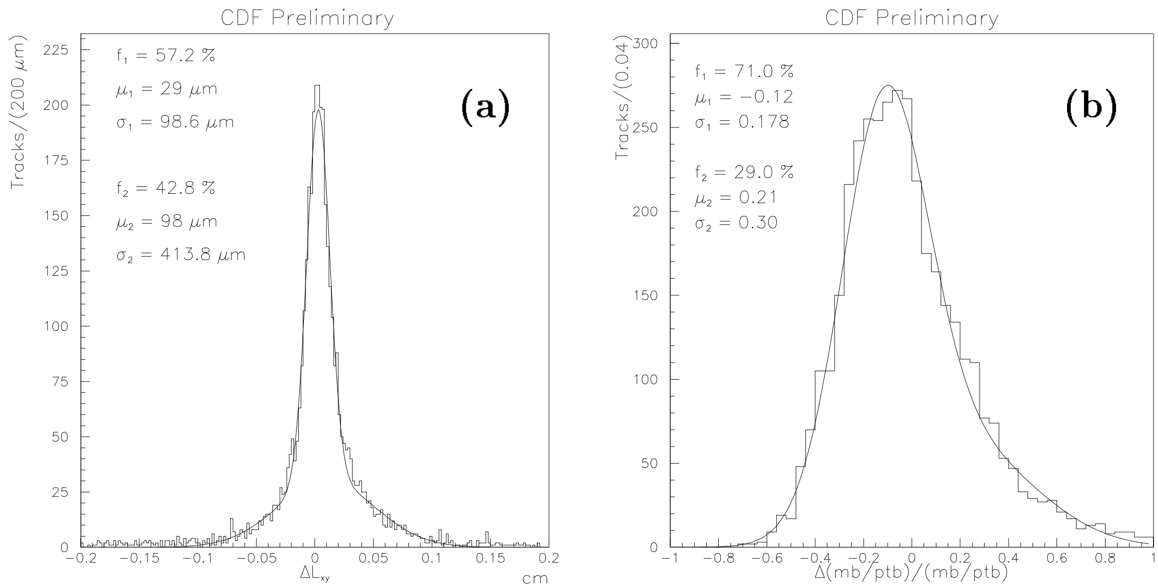

Figure 4: (a) $L_{\rm xy}$ resolution function and (b) $1/\beta\gamma$ resolution function as obtained from MC. Overlaid is a parametrization obtained as a sum of gaussians.

We then use the Monte Carlo to simulate $b\bar{b}$ events from where the kinematical correction factor $F_{\beta\gamma}$ is calculated. The $L_{\rm xy}$ resolution function is show 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 neccessarily centered at zero. The fraction of $b \to c \to \ell$ decays relative to the total number of b semi-leptonic decays $f_{\rm seq}$ is also obtained from MC. For this specific analysis we found that the b-tagging biases $f_{\rm seq}$, therefore we calculate an average fraction of $f_{\rm seq} = (19.4 \pm 0.6)\%$ for the away side and $f_{\rm seq} = (15.1 \pm 0.6)\%$ for the vertex side. Furthermore, on the vertex side $f_{\rm seq}$ is parametrized as a function of the measured $c\tau$ value.

Additional inputs to the fit are χ_s, which we assume to be saturated at 0.5, and F_d and F_s, which are the fractions of B^0 and B^0_S contained in our sample. For these we take the values 0.37 ± 0.03 and 0.15 ± 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:

$$x_d = 0.64 \pm 0.18 \pm 0.21$$

$$\Delta m_d = 0.44 \pm 0.12 \pm 0.14 \ ps^{-1}.$$

Description	Systematic error (−)	Systematic error (+)
Resolution scale	-0.07	+0.00
Sequential decay fraction	-0.17	+0.21
Backgrounds	-0.07	+0.01
Fraction of B species	-0.06	+0.00
Total	-0.21	+0.21

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 $p\overline{p}$ 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.

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