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**CDF**

**$b\bar{b}$  Production Correlations,  $B\bar{B}$  Mixing and  $\varepsilon_B$  at CDF**

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## ABSTRACT

We present preliminary measurements of  $b\bar{b}$  production correlations, the average  $B\bar{B}$  mixing, and a limit on the CP violating parameter  $\epsilon_b$  using dimuon events from the dual semileptonic decay of  $b\bar{b}$ . Data used in this analysis was taken during the 1992-1993 CDF run of the Fermilab Tevatron collider with an integrated luminosity of  $17.4 \pm 0.6 pb^{-1}$ . The results on  $b\bar{b}$  production correlations are compared to predictions of next-to-leading order QCD.

**1. Introduction**

In  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV, the strong coupling constant  $\alpha_s$  is small for heavy quark production processes and perturbative QCD is expected to provide reliable predictions. Studies of the  $b\bar{b}$  production correlations provide an opportunity to test perturbative QCD at next-to-leading order.<sup>1</sup> Dimuon events result from  $b\bar{b}$  production,  $c\bar{c}$  production, Drell Yan,  $J/\psi$ ,  $\Upsilon$ , hadronic punchthrough, and decay muons from pions and kaons. An impact parameter fitting technique is used to determine the  $b\bar{b}$  fraction of the dimuon events. Using this technique we measure  $\sigma_{b\bar{b}}$  as a function of  $p_T(b)$  and  $p_T(\bar{b})$ . The  $\mu$ - $\mu$  production correlations are also studied by examining the distribution of the opening angle between  $b$  and  $\bar{b}$  muons and the  $p_T$  distribution of  $b$  muons. A comparison of the number of  $b\bar{b}$  dimuons in like-sign (LS) events and opposite-sign (OS) events yields the average  $B\bar{B}$  mixing parameter  $\bar{\chi}$ . In addition the asymmetry between the number of  $\mu^+\mu^+$  and  $\mu^-\mu^-$  events is used to place a limit on the real part of  $\epsilon_b$  which gives rise to CP violation in  $B\bar{B}$  mixing.

**2. Data Selection**

Dimuon events from the dual semileptonic decay of  $b\bar{b}$  pairs are used in this analysis. In CDF muon identification is accomplished by associating a track in the central tracking chamber (CTC) and a track in the central muon chamber (CMU).<sup>2</sup> The dimuon data is collected with a three level dimuon trigger. The trigger requires at least 2 muons in the central region ( $|\eta| < 0.6$ ) at each level. Tight matching between a CTC track and a CMU track is required and  $P_T$  must be greater than 3 GeV/c for both muons. In addition, precision tracking in the silicon vertex detector is required for each muon track. The cascade decays of single b quarks and  $J/\psi$  dimuons are removed by requiring the dimuon invariant mass to be greater than 5 GeV/c<sup>2</sup>.

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### 3. The Impact Parameter Fitting Method

The generic impact parameter of a daughter track is directly proportional to the lifetime of the parent particle. The markedly different impact parameter distributions expected for muons from bottom decays, charm decays, and prompt sources allows the parent fractions to be determined.

Monte Carlo methods are used to establish the impact parameter distributions for muons from charm and bottom. The fraction of muons from sequential  $B$  decays is determined by Monte Carlo simulation. Jet data are used for the impact parameter distribution of prompt muons. The distribution from jet data is found to adequately represent that of muons from prompt sources (Upsilon, Drell-Yan, decay in-flight muons surviving offline tracking requirements, and hadron punchthrough).

Since there will be events with a muon from bottom decay and a muon from prompt decay a fit is performed in two dimensions. Each axis represents the impact parameter of one of the two muons. The two dimensional fitting technique exploits the fact that the impact parameter for each muon is an independent variable uncorrelated to that of the other. The 2-dimensional template distributions for each type of dimuon event are made by convoluting the relevant 1-dimensional distributions.

A binned maximum log likelihood method is used. The likelihood  $L$  can be defined as follows:

$$L = \prod_i \prod_j (l_{ij}^{n(i,j)} e^{-l_{ij}} / n(i,j)!) \quad (1)$$

$$l_{ij} = f_{bb} H_{bb}(i,j) + f_{dd} H_{dd}(i,j) + f_{sum} H_{sum}(i,j) \quad (2)$$

where  $i, j$  are bin indices and  $n(i, j)$  are number of events of the  $(i, j)$ th bin in the data.  $H_{bb}$  and  $H_{dd}$  represent the normalized two dimensional impact parameter distributions for  $b\bar{b}$  and prompt dimuon events and  $f$ 's are the corresponding fractions of each component. The template distribution  $H_{sum}$  is formed from the sum of the  $c\bar{c}$  component (both muons from charm decay) and the component from events with one bottom muon and one prompt muon. These two components can not be extracted separately from a simultaneous fit since the distributions are very similar to each other. The relative fractions for the two components in  $H_{sum}$  are arbitrarily fixed and the variations of  $f_{bb}$  due to different relative fractions are included in the systematic uncertainty.

Figure 1a shows the projections of the two dimensional distribution from the data and the contributions of each component obtained from two dimensional fitting with  $p_T \geq 3$  GeV/c for both muons.

## 4. Results

### 4.1. Production Cross Sections and Correlations

For the measurement of the  $b\bar{b}$  cross section, the number of the  $b\bar{b}$  dimuon events  $N_{b\bar{b}}$  obtained from the impact parameter fit is divided by the dimuon reconstruction efficiency  $eff$ , the acceptance  $A$ , the branching ratio of the dual semimuonic decay of a  $b\bar{b}$  pair,<sup>3</sup> and the integrated luminosity  $L$ .

$$\sigma(P_T(b) > 6.5 \text{ GeV}/c, P_T(\bar{b}) > P_T^{min}, |y^b|, |y^{\bar{b}}| < 1) = \frac{N_{b\bar{b}}}{eff \cdot A \cdot Br(b \rightarrow \mu X)^2 \cdot L} \quad (3)$$

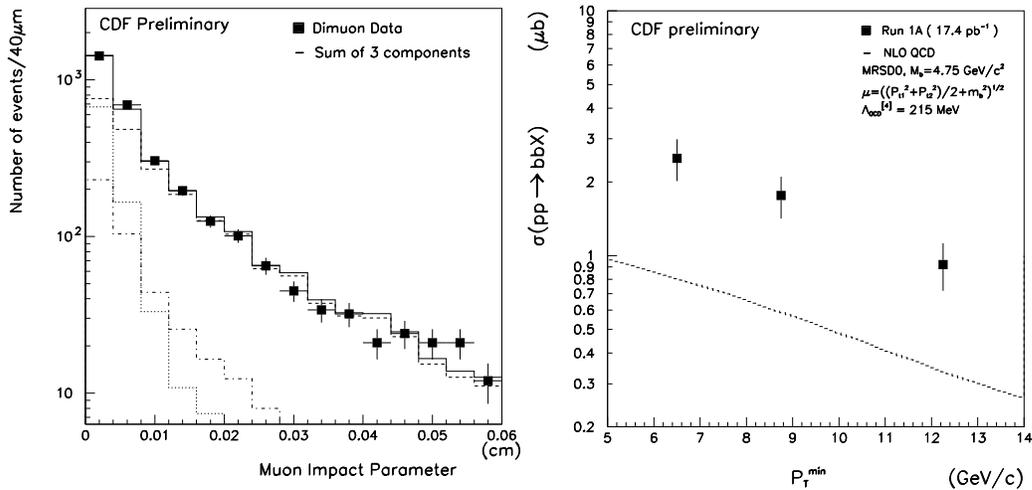


Fig. 1. a) Projections of the two dimensional distributions. The contributions of  $H_{bb}$ ,  $H_{dd}$ , and  $H_{sum}$  are denoted by dashed line, dotted line, and dash-dotted line. b)  $\sigma(P_T(b) > 6.5 \text{ GeV}/c, P_T(\bar{b}) > P_T^{\min}, |y^b|, |y^{\bar{b}}| < 1$ ).

Table 1.  $b\bar{b}$  cross sections

$P_T(b)$	$P_T^{\min}(\bar{b})$	$\sigma_{b\bar{b}}(\mu\text{b})$
$\geq 6.5 \text{ GeV}/c$	6.5 GeV/c	$2.69 \pm 0.15(stat) \pm 0.51(sys)$
	8.75 GeV/c	$1.91 \pm 0.19(stat) \pm 0.36(sys)$
	12.25 GeV/c	$1.12 \pm 0.13(stat) \pm 0.22(sys)$

The dimuon reconstruction efficiency is measured using  $J/\psi$  muons. The acceptance is determined using a  $b\bar{b}$  Monte Carlo generator based on next-to-leading order QCD calculations<sup>1</sup> and the CDF simulation package. The  $P_T^{\min}$  of  $\bar{b}$  quark is chosen such that 90% of the muons with  $P_T^1 < P_T < P_T^2$  also have  $P_T^{\bar{b}} > P_T^{\min}$ . The corresponding  $P_T^{\min}$  values are 6.5, 8.75, 12.25 GeV/c for  $(P_T^1, P_T^2) = (3, 5), (5, 7), (7, \infty)$  GeV/c. Table 1 shows the measurements of the  $b\bar{b}$  cross section.

The measured  $b\bar{b}$  cross sections are compared with theoretical predictions based on next-to-leading order calculation of QCD as shown in Figure 1b. The shape of the  $b\bar{b}$  cross section agrees with the theoretical prediction although the normalization is clearly higher for the data.

We also investigate the kinematic and geometrical correlations between the  $b\bar{b}$  muons. Using the fitting method, we plot the opening angle distribution between  $b\bar{b}$  muons and the  $P_T$  distribution of a bottom muon when  $P_T$  of the other bottom muon is greater than 3 GeV/c as shown in Figures 2a and 2b.

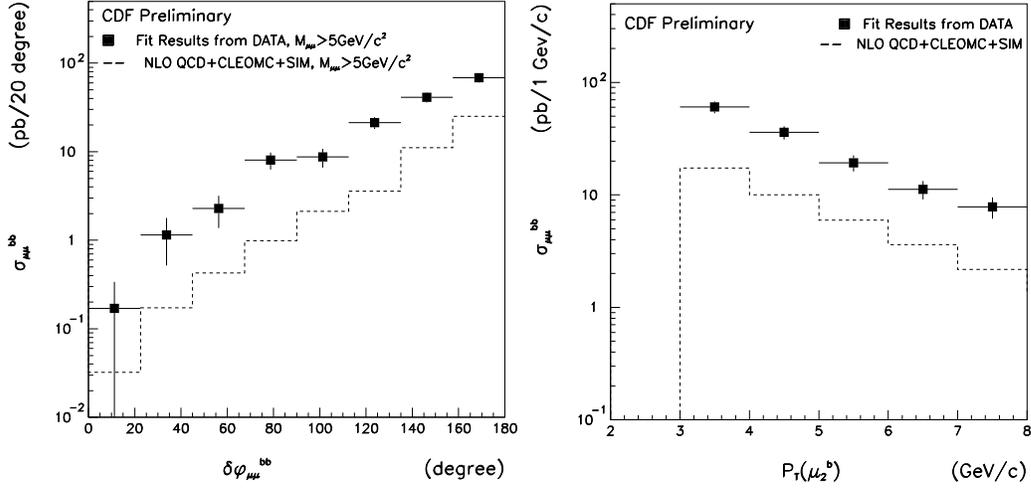


Fig. 2. a) opening angle distribution between  $b\bar{b}$  muons b)  $P_T$  distribution of a bottom muon with  $P_T$  of the other bottom muon  $\geq 3\text{GeV}/c$ .

#### 4.2. Average Mixing Parameter

The fitting method is used to obtain the  $b\bar{b}$  fraction in LS and OS dimuon events. From the ratio of LS to OS  $b\bar{b}$  dimuon events, the average  $B\bar{B}$  mixing parameter,  $\bar{\chi}$ , is extracted. We obtain  $882.4 \pm 55.5$  for LS  $b\bar{b}$  events and  $1804.4 \pm 102.9$  for OS  $b\bar{b}$  events, where the errors are from the fit. The ratio of the two numbers ( $R = 0.489 \pm 0.041$ ) is related to the average  $B\bar{B}$  mixing parameter  $\bar{\chi}$  by the following equation:

$$R = \frac{2f_{seq}(\bar{\chi}^2 + (1 - \bar{\chi})^2) + 2\bar{\chi}(1 - \bar{\chi})(1 + f_{seq}^2)}{(\bar{\chi}^2 + (1 - \bar{\chi})^2)(1 + f_{seq}^2) + 4f_{seq}\bar{\chi}(1 - \bar{\chi})} \quad (4)$$

where  $f_{seq} = 0.132 \pm 0.026$  is the fraction of sequential muons for  $p_T \geq 3 \text{ GeV}/c$ . The uncertainties of  $f_{seq}$  and charm fraction are taken into account in the systematics. Other sources of systematic uncertainties cancel out in the ratio  $R$ . The result for the average mixing parameter is  $\bar{\chi} = 0.118 \pm 0.021(stat) \pm 0.026(sys)$ .

#### 4.3. CP Violating Asymmetry

A charge asymmetry in the like-sign dimuon events can arise from CP violation in  $B\bar{B}$  mixing. The CP violating asymmetry,  $A_{CP}$ , is determined by correcting for any instrumental or reconstruction bias in the measured asymmetry in the number of  $\mu^+\mu^+$  and  $\mu^-\mu^-$  events. The charge asymmetry in dimuon events can be defined as:

$$A_{CP} = \frac{N(l^+l^+) - N(l^-l^-)}{N(l^+l^+) + N(l^-l^-)} = \frac{8(1 - \bar{\chi})}{D} \left\{ f_d \chi_d \frac{Re\epsilon_d}{1 + |\epsilon_d|^2} + f_s \chi_s \frac{Re\epsilon_s}{1 + |\epsilon_s|^2} \right\} \quad (5)$$

$$D = 2\bar{\chi}(1 - \bar{\chi}) + 2f_{seq}\{\bar{\chi}^2 + (1 - \bar{\chi})^2\} \quad (6)$$

where  $N$  denotes the number of  $b\bar{b}$  events and the subscripts of the CP violating parameter  $\epsilon$  denote  $B_d^0$  and  $B_s^0$  mesons. From the impact parameter fit for the  $b\bar{b}$  fraction we have  $452.3 \pm 39.1$   $b\bar{b}$  events for  $\mu^+\mu^+$  and  $430.1 \pm 39.3$   $b\bar{b}$  events for  $\mu^-\mu^-$ . After correcting for the muon reconstruction bias of the CDF detector, we have  $A_{CP} = (2.76 \pm 6.32(stat) \pm 3.28(sys)) \times 10^{-2}$ .

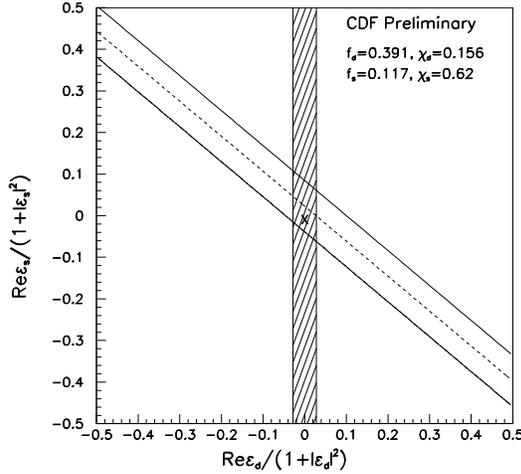


Fig. 3. The solid lines represent the  $\pm 1\sigma$  uncertainties and the dashed line represents the measured value of the asymmetry. The hatched region is from the CLEO measurement in  $B_d^0\bar{B}_d^0$  sample. The X represents the prediction of the standard model.

Using  $f_{seq} = 0.132 \pm 0.026$  from Monte Carlo simulations and the average mixing parameter from the Particle Data Group ( $\bar{\chi} = 0.133 \pm 0.011$ ), one obtains:

$$f_d\chi_d \frac{Re\epsilon_d}{1+|\epsilon_d|^2} + f_s\chi_s \frac{Re\epsilon_s}{1+|\epsilon_s|^2} = (1.74 \pm 3.99(stat) \pm 2.08(sys)) \times 10^{-3} \quad (7)$$

where  $f$ 's are fractions of neutral B mesons produced and  $\chi$ 's are the corresponding mixing parameters. This result gives one constraint for four quantities:  $Re\epsilon_d$ ,  $Im\epsilon_d$ ,  $Re\epsilon_s$ , and  $Im\epsilon_s$  which affect the dimuon charge asymmetry. Using the values of  $f_d$ ,  $f_s$ ,  $\chi_d$ , and  $\chi_s$  from the Particle Data Group, one can plot the region constrained by the above result in  $\frac{Re\epsilon_d}{1+|\epsilon_d|^2} - \frac{Re\epsilon_s}{1+|\epsilon_s|^2}$  space with the result of the CLEO experiment<sup>4</sup> as shown in Figure 3.

## References

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