Measurement of CP asymmetry in semileptonic B decays

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We present a measurement of the asymmetry between positive and negative same-sign muon pairs originating from semileptonic decays of pairs of B hadrons. Low transverse momentum dimuon pairs are evaluated to determine B hadron content using a log likelihood fit to two-dimensional impact parameter significance templates. Corrections are made for asymmetries arising from the detector, trigger, and hadrons which are reconstructed as muons. We measure a $B\overline{B}$ semileptonic asymmetry of

$$A_{SL} = 0.0080 \pm 0.0090(stat) \pm 0.0068(syst)$$

and calculate the semileptonic asymmetry contribution from B_s mixing as

$$A^s_{SL} = 0.020 \pm 0.028.$$

The analysis is based on an integrated luminosity of 1.6 fb^{-1} data collected up to January 2007.

I. INTRODUCTION

To date, CP violation in the B system has only been observed in fully reconstructed modes at the e^+e^- B factories. Although the fully reconstructed final states are quite clean, they suffer from low yields due to branching ratios and detector acceptance. A complementary technique for searching for CP violation at the Tevatron is to perform an inclusive analysis. In this note, we report a measurement of the CP asymmetry in same-sign dimuon events. This inclusive technique has the benefit of high statistical precision thanks to large semileptonic B branching ratios. In addition, the sample is integrated over all weakly decaying B species produced at the Tevatron. The challenge in this technique is that any CP violating effects are diluted by large contributions from known CP conserving processes.

In the Standard Model, same-sign events arise through neutral meson mixing and sequential decays of B hadrons ($b \to c \to \ell$). The CP asymmetry described above specifically excludes sequential decays; it is the CP asymmetry arising from neutral B meson mixing. The Standard Model prediction for A_{CP} is of order 10^{-3}, so an observation of a large asymmetry would be indicative of new physics. The CP asymmetry in B^0-$\overline{B^0}$ mixing has been measured to be quite small [1, 2], so a measurement of A_{CP} at the Tevatron can be interpreted as a search for CP violation in the mixing of B_s mesons.

Recently, D0 performed a measurement [3] that was consistent with zero with an uncertainty of ~0.5%. Our analysis technique is significantly different from the D0 measurement, but the two analyses have similar sensitivity.

II. ANALYSIS STRATEGY

In this analysis, we utilize a sample of same-sign (SS) dimuon events originating from $b\overline{b}$ production, where each muon originates from the decay of a unique B hadron. Our sample of includes contributions from other real and fake sources of muons. We must account for these contributions in order to accurately extract the CP asymmetry arising from B decays. We follow the technique of Refs. [4, 5] and fit the two-dimensional impact parameter distribution of the two muons. This takes advantage of CDF's superior impact parameter resolution to unfold contributions from prompt, charm and B sources.

Our trigger and data selection produces a large dimuon event collection enriched in muons from B decays. A trigger cut of dimuon invariant mass > 5 GeV eliminates sequential dimuons, and a dimuon tranverse opening angle of $\delta\phi < 3.135$ removes cosmic rays. These signal dimuon events still contain prompt and charm contributions. Section III describes the dimuon $d_0/\sigma(d_0)$ fitting method used to extract the fraction of $\mu^+\mu^+$ and $\mu^-\mu^-$ events that are from b events. The two additional analysis components are corrections to the raw asymmetry of the fitted $\mu^+\mu^+$ and $\mu^-\mu^-$ numbers. Some of the dimuon events fitted to be of B origin in fact contain a kaon or pion from a B decay which fakes a muon in the detector. The significant asymmetry introduced by these events must be measured as a correction . Finally, the detector or event trigger may introduce a $+/-$ asymmetry which must also be applied as a correction. These adjustments are discussed in Section IV.

III. IMPACT PARAMETER FITTING

The impact parameter of a muon provides a good way to identify muons originating from heavy flavor. Prompt tracks in the absence of a measurement resolution and failed pattern recognition would have impact parameters of 0, but these effects cause a Gaussian smearing and some small non-Gaussian tails respectively. Additionally, longer lived B hadrons will have a much broader distribution than prompt tracks. But since a large fraction of events with muons from B decays would be lost separating prompt and charm muons from B muons by cutting on impact parameter, a binned negative log likelihood fit is performed using two-dimensional impact parameter significance templates with one muon plotted along each dimension to determine the B content. The 2D method allows the identification of the BP fraction where one muon comes from a b hadron decay and the other muon is prompt. While there is no contribution expected from $c\overline{c}$ to the SS real dimuon sample, a $C\overline{C}$ component is included in the SS fits for cases where a hadron from a c decay fakes a muon. The 2D templates are constructed by randomly selecting values from the appropriate $d_0/\sigma(d_0)$ distributions. The BB template uses the 1-dimensional distributions for muons coming from B for each axis, and BP template selects one axis from the B distribution and one from the P distribution. Table I lists the percentages and errors are the returned values of the parameters corresponding to the templates described above as components of the $\mu^+\mu^-$, $\mu^+\mu^+$, and $\mu^-\mu^-$ signal data all fitted simultaneously. The projections of the $\mu^+\mu^+$ fit are shown Figure 2.

TABLE I: Fit results. All numbers listed in percent.

component	opposite sign(OS) ($\mu^+\mu^-$)	same-sign ($\mu^+\mu^+$)	same-sign ($\mu^-\mu^-$)
PP	21.29 $\pm$ 0.17	28.58 $\pm$ 0.28	25.21 $\pm$ 0.30
BB	42.90 $\pm$ 0.19	45.31 $\pm$ 0.32	50.42 $\pm$ 0.35
BP	6.78 $\pm$ 0.28	16.95 $\pm$ 0.48	17.66 $\pm$ 0.53
CC	29.03 $\pm$ 0.38	9.16 $\pm$ 0.64	6.71 $\pm$ 0.70
# BB	281,252	106,519	103,143

IV. ASYMMETRY CORRECTIONS TO THE BB SAMPLE

There is a significant contribution of real $b\bar{b}$ decays where at least one reconstructed muonh is not a real physics muon. A pion or kaon from a hadronic b decay has a small probability to punch-through the calorimeters and other material in front of the muon chambers. Similarly, such a particle may decay in flight producing a muon with a trajectory indistinguishable from the original hadron. In both cases, these fake muons are actually of $b\bar{b}$ origin and are irreducible as background since their signature as a muon is the same as that of real muons. The charge asymmetry of kaon punch-through requires that these be removed for the asymmetry measurement and the uncertainty on this correction is a systematic uncertainty of the measurement.

Since we are expecting a sub-percent uncertainty we also consider and correct for asymmetries introduced experimentally.

A. Fake Muon Charge Asymmetry

The nuclear cross section of K^+ hadrons is different than that of K^- hadrons. As a result, significantly more K^+ particles fake muons in the outer muon detectors. This asymmetric effect must be corrected for in the SS dimuon sample according to the probabilities that muons in the final same sign totals are really fakes. The correction is made by then assessing the relative probability that a π, μ, or K meeting the fiducial requirements is produced in B decays, and the probability that each would be reconstructed as a muon.

We use a sample of $D^{*+} \to D^0\ \pi^+_{soft}$, and $D^0 \to K^-\ \pi^+$ decays to identify the hadrons. The D^0 selection is made using only tracking information and the mass peak is fitted with a double Gaussian for background and signal. A mass fit is also performed for the subsample of these hadrons which are found to be reconstructed as muons to determine the fake rate. Figure 3 shows the D^0 peaks used for the K^+ calculation.

The normalization of K to μ and π to μ from B decays is taken from PYTHIA Monte Carlo. umming the total number of $\mu^+\mu^+$ and $\mu^-\mu^-$ pairs which include at least one hadron we find a contamination of 7382 $\mu^+\mu^+$ and 5130 $\mu^-\mu^-$ pairs from fake muons.

B. Detector Acceptance

The detector components used in the analysis are symmetric in ϕ with the exception of the outer muon detector. We probe the acceptance of this system with Monte Carlo and correct for a discrepancy less than 0.1 %. We investigated the response of the muon chambers and the efficency of the central tracker and found no significant asymmtetry for our sample.

C. Trigger Efficiency

The trigger efficiency was probed by reconstructing $J/\Psi \to \mu^+\mu^-$ events where one muon was unbiased by the trigger. For muons with our kinematic requirements we find and correct for an asymmetry of about 0.1 %.

V. MEASURED ASYMMETRY

The measured asymmetry before corrections with only statistical uncertainty is $A_{raw} = 0.0146 \pm 0.0049$. The inclusive CP asymmetry is related to the raw asymmetry in the following way:

$$A_{corr} = \frac{N^{++}_{true} - N^{--}_{true}}{N^{++}_{true} + N^{--}_{true}}, \quad A_{obs} = \frac{N^{++}_{obs} - N^{--}_{obs}}{N^{++}_{obs} + N^{--}_{obs}} \tag{1}$$

The true number of same-sign dimuons are related to the observed number of dimuons by the squared corrections for single muon trigger efficiency and detector acceptance. Here ϵ is used to represent the product of these correction factors.

$$\begin{aligned} N^{++}_{true} &= N^{++}_{pass} + N^{++}_{fail} \\ N^{++}_{obs} &= N^{++}_{true} \times \epsilon^2_{+} \\ N^{++}_{fail} &= N^{++}_{true} \times 2\epsilon_{+}(1-\epsilon_{+}) + N^{++}_{true} \times (1-\epsilon_{+})^2 \end{aligned} \tag{2}$$

The relationships found in equation 2 also holds true for N^{--}. Since N_{obs} is the observed number of dimuons from fitting the data,

$$A_{corr} = \frac{N^{++}_{obs}(\frac{1}{\epsilon^2_{+}}) - N^{--}_{obs}(\frac{1}{\epsilon^2_{-}})}{N^{++}_{obs}(\frac{1}{\epsilon^2_{+}}) + N^{--}_{obs}(\frac{1}{\epsilon^2_{-}})} = \frac{N^{++}_{obs} - N^{--}_{obs}(\frac{\epsilon_{+}}{\epsilon_{-}})^2}{N^{++}_{obs} + N^{--}_{obs}(\frac{\epsilon_{+}}{\epsilon_{-}})^2} \tag{3}$$

From the measured asymmetry of the detector accpetance and trigger efficiency we apply the correction $(\epsilon_{+}/\epsilon_{-})^2 = 0.9995 \pm 0.0014$ to equation 3. Using the values of N_{obs} after they have been corrected for fake muons we find $A_{corr} = 0.0149 \pm 0.0049$.

Finally, the true BB asymmetry must be corrected for the physical asymmetry introduced by kaons which fake muons. The corrected asymmetry, after removing hadrons from B decays faking muons, is measured to be $A_{BB} = 0.0044 \pm 0.0049$. This asymmetry is not corrected for sequential decays.

VI. SYSTEMATIC ERROR EVALUATION

Systematic uncertainty from fake asymmetry correction is measured by varying each hadron fake rate - K^+, K^-, π^+, π^- - by 1σ to find δA for the correction. Additionally, the ratios of hadrons to muons and charge correlation each are varied by 1σ and all δAs are summed in quadrature. The total measured systematic uncertainty from the fake correction is $\delta A = 0.0028$.

Systematic uncertainty for the single muon corrections is evaluated as the uncertainty on the correction times 2, since the correction is squared for dimuon pairs. The systematic uncertainty of the asymmetry due to the trigger efficiency is $\delta A = 0.0012$. It is $\delta A = 0.0007$ for the detector acceptance.

To assess a systematic uncertainty from possible bias in the fitting techinique, we look at the variation in raw asymmetry from robustness checks performed with varied template shapes and on several subsamples. We determine a fitting uncertainty based on the fit variations of 0.2%.

TABLE II: Systematic Uncertainties

Source of Uncertainty	δA
Fake muon corr.	0.0028
Trigger efficiency corr.	0.0012
Detector acceptance corr.	0.0007
Fitting Uncertainty	0.0020
Total	0.0037

VII. RESULTS

We have measured the same-sign dimuon asymmetry from decays of $b\bar{b}$ production using pairs with two 3 GeV CMUP muons and an invariant mass of > 5 GeV. Selected pairs were fitted to signal and background templates to determine the fraction of BB hadron pairs using the impact parameter significance as an indication of lifetime. Corrections were made for measured asymmetries from the detector, event trigger, and kaons from B decays which fake CMUP muons. The corrected asymmetry we measure is

$$A_{BB} = 0.0044 \pm 0.0049(stat) \pm 0.0037(syst). \tag{4}$$

The semileptonic asymmetry is obtained by removing the contribution of CP symmetric described in Section **??**. We measure the fraction of these backgrounds to be $f_{WS} = 0.102 \pm 0.015$, where this fraction is all wrong-sign contributions of a single muon B decay. This includes multiple heavy flavor prodcution, but is primarily sequential decays. There is also a small contribution of right-sign sequential decays from the case where the virtual W from the $b \to c$ transition decays hadronically to charm rather than semimuonically and the charm decays to a muon. For dimuon events we find the following fractions:

- $f_{DD} = 0.77 \pm 0.02$, two direct muon decays
- $f_{DS} = 0.18 \pm 0.03$, one sequential decay resulting in a wrong-sign muon
- $f_{DS}^{RS} = 0.040 \pm 0.004$, one direct decay, and one sequential decay resulting in a right-sign muon
- $f_{SS} = 0.010 \pm 0.002$, two sequential decays resulting in two wrong-sign muons

Thus N^{++} and N^{--} can be defined as follows where χ is the mixing probability for B, $\overline{\chi}$ is the mixing probability for $\overline{B}$, and $\chi_0 = \frac{1}{2}(\chi + \overline{\chi})$:

$$\begin{aligned} N^{++} &= N_{BB}\{(f_{DD} + f_{DS}^{RS})\chi(1-\chi_0) + \frac{1}{2}f_{DS}[1 - 2\chi_0(1-\chi_0)] + f_{SS}\overline{\chi}(1-\chi_0)\} \\ N^{--} &= N_{BB}\{(f_{DD} + f_{DS}^{RS})\overline{\chi}(1-\chi_0) + \frac{1}{2}f_{DS}[1 - 2\chi_0(1-\chi_0)] + f_{SS}\chi(1-\chi_0)\} \end{aligned} \tag{5}$$

$$A_{BB} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{(f_{DD} + f_{DS}^{RS} - f_{SS})(\chi - \overline{\chi})(1-\chi_0)}{(f_{DD} + f_{DS}^{RS} + f_{SS})(\chi + \overline{\chi})(1-\chi_0) + f_{DS}[1 - 2\chi_0(1-\chi_0)]} \tag{6}$$

We now use the definition of χ_0 and divide through by $2\chi_0(1-\chi_0)$ to obtain the following relation between the physics quantity off interest $(\chi - \overline{\chi})/(\chi + \overline{\chi})$:

$$A_{BB} = \frac{(f_{DD} + f_{DS}^{RS} - f_{SS}) \times [\frac{\chi - \overline{\chi}}{\chi + \overline{\chi}}]}{f_{DD} + f_{DS}^{RS} + f_{SS} + f_{DS}\frac{1-2\chi_0(1-\chi_0)}{2\chi_0(1-\chi_0)}} \tag{7}$$

Using the world average $\chi_0 = 0.127 \pm 0.006$, and the fractions measured above we find

$$A_{SL}^{\mu\mu} = \frac{(\chi - \overline{\chi})}{(\chi + \overline{\chi})} = (1.83 \pm 0.15) \times A_{BB} \tag{8}$$

$$A_{SL}^{\mu\mu} = 0.0080 \pm 0.0090(stat) \pm 0.0068(syst) \tag{9}$$

The world's best measurement of the same-sign dimuon charge asymmetry made by $D\emptyset$, $A_{SL}^{\mu\mu} = -0.0053 \pm 0.0025(stat) \pm 0.0018(syst)$. Following their strategy to use the B factory measurements of $A_{SL}^{d} = -0.0005 + -0.0056$, and world-averages of $f_s Z_s = 0.110 \pm 0.012$and $f_d Z_d = 0.150 \pm 0.004$. We can use Equation 10 to extract A_{SL}^{s} [6**?**]. We use input values which reflect updated results.

$$A_{SL}^{\mu\mu} = \frac{(f_d Z_d) A_{SL}^d + (f_s Z_s) A_{SL}^s}{f_d Z_d + f_s Z_s} \tag{10}$$

We find the following, where the systematic error is our measured systematic combined with the uncertainty on the inputs:

$$A_{SL}^s = 0.020 \pm 0.021(stat) \pm 0.016(syst) \pm 0.009(inputs), \tag{11}$$

where the final term is the uncertainty that arises from f_s, Z_s, f_d and Z_d. We can then use the relation [7]:

$$A_{SL}^s = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s \tag{12}$$

to extract an allowed contour in the (ϕ_s,$\Delta\Gamma_s$) plane. Using $\Delta M_s = 17.8 \pm 0.1\,\mathrm{ps}^{-1}$, the 68% contour is shown in Fig. 4. In the future, this result can be combined with CDF measurements of $\Delta\Gamma_s$ to extract an allowed range for ϕ_s.

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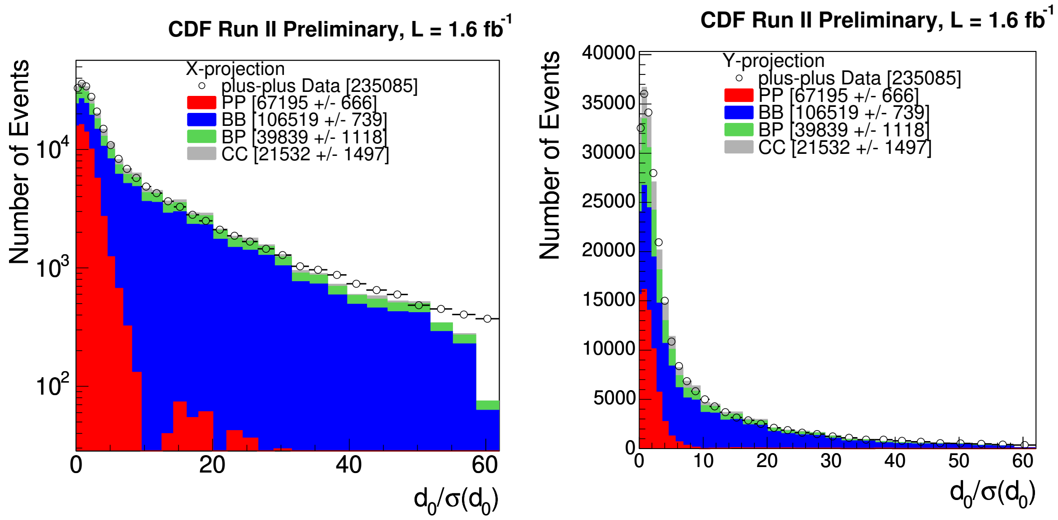

FIG. 1: Projection of fit results for $\mu^+\mu^+$ sample shown in linear and log scale.

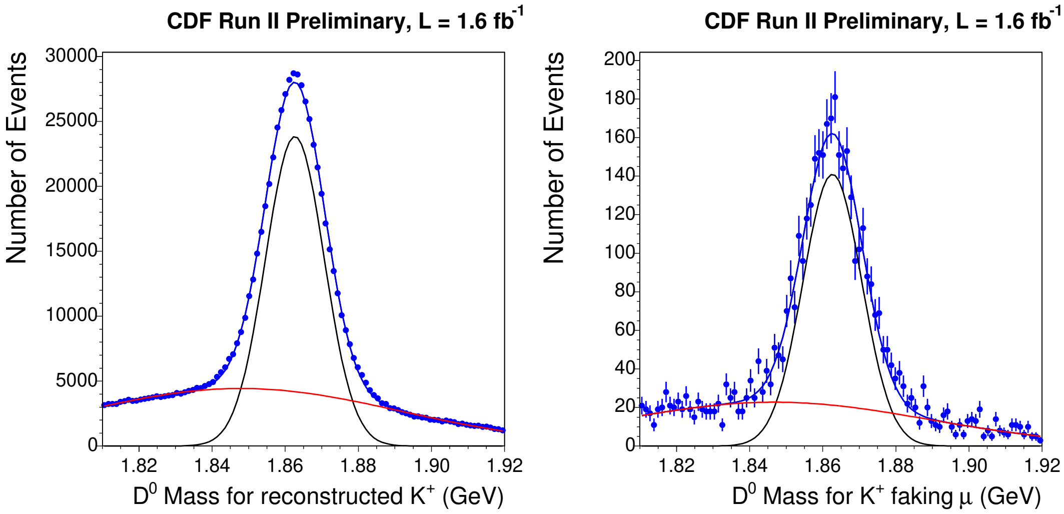

FIG. 2: The D^0 mass region for K^+ and for K^+ reconstructed as muons.

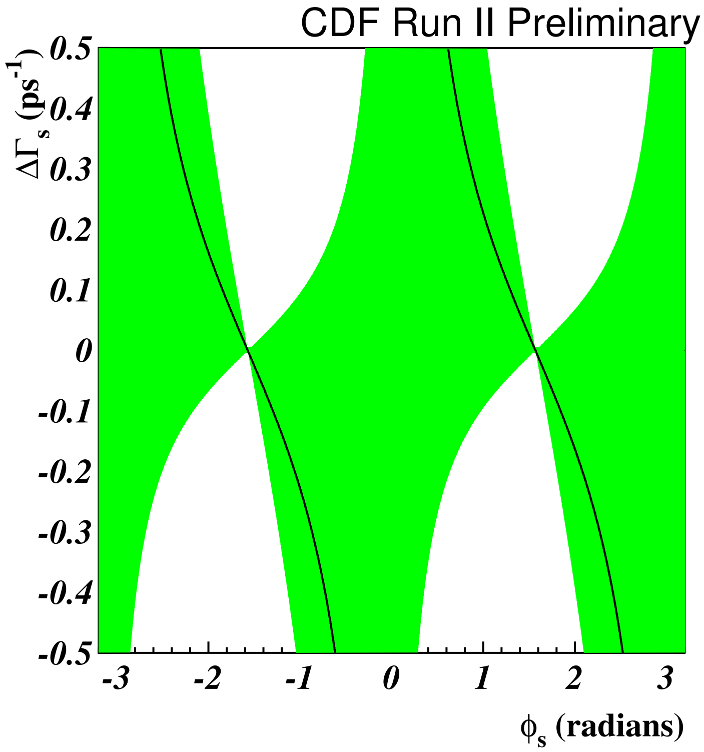

FIG. 3: This result shown in the ϕ_s-$\Delta\Gamma_s$ plane. The lines represent the central value, the green region is the 68% allowed contour.