Background dependence of dimuon asymmetry in $\bar{p}p$ interactions at $\sqrt{s} = 1.96$ TeV

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The D0 Collaboration has reported an anomalous charge asymmetry in the production of same-sign muon pairs at the Fermilab Tevatron. The magnitude of this effect depends on the subtraction of several backgrounds, the most notable of which is due to kaons being misidentified as muons either through decays in flight or punch-through. The present authors suggested a check on such backgrounds consisting of a tight restriction on the muon impact parameter $b$, to confirm that this excess was indeed due to $B(s)$ meson decays. The D0 Collaboration has performed a related check applying transverse impact parameter (IP) restrictions, whose implications are discussed. We study background asymmetry predictions for events involving two muons with IP bounds which are complementary to each other. These predictions may be used in future measurements of the net charge asymmetry from $B(s)$ decays.

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I Introduction

Last year the D0 Collaboration reported a charge asymmetry of about 40 times the standard model value in the production of same-sign muon pairs at the Fermilab Tevatron [1,2]. The magnitude of the effect depended on the subtraction of several backgrounds, notably muons due to misidentified or decaying kaons. The cross section for $K^-$ on matter is greater than that for $K^+$ on matter, so that $K^+$ decays in flight pose a greater source of muons than $K^-$ decays in flight. We suggested that a tight restriction on the muon impact parameter $b$ could test whether this asymmetry was indeed due to $B$ meson decays [3]. In an updated version of their analysis, employing a larger data sample, the D0 Collaboration has implemented this suggestion, confirming their claim for a larger-than-predicted charge asymmetry and providing partial separation of $B^0$ and $B_s$ contributions to the charge asymmetry [4]. The present paper is devoted to a discussion of their results and their relation to our suggestion.
In Section II we use numbers of dimuon events corresponding to different choices of transverse impact parameter (IP) \([4]\) to estimate the effective value of a related parameter \(b > \text{IP}\). In Section III we show that for maximum values of IP < (50, 80, 120) \(\mu m\), scaling the kaon background by a factor of \(\approx 2/3\) leads to a vanishing signal for the dimuon charge asymmetry, while the net inclusive muon charge asymmetry is shifted away from zero. For minimum values of IP > (50, 80, 120) \(\mu m\), with much smaller kaon background, rescaling of that background does not alter the dimuon and inclusive muon asymmetries significantly. Section IV discusses predictions of asymmetries for two muons involving a minimum IP for one and a maximum IP for the other. We conclude in Section V.

II IMPACT PARAMETERS IP AND \(b\)

In their latest study of the like-sign dimuon charge asymmetry at the Tevatron \([4]\), the D0 Collaboration investigated the dependence of this asymmetry on the transverse impact parameter IP, a quantity equivalent to what we called \(b_{\perp}\) \([3]\). We advocated excluding events with an impact parameter \(b\) greater than a chosen value \(b_0\). If the average impact parameter in \(b\) quark decays is \(\langle b \rangle\), the remaining fraction of dimuons from pairs of hadrons containing \(b\) quarks will be \(1 - \exp(-b_0/\langle b \rangle)^2\). Based on a study by the CDF Collaboration \([5]\), we estimated \(\langle b \rangle = 350 \mu m\). For \(b_0 = 100 \mu m\), a value we advocated in Ref. \([3]\), this quantity is then 0.062. Such a sample, thus, should be highly depleted of dimuons from \(b\) decays.

Requiring events to involve dimuons with a certain maximum IP (\(\equiv b_{\perp}\)) is less stringent than requiring them both to have the same maximum value of \(b\), since \(b > \text{IP}\). The two are related by

\[
b = [\text{IP}^2 + (b_{\parallel} \sin \psi)^2]^{1/2},
\]

where \(b_{\parallel}\) and \(\psi\) were defined in Ref. \([3]\). It is difficult to impose stringent requirements on \(b_{\parallel}\) \([6, 7]\), which is why the D0 Collaboration chose instead to restrict the parameter IP. With their most stringent constraint, we find their sample of dimuons from \(b\) decays to be reduced by a factor of 6.

The D0 Collaboration studies samples with both muons having IP either less than or greater than the values 50, 80, and 120 \(\mu m\). We have been provided \([6]\) with the effect these cuts have on sample sizes. From this information we are able to extract effective values of \(b_0\) which indeed exceed IP, by factors of 2.7 to 3.6. In what follows we present details of the calculation.

The numbers of dimuon events both of whose muons have IP above 50, 80, and 120 \(\mu m\) are shown in Table I, while the numbers of events with IP less than 50, 80, and 120 \(\mu m\) are shown in Table II. The number of dimuon events due to \(b\) decays is

\[N_{\mu\mu, b} = N_{\mu\mu}^{>\mu \mu} F_{SS}^{>\mu \mu} R, \quad N_{\mu\mu, b}^{<\mu \mu} = N_{\mu\mu}^{<\mu \mu} F_{SS}^{<\mu \mu} R.\]

where the quantities \(F_{SS}\) are given in Tables XXI and XXII of Ref. \([4]\), while \(R = 94\% \) \([6]\) is the fraction of the “SS” sample coming from \(b\) hadron decays. Here we use the superscripts \(>\mu \mu\) and \(<\mu \mu\) to indicate that both muons have IP either above or below the given value. The subscript “SS” \([1, 2, 4]\) refers to muons both arising from decays
Table I: Number of dimuon events with both muons having IP above 50, 80, and 120 \( \mu m \).

| \( \text{IP}_{\min} \) (\( \mu m \)) | \( N_{\mu\mu}^{>>} \) (10\(^6\)) | \( F_{SS}^{>>} \) (%) | \( N_{\mu\mu,b}^{>>} \) (10\(^6\)) |
|--------------------------|-----------------|-----------------|-----------------|
| 50                       | 1.680           | 85.63±3.74      | 1.352±0.059     |
| 80                       | 1.152           | 89.88±5.10      | 0.973±0.055     |
| 120                      | 0.714           | 91.79±7.65      | 0.616±0.051     |

Table II: Number of dimuon events with both muons having IP below 50, 80, and 120 \( \mu m \).

| \( \text{IP}_{\max} \) (\( \mu m \)) | \( N_{\mu\mu}^{<<} \) (10\(^6\)) | \( F_{SS}^{<<} \) (%) | \( N_{\mu\mu,b}^{<<} \) (10\(^6\)) |
|--------------------------|-----------------|-----------------|-----------------|
| 50                       | 1.527           | 43.42±3.75      | 0.623±0.054     |
| 80                       | 2.174           | 48.76±2.84      | 0.996±0.058     |
| 120                      | 2.857           | 53.66±2.68      | 1.441±0.072     |

of particles at short distances from the interaction point. Muons produced by particles traveling long distances before decaying in the detector are labeled “L”.

The total sample of dimuons due to \( b \) hadron decays is \( N_{\mu\mu,b} = N_{\mu\mu}^{<<} + N_{\mu\mu}^{>>} + N_{\mu\mu,b}^{<<} \), where the last term is the contribution from events in which one muon has IP greater than the indicated value and the other has IP less than the indicated value. We can calculate this term from the first two:

\[
N_{\mu\mu,b}^{<<} = 2[N_{\mu\mu,b}^{<<}N_{\mu\mu,b}^{>>}]^{1/2} .
\]

(3)

We should get the same value of \( N_{\mu\mu,b} \) for each value of IP; the values we obtain from the data provided to us are \((3.81±0.17, 3.94±0.16, 3.94±0.18) \times 10^6\) events for IP = (50,80,120) \( \mu m \). These are within statistical errors of one another.

The effective values of \( b_0 \) may now be calculated from the fractions of dimuon events due to \( b \) hadron decays with IP greater than a given amount:

\[
[\exp(-b_0/\langle b \rangle)]^2 = N_{\mu\mu,b}^{>>}/N_{\mu\mu,b} ,
\]

(4)

yielding \( b_0/\langle b \rangle = (0.518, 0.699, 0.928) \) for IP = (50,80,120) \( \mu m \). With \( \langle b \rangle = 350 \mu m \) as estimated in Ref. [3], this yields \( b_0 = (181, 245, 325) \mu m \), values which exceed the corresponding ones of IP by factors of (3.6,3.1,2.7).

For the most stringent constraint, taking events with IP < 50 \( \mu m \) for both muons, the D0 collaboration is left with \( N_{\mu\mu,b}^{<<}/N_{\mu\mu,b} = 0.164 \pm 0.015 \), or a sample of about 1/6 the size of that employed without imposing bounds on IP values. We note that while the asymmetry derived in the latter case, \( A_{sl}^b = -0.787 \pm 0.172 \pm 0.093 \) is 3.9\( \sigma \) away from zero [4], a considerably larger asymmetry obtained for IP < 50 \( \mu m \), \( A_{sl}^b =
Table III: Contributions of background sources to charge asymmetry in like-sign dimuon sample for nominal analysis of Ref. [4].

| Source | Asymmetry |
|--------|-----------|
| $F_K A_K \times 10^2$ | +0.633 $\pm$ 0.031 |
| $F_\pi A_\pi \times 10^2$ | $-0.002 \pm 0.023$ |
| $F_p A_p \times 10^2$ | $-0.016 \pm 0.019$ |
| $(2 - F_{bkg})\Delta \times 10^2$ | $-0.212 \pm 0.030$ |
| $A_{bkg} \times 10^2$ | $+0.402 \pm 0.053$ |
| $A \times 10^2$ | $+0.126 \pm 0.041$ |
| $(A - A_{bkg}) \times 10^2$ | $-0.276 \pm 0.067$ |

$-2.779 \pm 0.674 \pm 0.694$, is nonzero at 2.9$\sigma$. The reason for the larger measured asymmetry for muons with low IP may be that it is driven more by $B_s$ decays than by $B^0$ decays [3].

### III RESCALING THE KAON BACKGROUND

In this Section we examine whether rescaling the kaon charge asymmetry background from the value determined in Ref. [4] can lead to a vanishing charge asymmetry for same-sign muon pairs originating from $B_{(s)}$ decays. We will also discuss the implication of such rescaling on the inclusive muon charge asymmetry.

Using the notations of Ref. [4], the measured like-sign dimuon asymmetry $A$ is related to the charge asymmetry from $B_{(s)}$ decays $A_{b_{sl}}$ through

$$A = (F_{SS}C_b + F_{SL}C_b) A_{b_{sl}}^b + F_K A_K + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

$$\equiv (F_{SS}C_b + F_{SL}C_b) A_{b_{sl}}^b + A_{bkg} .$$ \hspace{1cm} (5)

Here $F_{SS}C_b + F_{SL}C_b$ is an effective dilution factor depending on fractions of dimuon events with two short ($S$) muons and with one short and one long ($L$) muon, while $F_x$ and $A_x$ ($x = K, \pi, p$) are fractions and asymmetries of muons produced by kaons, pions and protons, respectively. The term $(2 - F_{bkg})\Delta$ [$F_{bkg} \equiv F_K + F_\pi + F_p$, $\Delta = (-0.132 \pm 0.019)$%] represents a contribution from muon track reconstruction asymmetry.

We begin by quoting in Table [III] some relevant entries from Table XII of Ref. [4] for like-sign dimuon events, which are the main source of statistical weight supporting the claim for a charge asymmetry $A_{b_{sl}}^b$. In Table [III] the dominant contribution to $A_{bkg}$ is from the charge asymmetry in kaon tracks. The final result for the dimuon charge asymmetry is given by $(A - A_{bkg})$ divided by an effective dilution factor, $F_{SS}C_b + F_{SL}C_b = 0.342 \pm 0.028$, or

$$A_{b_{sl}}^b = (-0.808 \pm 0.202 \text{ (stat)} \pm 0.222 \text{ (syst)})\%.$$ \hspace{1cm} (6)

Thus a reduction of the kaon background by a factor of 0.56 to 0.356 would be required to achieve a vanishing value of $A - A_{bkg}$ or of $A_{b_{sl}}^b$. 

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Table IV: Contributions of background sources to charge asymmetry in like-sign dimuon sample for analysis of Ref. [4] with the restriction IP < (50,80,120) μm.

| Source                  | Asymmetry       |
|-------------------------|-----------------|
|                         | IP < 50 μm      | IP < 80 μm | IP < 120 μm |
| $F_K A_K \times 10^2$   | +1.421 ± 0.066  | +1.203 ± 0.053 | +1.047 ± 0.051 |
| $F_\pi A_\pi \times 10^2$ | +0.016 ± 0.051  | −0.001 ± 0.002 | −0.003 ± 0.039 |
| $F_p A_p \times 10^2$   | −0.028 ± 0.041  | −0.029 ± 0.035 | −0.027 ± 0.032 |
| $(2 - F_{bkg}) \Delta \times 10^2$ | −0.166 ± 0.021  | −0.179 ± 0.023 | −0.188 ± 0.025 |
| $A_{bkg} \times 10^2$   | +1.243 ± 0.096  | +0.994 ± 0.082 | +0.829 ± 0.077 |
| $A \times 10^2$         | +0.715 ± 0.083  | +0.683 ± 0.069 | +0.555 ± 0.060 |
| $(A - A_{bkg}) \times 10^2$ | −0.527 ± 0.127  | −0.311 ± 0.107 | −0.274 ± 0.098 |

Table V: Contributions of background sources to charge asymmetry in like-sign dimuon sample for analysis of Ref. [4] with the restriction IP > (50,80,120) μm.

| Source                  | Asymmetry       |
|-------------------------|-----------------|
|                         | IP > 50 μm      | IP > 80 μm | IP > 120 μm |
| $F_K A_K \times 10^2$   | +0.205 ± 0.060  | +0.104 ± 0.074 | +0.113 ± 0.087 |
| $F_\pi A_\pi \times 10^2$ | +0.001 ± 0.007  | −0.002 ± 0.003 | −0.001 ± 0.002 |
| $F_p A_p \times 10^2$   | −0.005 ± 0.005  | −0.004 ± 0.002 | −0.002 ± 0.002 |
| $(2 - F_{bkg}) \Delta \times 10^2$ | −0.244 ± 0.035  | −0.236 ± 0.036 | −0.237 ± 0.037 |
| $A_{bkg} \times 10^2$   | −0.043 ± 0.071  | −0.139 ± 0.083 | −0.127 ± 0.093 |
| $A \times 10^2$         | −0.302 ± 0.079  | −0.386 ± 0.094 | −0.529 ± 0.120 |
| $(A - A_{bkg}) \times 10^2$ | −0.259 ± 0.106  | −0.247 ± 0.125 | −0.402 ± 0.152 |

Ref. [4] considered a set of variations on their nominal analysis entailing the restrictions IP < (50,80,120) μm and IP > (50,80,120) μm. We are grateful to the D0 Collaboration for sharing the respective entries in Table [III] corresponding to each of these criteria [8]. The results shown in Tables [IV] and [V] were obtained by summing products such as $F_K A_K$ over muon $p_T$ bins.

For comparison, we quote in Tables [VI] and [VII] the dominant contributions $F_K A_K$ and $(2 - F_{bkg}) \Delta$ using averaged values of $A_K$ and $F_x$ from Tables VII and XXI, XXII in Ref. [4], respectively. We note the insignificant differences between values of background asymmetries in Tables [VI] and [VII] and between those in Table [V] and [VI]. Thus, in the next section, where we discuss charge asymmetries in dimuon events with other IP constraints, we will use averaged values of fractions and asymmetries rather than summing their products over muon $p_T$ bins.

If we wish to rescale $F_K A_K$ by a common factor $\lambda$, we may parametrize

$$A - A_{bkg} = A_0 - \lambda F_K A_K \ ,$$

with the values of $A_0 \equiv A - \left[F_\pi A_\pi + F_p A_p + (2 - F_{bkg}) \Delta\right]$ and $F_K A_K$ given in Table
Table VI: Dominant contributions of background sources to charge asymmetry in like-sign dimuon sample with the restriction $\text{IP} < (50, 80, 120) \mu\text{m}$. We use average values of $A_K$ and $F_x$.

| Source          | IP < 50 $\mu\text{m}$ | IP < 80 $\mu\text{m}$ | IP < 120 $\mu\text{m}$ |
|-----------------|------------------------|------------------------|-------------------------|
| $F_KA_K \times 10^4$ | +1.37 $\pm$ 0.05        | +1.16 $\pm$ 0.04        | +1.05 $\pm$ 0.04        |
| $(2 - F_{\text{bkg}})\Delta \times 10^2$ | $-0.158 \pm 0.023$ | $-0.173 \pm 0.025$ | $-0.181 \pm 0.026$ |

Table VII: Dominant contributions of background sources to charge asymmetry in like-sign dimuon sample with the restriction $\text{IP} > (50, 80, 120) \mu\text{m}$. We use average values of $A_K$ and $F_x$.

| Source          | IP > 50 $\mu\text{m}$ | IP > 80 $\mu\text{m}$ | IP > 120 $\mu\text{m}$ |
|-----------------|------------------------|------------------------|-------------------------|
| $F_KA_K \times 10^4$ | +0.31 $\pm$ 0.09        | +0.23 $\pm$ 0.13        | +0.22 $\pm$ 0.20        |
| $(2 - F_{\text{bkg}})\Delta \times 10^2$ | $-0.243 \pm 0.035$ | $-0.249 \pm 0.036$ | $-0.252 \pm 0.037$ |

The effect of rescaling the contribution of $F_KA_K$ may be seen in Figs. 1 - 4. For no constraint on IP and for maximum values of $\text{IP} < (50, 80, 120) \mu\text{m}$, a common choice of $\lambda \approx 2/3$ shifts derived values of $A - A_{\text{bkg}}$ to within 1σ of zero. With the exception of $\text{IP} > 120 \mu\text{m}$, it is always possible to choose a value of $\lambda > 0.66$ such that $A - A_{\text{bkg}}$ is within 2σ of zero. However, for $\text{IP} > 120 \mu\text{m}$, with $\lambda = 1$ the value of $A - A_{\text{bkg}} = -0.402 \pm 0.152$ is 2.6σ from zero, and quite insensitive to rescaling of $F_KA_K$.

Effects of rescaling the kaon asymmetry background may also be studied in the inclusive muon asymmetry $a$, which is less sensitive than $A$ to a nonzero value of $A_{\text{sl}}^b$.

Table VIII: Parameters in Eq. (7) for rescaling contribution of kaon background. The nominal parameters [4] involve only a very weak restriction on impact parameter (IP).

| Criterion  | $A_0 \times 10^2$ | $F_KA_K \times 10^4$ |
|------------|-------------------|----------------------|
| Nominal    | +0.356 $\pm$ 0.059 | 0.633 $\pm$ 0.031    |
| IP < 50 $\mu\text{m}$ | +0.893 $\pm$ 0.108 | 1.421 $\pm$ 0.066    |
| IP < 80 $\mu\text{m}$ | +0.892 $\pm$ 0.081 | 1.203 $\pm$ 0.053    |
| IP < 120 $\mu\text{m}$ | +0.773 $\pm$ 0.082 | 1.047 $\pm$ 0.051    |
| IP > 50 $\mu\text{m}$ | $-0.054 \pm 0.087$ | 0.205 $\pm$ 0.060    |
| IP > 80 $\mu\text{m}$ | $-0.144 \pm 0.101$ | 0.104 $\pm$ 0.074    |
| IP > 120 $\mu\text{m}$ | $-0.289 \pm 0.126$ | 0.113 $\pm$ 0.087    |
Figure 1: Dependence of net dimuon asymmetry $A - A_{bg}$ on scale factor $\lambda$ for the nominal analysis of Ref. [4]. Solid, dashed, dot-dashed, and dotted sloping lines denote central, $\pm 1\sigma$, $\pm 2\sigma$, and $\pm 3$ sigma values, respectively. Values of $\lambda$ to left of vertical line give net asymmetries differing from zero (horizontal line) by less than $2\sigma$. $A - A_{bg}$ is within $2\sigma$ of zero for $\lambda < 0.76$.

Figure 2: Dependence of net dimuon asymmetry $A - A_{bg}$ on scale factor $\lambda$ for (left) IP $< 50 \mu m$; (right) IP $> 50 \mu m$. Lines as in Fig. 1. $A - A_{bg}$ is within $2\sigma$ of zero for $\lambda < (0.80, 0.66)$.
Figure 3: Dependence of net dimuon asymmetry $A - A_{bg}$ on scale factor $\lambda$ for (left) IP $< 80 \mu m$; (right) IP $> 80 \mu m$. Lines as in Fig. 1. $A - A_{bg}$ is within $2\sigma$ of zero for $\lambda < (0.92, 1.00)$.

Figure 4: Dependence of net dimuon asymmetry $A - A_{bg}$ on scale factor $\lambda$ for (left) IP $< 120 \mu m$; (right) IP $> 120 \mu m$. Lines as in Fig. 1. $A - A_{bg}$ is within $2\sigma$ of zero for $\lambda < 0.92$ (left) but for no positive value of $\lambda$ when IP $> 120 \mu m$. 
The measured values of $a - a_{\text{bkg}}$ for all IP constraints are consistent with zero \cite{4,8}. This is expected because the contribution of $A_{sl}^b$ to this difference is proportional to $c_b$ which is much smaller than $C_b$. (See Eq. (5) above and Eq. (7) in Ref. \cite{4} with values of $C_b$ and $c_b$ given in this reference.) We checked that rescaling the kaon background contribution to $a$ by $\lambda \approx 2/3$ leaves values of $a - a_{\text{bkg}}$ consistent with zero within $1\sigma$ for IP $> 80, 120 \, \mu\text{m}$ and within less than $3\sigma$ for IP $> 50 \, \mu\text{m}$. However, for IP $< 50, 80, 120 \, \mu\text{m}$ this scaling moves $a - a_{\text{bkg}}$ significantly ($6\sigma$) away from zero. Thus we conclude that a solution $A_{sl}^b = 0$ cannot be obtained consistently for all IP constraints by introducing a common rescaling factor for the background kaon asymmetry.

IV  MAXIMUM & MINIMUM IP FOR TWO $\mu$’S

So far D0 has analyzed dimuon events in which the two muons have IP either less or greater than the values 50, 80 and 120 $\mu\text{m}$. Other events, which have not yet been studied in the D0 sample, involve one muon with IP less than 50, 80 or 120 $\mu\text{m}$ and a second muon having IP greater than the same value. The numbers of events in the three classes, $N_{\mu\mu}^{<<}, N_{\mu\mu}^{>>}$ and $N_{\mu\mu}^{<>}$, are listed in Table IX for the three IP values. This Table also quotes the calculated total number of dimuon events $N_{\mu\mu}^{\text{total}}$ for the three IP values. The total numbers are in reasonable agreement with each other. Their deviation by 7\% relative to the number $6.019 \times 10^6$ quoted in Ref. \cite{4} for events with no IP constraint may be due to a second order effect \cite{9}.

Table IX: Number of dimuon events with muons having IP either below or above 50, 80, and 120 $\mu\text{m}$.

| IP  | $N_{\mu\mu}^{<<}$ | $N_{\mu\mu}^{>>}$ | $N_{\mu\mu}^{<>}$ | $N_{\mu\mu}^{\text{total}}$ |
|-----|-------------------|-------------------|-------------------|-----------------------------|
| ($\mu\text{m}$) | ($10^6$) | ($10^6$) | ($10^6$) | ($10^6$) |
| 50  | 1.527            | 1.680            | 3.203            | 6.410                       |
| 80  | 2.174            | 1.152            | 3.165            | 6.491                       |
| 120 | 2.857            | 0.714            | 2.856            | 6.427                       |

Noting that about half of the total like-sign dimuon events have not yet been studied experimentally ($N_{\mu\mu}^{<>}/N_{\mu\mu}^{\text{total}} \sim 1/2$), we wish to discuss their expected charge asymmetries. For this discussion we need the fraction of background events $F_{x}^{<>}(x = K, \pi, p)$. Using

$$N_{\mu\mu}^{<>} = 2(N_{\mu\mu}^{<<}N_{\mu\mu}^{>>})^{1/2}, \quad N_{x}^{<>} = 2(N_{x}^{<<}N_{x}^{>>})^{1/2}, \quad N_{x} = F_{x}N_{\mu\mu}, \quad (8)$$

one has

$$F_{x}^{<>} = (F_{x}^{<<}F_{x}^{>>})^{1/2}, \quad (x = K, \pi, p). \quad (9)$$

Thus, fraction of background events from kaons, pions and protons in the class <> under consideration may be calculated from corresponding fractions given in Tables XXI and
XXII of Ref. [4] for the two classes $<<$ and $>>$. These fractions are listed in Table X for IP = 50, 80, 120 $\mu$m. The three calculated fractions of kaons for events of the class $<>$ are equal within $1\sigma$ to the fraction measured by D0 for events with no restrictions on IP [4], $F_K \times 10^2 = 13.78 \pm 0.38$. We note that kaon fractions $F_K <<$ are about twice larger than the fractions $F_K >>$, while $F_K >>$ are about twice smaller than these fractions.

Table X: Fractions of background events of type $<<$ and $>>$ from Ref. [4] and fractions of events of type $<>$ given by Eq. (9) for IP = 50, 80, 120 $\mu$m.

| Fraction  | IP = 50 $\mu$m | IP = 80 $\mu$m | IP = 120 $\mu$m |
|-----------|----------------|----------------|-----------------|
| $F_K << \times 10^{-2}$ | 28.03 ± 0.95 | 23.79 ± 0.74 | 21.49 ± 0.62 |
| $F_\pi << \times 10^{-2}$ | 51.72 ± 3.18 | 44.26 ± 2.63 | 40.47 ± 2.26 |
| $F_p << \times 10^{-2}$ | 0.77 ± 0.29 | 0.66 ± 0.25 | 0.59 ± 0.23 |
| $F_K >> \times 10^{-2}$ | 6.31 ± 1.73 | 4.79 ± 2.59 | 4.48 ± 4.05 |
| $F_\pi >> \times 10^{-2}$ | 9.51 ± 2.36 | 6.39 ± 2.95 | 4.43 ± 3.95 |
| $F_p >> \times 10^{-2}$ | 0.11 ± 0.06 | 0.03 ± 0.04 | 0.03 ± 0.05 |

Results of asymmetries for background sources are given in Table XI. The calculated background asymmetries, for samples involving one muon with IP larger than 50, 80 or 120 $\mu$m and a second muon with IP smaller than the same value, should be compared with corresponding future results by D0. They may be used to extract the net charge asymmetry for $B_{(s)}$ decays $A_{sl}^B$ from the raw asymmetry $A$.

Table XI: Asymmetries calculated for background events of type $<>$ defined in the text for IP = 50, 80, 120 $\mu$m.

| Asymmetry | IP = 50 $\mu$m | IP = 80 $\mu$m | IP = 120 $\mu$m |
|-----------|----------------|----------------|-----------------|
| $F_K << A_K \times 10^2$ | +0.649 ± 0.091 | +0.521 ± 0.141 | +0.479 ± 0.217 |
| $F_\pi <> A_\pi \times 10^2$ | -0.007 ± 0.018 | -0.005 ± 0.013 | -0.004 ± 0.011 |
| $F_p <> A_p \times 10^2$ | -0.002 ± 0.010 | -0.001 ± 0.005 | -0.001 ± 0.005 |
| $(2 - F_{bkg} <<) A \times 10^2$ | -0.217 ± 0.032 | -0.228 ± 0.033 | -0.233 ± 0.035 |
| $A_{bkg} \times 10^2$ | +0.423 ± 0.099 | +0.287 ± 0.145 | +0.241 ± 0.220 |

V CONCLUSIONS

We have examined the relation between the impact parameter (IP) selections performed in Ref. [4] and those we suggested in Ref. [3]. We find that the minimum transverse IP of
(50, 80, 120) µm considered in Ref. [4] is equivalent to a value of the parameter \( b_0 \) which exceeds IP by factors of 2.7 to 3.6. For the most stringent criterion, taking events with \( \text{IP} < 50 \) µm for both muons the sample of dimuons from \( B_s \) decays is reduced to about 1/6 the size of the sample involving no bounds on IP. Fractions of backgrounds from kaons and pions in the former sample are each about twice as large as in the latter sample. In spite of the considerably smaller sample of signal events with \( \text{IP} < 50 \) µm and the larger background, the statistical significance of \( A - A_{\text{bkg}} = (-0.527 \pm 0.127)\% \) measured for \( \text{IP} < 50 \) µm is 4.1σ, the same as measured for dimuons with no IP constraint, \( A - A_{\text{bkg}} = (-0.276 \pm 0.067)\% \). (See Tables III and IV.)

We asked whether a rescaling of the parameter \( F_K A_K \) describing kaon background asymmetry could lead to annulment of the claimed charge asymmetry for same-sign muon pairs from \( B_s \) decays. For selections of maximum impact parameters \( \text{IP} < (50, 80, 120) \) µm, a rescaling by a factor of \( \lambda \approx 2/3 \) led to reduction of the net charge asymmetry to within 1σ of zero. However, for minimum impact parameters \( \text{IP} > (50, 80, 120) \) µm, with greatly reduced kaon backgrounds, this was not so, and for \( \text{IP} > 120 \) µm, no positive choice of \( \lambda \) reduced the net asymmetry to less than 2σ from zero.

In contrast, while introducing a rescaling factor \( \lambda \approx 2/3 \) in inclusive muon samples is consistent with \( A_{\text{sl}}^b = 0 \) for \( \text{IP} > 50, 80, 120 \) µm, it leads to a nonzero asymmetry for \( \text{IP} < 50, 80, 120 \) µm.

We calculated background asymmetries for dimuon samples in which one muon has a maximum IP while the other has a minimum IP, for the three cases \( \text{IP} = 50, 80, 120 \) µm. These calculated asymmetries, expected to be confirmed in future studies by D0, may be used for measuring \( A_{\text{sl}}^b \) in these samples.

The fraction of dimuons from kaons was seen to decrease by imposing a minimim value for the impact parameter IP. For instance, the background asymmetry from kaons was reduced from \( F_K A_K = (0.633 \pm 0.031)\% \) with no IP restriction to \( F_K A_K = (0.205 \pm 0.060)\% \) for \( \text{IP} > 50 \) µm. The corresponding number of like-sign dimuon events decreased by about a factor 1/4 (see Table IX), and the significance of a nonzero \( A - A_{\text{bkg}} \) went down from 4.1σ to 2.4σ (see Table V). In future studies of the same-sign dimuon charge asymmetry we thus advocate emphasis on reduction of kaon background by choosing a minimum value of impact parameter, even if at the cost of statistics. Such studies could, in principle, be performed by other collaborations such as CDF at the Fermilab Tevatron and LHCb at the CERN Large Hadron Collider.

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References

[1] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. D82 (2010) 032001 [arXiv:1005.2757 [hep-ex]].

[2] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 105 (2010) 081801 [arXiv:1007.0395 [hep-ex]].

[3] M. Gronau and J. L. Rosner, Phys. Rev. D 82 (2010) 077301 [arXiv:1007.4728 [hep-ph]].

[4] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. D84 (2011) 052007 [arXiv:1106.6308 [hep-ex]].

[5] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. D 77 (2008) 072004 [arXiv:0710.1895 [hep-ex]].

[6] G. Borissov, private communication.

[7] B. Hoeneisen, private communication.

[8] See supplemental material in http://www-d0.fnal.gov/Run2Physics/WWW/results/final/B/B11B/.