PROCEEDINGS OF SCIENCE

Multi-muon events at CDF

F. Happacher on behalf of the CDF collaboration
Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy
E-mail: `fabhap@fnal.gov`

We report a study of multi-muon events produced at the Fermilab Tevatron collider and recorded by the CDF II detector. In a data set acquired with a dedicated dimuon trigger and corresponding to an integrated luminosity of 2100 pb^{-1}, we isolate a significant sample of events in which at least one of the identified muons has large impact parameter and is produced outside the beam pipe of radius 1.5 cm. We are unable to fully account for the number and properties of the events through standard model processes in conjunction with our current understanding of the CDF II detector, trigger and event reconstruction. Several topological and kinematic properties of these events are also presented. In contrast, the production cross section and kinematics of events in which both muon candidates are produced inside the beam pipe are successfully modeled by known QCD processes which include heavy flavor production. The presence of these anomalous multi-muon events offers a plausible resolution to long-standing inconsistencies related to $b\bar{b}$ production and decay.

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1. Introduction

This study reports the observation of an anomalous muon production in $p\bar{p}$ interactions at $\sqrt{s} = 1.96$ TeV. The analysis was motivated by the presence of several inconsistencies that affect or affected the $b\bar{b}$ production at the Tevatron: (a) the ratio of the observed $b\bar{b}$ correlated production cross section to the exact next-to-leading-order (NLO) QCD prediction [1] is 1.15 ± 0.21 when b quarks are selected via secondary vertex identification, whereas this ratio is found to be significantly larger than two when b quarks are identified through their semileptonic decays [2]; (b) sequential semileptonic decays of single b quarks are considered to be the main source of dilepton events with invariant mass smaller than that of a b quark. However, the observed invariant mass spectrum is not well modeled by the standard model (SM) simulation of this process [3]; and (c) the value of $\bar{\chi}$, the average time integrated mixing probability of b flavored hadrons derived from the ratio of muon pairs from b and $\bar{b}$ quarks semileptonic decays with opposite and same sign charge, is measured at hadron colliders to be larger than that measured by the LEP experiments [4, 5]. This analysis extends a recent study [6] by the CDF collaboration which has used a dimuon data sample to measure the correlated $\sigma_{b\to\mu,\bar{b}\to\mu}$ cross section. After briefly describing that study, it is shown that varying the dimuon selection criteria isolates a sizable, but unexpected background that contains muons with an anomalous impact parameter [7] distribution. Further investigation shows that a smaller fraction of these events also has anomalously large track and muon multiplicities. We are unable to account for the size and properties of these events in terms of known SM processes, even in conjunction with possible detector mismeasurement effects.

The CDF II detector [8] consists of a magnetic spectrometer, based on a 96-layer drift chamber, surrounded by electromagnetic and hadron calorimeters and muon detectors. Precision impact parameter and vertex determinations are provided by three slicon tracking devices collectively referred to in this report as the “SVX". The SVX is composed of eight layers of silicon microstrip detectors ranging in radius from 1.5 to 28 cm in the pseudorapidity region $|\eta| < 1$.

2. Study of the data sample composition

The study presented here, which is further detailed in Ref.[9], uses the same data and Monte Carlo simulated samples, and the same analysis methods described in Ref. [6]. We use events containing two central ($|\eta| < 0.7$) muons, each with transverse momentum $p_T \geq 3$ GeV$/c$, and with invariant mass larger than 5 GeV$/c^2$. In Ref.[6], the value of $\sigma_{b\to\mu,\bar{b}\to\mu}$ is determined by fitting the impact parameter distribution of these primary muons with the expected shapes from all known sources. To ensure an accurate impact parameter determination, Ref. [6] uses a subset of dimuon events in which each muon track is reconstructed in the SVX with hits in the two inner layers and in at least four of the inner six layers. The data are nicely described by a fit with contributions from the following QCD processes: semileptonic heavy flavor decays, prompt quarkonia decays, Drell-Yan production, and instrumental backgrounds from hadrons mimicking the muon signal. Using the fit result, shown in Fig. 1, Ref. [6] reports $\sigma_{b\to\mu,\bar{b}\to\mu} = 1549 \pm 133$ pb for muons with $p_T \geq 3$ GeV$/c$ and $|\eta| \leq 0.7$.

This result is in good agreement with theoretical expectations as well as with analogous measurements that identify b quarks via secondary vertex identification [10, 11]. However, it is also substantially smaller than previous measurements of this cross section [12, 13], and raises some concern about the composition of the initial dimuon sample prior to the SVX requirements. The tight SVX requirements used in Ref. [6] select events in which both muons arise from parent particles that have decayed within a distance of $\simeq 1.5$ cm from the $p\bar{p}$ interaction primary vertex in the plane transverse to the beam line. Using Monte Carlo simulations, we estimate that approximately 96% of the dimuon events contributed by known QCD processes satisfy this latter condition. Since the events selected in [6] are well described by known QCD processes, we can independently estimate the efficiency of the tight SVX requirements. Using control samples of data from various sources and the sample composition determined by the fit to the muon impact parameter distribution, we estimate that $(24.4 \pm 0.2)\%$ of the initial sample should survive the tight SVX requirements, whereas only $(19.30 \pm 0.04)\%$ actually do. This suggests the presence of an additional background that has been suppressed when making the tight SVX requirements. The size of this unexpected dimuon source is estimated as the difference of the total number of dimuon events, prior to any SVX requirements, and the expected contribution from the known QCD sources. This latter contribution is estimated as the number of events surviving the tight SVX requirements divided by the efficiency of that selection. In a data set corresponding to an integrated luminosity of 742 pb^{-1}, 143743 dimuon events survive the tight SVX cuts. Dividing this number by the 24.4% efficiency of the tight SVX selection criteria we expect 589111 ± 4829 QCD events to contribute to the initial sample whereas 743006 are observed. The difference, 153895 ± 4829 events, is comparable in magnitude to the expected dimuon contribution from $b\bar{b}$ production, 221564 ± 11615. This estimate assumes the unexpected source of dimuon events is completely rejected by the tight SVX requirements. Most CDF analyses use a set of SVX criteria, referred in the following as standard SVX, in which tracks are required to have hits in at least three of the eight SVX layers. This standard SVX selection accepts muons from parent particles with decay lengths as long as 10.6 cm. Applying the standard SVX selection reduces the estimated size of the unknown dimuon source by a factor of two, whereas 88% of the known QCD contribution is expected to survive.

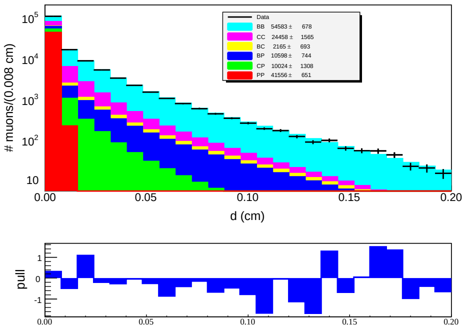

Figure 1: Impact parameter distribution of muons contributed by different physics processes.

A summary of the estimates of the size of this unexpected source of dimuon events, whimsically called ghost events, for various sets of SVX criteria is shown in Table 1. In this table and throughout this report the expected contribution from known QCD sources, referred to as QCD contribution, will be estimated from the sample of dimuons surviving the tight SVX requirements and properly accounting for the relevant SVX efficiencies using the sample composition from the fits of Ref. [6]. We elect to follow this approach since the tight

Table 1: Number of events that pass different SVX requirements. Dimuons are also split into pairs with opposite (*OS*) and same (*SS*) sign charge.

Type	No SVX	Tight SVX	Standard SVX
Total	743006	143743	590970
Total *OS*		98218	392020
Total *SS*		45525	198950
QCD	589111 ± 4829	143743	518417 ± 7264
QCD *OS*		98218	354228 ± 4963
QCD *SS*		45525	164188 ± 2301
Ghost	153895 ± 4829	0	72553 ± 7264
Ghost *OS*		0	37792 ± 4963
Ghost *SS*		0	34762 ± 2301

SVX sample provides a well understood sample [6]. The ghost contribution will always be estimated from the total number of events observed in the data after subtracting the expected QCD contribution. Table 1 shows also the event yields separately for the subset of events in which the dimuons have opposite-sign (*OS*) and same-sign (*SS*) charge. The ratio of OS to SS dimuons is approximately 2:1 for QCD processes but is approximately 1:1 for the ghost contribution. At this stage it is worth commenting further on the set of inconsistencies related to $b\bar{b}$ production and decay mentioned above. The general observation is that the measured $\sigma_{b\to\mu,\bar{b}\to\mu}$ increases as the SVX requirements are made looser and is almost a factor of two larger than that measured in Ref. [6] when no SVX requirements are made [13]. As mentioned above, the magnitude of the ghost contribution is comparable to the $b\bar{b}$ contribution when no SVX selection is made and in combination would account for the measurement reported in Ref. [13]. Similarly, for the standard SVX criteria, the magnitude of the ghost contribution, when added to the expected $b\bar{b}$ contribution of 194976 ± 10221 events, coincides with the cross section measurement reported in Ref. [12] and the $\bar{\chi}$ value reported in Ref. [4] since these measurements use similar sets of silicon criteria. Moreover, as demonstrated in [9], when applying the tight SVX criteria to initial muons, the invariant mass spectrum of combinations of an initial muon with an additional accompanying muon is well described by known QCD sources and is dominated by sequential semileptonic heavy flavor decays. In contrast, without any SVX requirement the invariant mass spectrum cannot be modeled with the SM simulation and the inconsistencies at low invariant mass reported in [3] are reproduced. Thus, this unknown source of dimuon events seems to offer a plausible resolution to these long-standing inconsistencies related to $b\bar{b}$ production and decay. The remainder of this paper is dedicated to a further exploration of these events. The nature of the anomalous events can be characterized by four main features. The impact parameter distribution of the initial muon pair cannot be readily understood in terms of known SM processes. In small angular cones around the initial muons the rate of additional muons is significantly higher than that expected from SM processes. The invariant mass of the initial and additional muons looks different from that expected from sequential semileptonic decays of heavy flavor hadrons. The impact parameter distribution of the additional muons has the same anomalous behavior as the initial muons. We will discuss these features in turn. As shown in Fig. 2, muons due to ghost events have an impact parameter distribution that is completely different from that of muons due to QCD events.

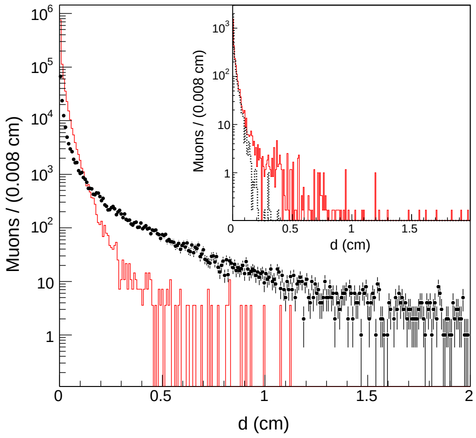

Figure 2: Impact parameter distribution of muons contributed by ghost (•) and QCD (histogram) events. Muon tracks are selected with the standard SVX requirements. The detector resolution is $\simeq 30\ \mu$m. The insert shows the distribution of simulated muons (histogram) that pass the same analysis selection as the data and arise from in-flight-decays of pions and kaons produced in a QCD heavy flavor simulation. The dashed histogram shows the impact parameter of the parent hadrons.

A number of potential background sources have been evaluated. The one expected to contribute significantly arises from in-flight-decays of pions and kaons. Based upon a generic QCD simulation, we predict a contribution of 57000 events [9], 44% and 8% of which pass the standard and tight SVX selection, respectively. The uncertainty of this prediction is difficult to assess, but, as shown by the insert in Fig. 2, in-flight decays alone cannot account for the shape of the muon impact parameter distribution in ghost events. A minor contribution of K^0_S and hyperon decays in which the punchthrough of a hadronic prong mimics a muons signal has been also investigated [9]. Secondary interactions in the tracking volume are also possible candidates, and more difficult to quantify. The possibility of instrumental effects, trigger and reconstruction biases have been investigated in detail in Ref. [9]. For example, we have verified the soundness of large impact parameter tracks by measuring the lifetime of K^0_S decays reconstructed in the same data set used for this analysis.

3. Events with additional muons

We search QCD and ghost events that contain a pair of initial muons that pass our analysis selection (without any SVX requirement) for additional muons with $p_T \geq 2$ GeV$/c$ and $|\eta| \leq 1.1$. We have the following motivations: (a) events acquired because of in-flight decays or secondary interactions are not expected to contain an appreciable number of additional muons; (b) QCD events that might appear in the ghost sample because of not-yet-understood detector malfunctions should not contain more additional leptons than QCD events with well reconstructed initial dimuons; and (c) we want to investigate if the anomaly reported in Ref. [3] is also related to the presence of the unexpected background. According to the simulation [9], additional muons arise from sequential decays of single b hadrons. In addition, one expects a contribution due to hadrons mimicking the muon signal. In the data, 9.7% of the dimuon events contain an additional muon (71835 out of 743006 events). The contribution of events without heavy flavor, such as all conventional sources of ghost events mentioned above, is depressed by the request of an additional muon. For example, in events containing a $\Upsilon(1S)$ or K^0_S candidate and are included in the dimuon sample, the probability of finding an additional muon is (0.90 ± 0.01)% and (1.7 ± 0.8)%, respectively. However, the efficiency of the tight SVX selection in dimuon events that contain additional muons drops from

0.1930 ± 0.0004 to 0.166 ± 0.001. This observation anticipates that a fraction of ghost events contains more additional muons than QCD data.

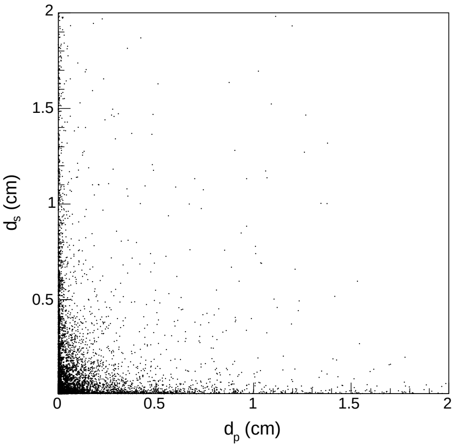

Figure 3: Two-dimensional distribution of the impact parameter of an initial muon, d_{0p}, versus that, d_{0s}, of additional muons in ghost events. Muons are selected with standard SVX requirements.

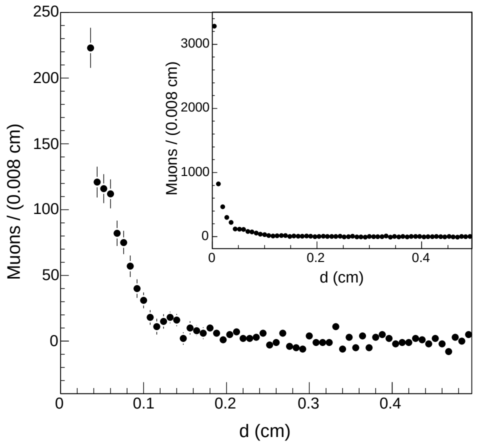

Figure 4: Exploded impact parameter distribution of additional muons in QCD events. The entire distribution is shown in the insert. Muons are selected without any SVX requirements.

This paragraph summarizes a detailed study of the rate and kinematic properties of events that contain at least three muons reported in Ref. [9]. This study uses a data set of larger integrated luminosity that corresponds to 1131090 ± 9271 QCD and 295481 ± 9271 ghost events. Reference [9] shows that the rate and kinematics of three-muon combinations are correctly modeled by the QCD simulation only if the two initial muons are selected with the tight SVX requirement. Muon pairs due to b sequential decays peak at small invariant masses and small opening angles. The distributions of analogous pairs in the unexpected background have a quite similar behaviour. However, combinations of initial and additional muons in ghost events have a smaller opening angle and a smaller invariant mass than those from sequential b decays [9].

Therefore, the study of ghost events is further restricted to muons and tracks contained in a cone of angle $\theta \leq 36.8^\circ$ ($\cos\theta \geq 0.8$) around the direction of each initial muon. As reported in Ref. [9], less than half of the OS and SS muon combinations in ghost events can be accounted for by fake muons, and ghost events are shown to contain a fraction of additional real muons (9.4%) that is four times larger than that of QCD events (2.1%). Reference [9] investigates at length the possibility that the predicted rate of fake muons is underestimated. The fraction of additional real muons in QCD and ghost events is verified by selecting additional muons with $p_T \geq 3$ GeV/c and $|\eta| \leq 0.7$. In this case, because of the larger number of interaction lengths traversed by hadronic tracks, the fake rate is negligible [6]. In this study the muon detector acceptance is reduced by a factor of five but the rate of such additional muons is (0.40 ± 0.01)% in QCD and (1.64 ± 0.08)% in ghost events.

Figure 3 shows the two-dimensional distribution of the impact parameter of an initial muon versus that of all additional muons in a $\cos\theta \geq 0.8$ cone around its direction. The impact parameter distribution of the additional muons is found to be as anomalous as that of primary muons.

However, the impact parameter of the additional and initial muons are weakly correlated (the correlation factor is $\rho_{d_{0p}d_{0s}} = 0.03$). For comparison, Fig. 4 shows that the impact parameter distribution of additional muons in QCD events is not anomalous at all. It is difficult to reconcile the rate and characteristics of these anomalous events with expectations from known SM sources. Although one can never rule out the possibility that these data could be at least partially explained by detector effects not presently understood, we will present some additional properties of the ghost sample. Figure 5 (a) shows the distribution of the number of muons found in a $\cos\theta \geq 0.8$ cone around a primary muon in ghost events. In the plot, an additional muon increases the multiplicity by 1 when of opposite and by 10 when of same sign charge as the initial muon. Leaving aside the case in which no additional muons are found, it is interesting to note that an increase of one unit in the muon multiplicity corresponds in average to a population decrease of approximately a factor of seven. This factor is very close to the inverse of the $\tau \to \mu$ branching fraction (0.174) multiplied by the 83% efficiency of the muon detector, and makes it hard to resist the interpretation that these muons arise from τ decays with a kinematic acceptance close to unity. The multiplicity distribution corrected for the fake muon contribution [9] is shown in Fig. 5 (b). The fake contribution is evaluated on a track-by-track basis using the probability that pions from D^0 mesons from B hadron decays mimic a muon signal. Unfortunately, the multiplicity distribution of muons and tracks contained in a 36.8° cone around the direction of such D^0 mesons does not have the high multiplicity tail of ghost events. In the D^0 control sample, we do not observe any dependence of the fake rate on the track and muon multiplicity, but we also cannot rule out a drastic increase of the fake probability per track in events with multiplicities much larger than those of QCD standard processes. A study based on higher quality muons [9] does not show any evidence of that being the case.

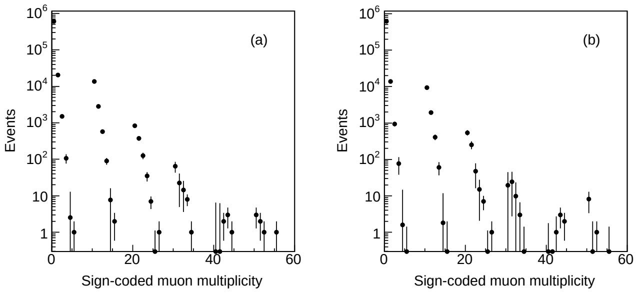

Figure 5: Multiplicity distribution of additional muons found in a $\cos\theta \geq 0.8$ cone around the direction of a primary muon before (a) and after (b) correcting for the fake muon contribution. An additional muon increases the multiplicity by 1 when it has opposite and by 10 when it has same sign charge as the initial muon.

4. Conclusions

We report the observation of anomalous muon production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$. This unknown source of dimuon events seems to offer a plausible resolution to long-standing inconsistencies related to $b\bar{b}$ production and decay. A significant fraction of these events has features that cannot be explained with our current understanding of the CDF II detector, trigger and event reconstruction.

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