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An additional study of multi-muon events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

CDF Collaboration

T. Aaltonen [v], B. Álvarez González [i,24], S. Amerio [as], D. Amidei [aj], A. Anastassov [an], A. Annovi [r], J. Antos [l,m], G. Apollinari [p], A. Apresyan [ba], T. Arisawa [bl], A. Artikov [n], W. Ashmanskas [p], B. Auerbach [bo], F. Azfar [ar], W. Badgett [p], A. Barbaro-Galtieri [ae], V.E. Barnes [ba], B.A. Barnett [x], P. Barria [ax], P. Bartos [l,m], M. Bauce [at], F. Bedeschi [av], D. Beecher [ag], S. Behari [x], G. Bellettini [aw], J. Bellinger [bn], D. Benjamin [o], A. Beretvas [p], A. Bhatti [bc], M. Binkley [p,1], D. Bisello [at], I. Bizjak [ag,28], K.R. Bland [d], B. Blumenfeld [x], A. Bocci [o], A. Bodek [bb], D. Bortoletto [ba], J. Boudreau [az], A. Boveia [k], B. Brau [p,2], L. Brigliadori [f], A. Brisuda [l,m], C. Bromberg [ak], E. Brucken [v], M. Bucciantonio [aw], J. Budagov [n], H.S. Budd [bb], S. Budd [w], K. Burkett [p], G. Busetto [at], P. Bussey [t], C. Calancha [ah], M. Campanelli [ak], M. Campbell [aj], B. Carls [w], D. Carlsmith [bn], R. Carosi [av], S. Carrillo [q,12], S. Carron [p], B. Casal [i], M. Casarsa [p], A. Castro [f], P. Catastini [u], D. Cauz [bg], V. Cavaliere [w], A. Cerri [ae,7], L. Cerrito [ag,18], Y.C. Chen [a], G. Chiarelli [av], G. Chlachidze [p], F. Chlebana [p], K. Cho [y,z,aa,ab,ac,ad], D. Chokheli [n], J.P. Chou [u], W.H. Chung [bn], Y.S. Chung [bb], C.I. Ciobanu [au], M.A. Ciocci [ax], A. Clark [s], C. Clarke [bm], G. Compostella [at], M.E. Convery [p], M. Corbo [au], M. Cordelli [r], C.A. Cox [g], D.J. Cox [g], F. Crescioli [aw], C. Cuenca Almenar [bo], J. Cuevas [i,24], D. Dagenhart [p], N. d'Ascenzo [au,22], M. Datta [p], P. de Barbaro [bb], S. De Cecco [bd], M. Dell'Orso [aw], L. Demortier [bc], J. Deng [o,4], M. Deninno [e], F. Devoto [v], M. d'Errico [at], A. Di Canto [aw], B. Di Ruzza [av], J.R. Dittmann [d], M. D'Onofrio [af], S. Donati [aw], P. Dong [p], M. Dorigo [bg], T. Dorigo [as], K. Ebina [bl], A. Eppig [aj], R. Erbacher [g], D. Errede [w], S. Errede [w], N. Ershaidat [au,27], H.C. Fang [ae], J.P. Fernandez [ah], C. Ferrazza [ay], R. Field [q], G. Flanagan [ba,20], R. Forrest [g], M.J. Frank [d], M. Franklin [u], J.C. Freeman [p], Y. Funakoshi [bl], I. Furic [q], M. Gallinaro [bc], J. Galyardt [j], J.E. Garcia [s], A.F. Garfinkel [ba], P. Garosi [ax], H. Gerberich [w], E. Gerchtein [p], S. Giagu [be], V. Giakoumopoulou [c], P. Giannetti [av], K. Gibson [az], C.M. Ginsburg [p], N. Giokaris [c], P. Giromini [r], M. Giunta [av], G. Giurgiu [x], V. Glagolev [n], D. Glenzinski [p], M. Gold [am], N. Goldschmidt [q], A. Golossanov [p], G. Gomez [i], G. Gomez-Ceballos [ai], M. Goncharov [ai], O. González [ah], I. Gorelov [am], A.T. Goshaw [o], K. Goulianos [bc], C. Grosso-Pilcher [k], R.C. Group [bk,p], J. Guimaraes da Costa [u], Z. Gunay-Unalan [ak], C. Haber [ae], S.R. Hahn [p], E. Halkiadakis [bf], A. Hamaguchi [aq], J.Y. Han [bb], F. Happacher [r], K. Hara [bi], D. Hare [bf], M. Hare [bj], K. Hatakeyama [d], M. Herndon [bn], S. Hewamanage [d], D. Hidas [bf], A. Hocker [p], W. Hopkins [p,8], S. Hou [a], R.E. Hughes [ao], M. Hurwitz [k], U. Husemann [bo], M. Hussein [ak], J. Huston [ak], G. Introzzi [av], M. Iori [be], A. Ivanov [g,16], D. Jang [j], B. Jayatilaka [o], E.J. Jeon [y,z,aa,ab,ac,ad], M.K. Jha [e], S. Jindariani [p], W. Johnson [g], M. Jones [ba], K.K. Joo [y,z,aa,ab,ac,ad], S.Y. Jun [j], T.R. Junk [p], A. Kasmi [d], Y. Kato [aq,15], W. Ketchum [k], B. Kilminster [p], D.H. Kim [y,z,aa,ab,ac,ad], H.S. Kim [y,z,aa,ab,ac,ad], H.W. Kim [y,z,aa,ab,ac,ad], J.E. Kim [y,z,aa,ab,ac,ad], M.J. Kim [r], S.B. Kim [y,z,aa,ab,ac,ad], S.H. Kim [bi], Y.K. Kim [k], N. Kimura [bl], M. Kirby [p], S. Klimenko [q], K. Kondo [bl], D.J. Kong [y,z,aa,ab,ac,ad], J. Konigsberg [q], D. Krop [k], N. Krumnack [d,13], M. Kruse [o], M. Kurata [bi], S. Kwang [k], A.T. Laasanen [ba], S. Lami [av], S. Lammel [p], M. Lancaster [ag], R.L. Lander [g], K. Lannon [ao,23], A. Lath [bf], G. Latino [aw], H.S. Lee [k], J.S. Lee [y,z,aa,ab,ac,ad], S. Leo [aw], S. Leone [av], A. Limosani [o,19], C.-J. Lin [ae], J. Linacre [ar], M. Lindgren [p], A. Lister [s], D.O. Litvintsev [p], C. Liu [az], Q. Liu [ba], T. Liu [p], S. Lockwitz [bo], A. Loginov [bo], D. Lucchesi [at], P. Lujan [ae], P. Lukens [p], G. Lungu [bc], J. Lys [ae], R. Lysak [l,m], R. Madrak [p], K. Maeshima [p], K. Makhoul [ai], S. Malik [bc], G. Manca [af,3], A. Manousakis-Katsikakis [c], F. Margaroli [ba], R. Martínez-Ballarín [ah], P. Mastrandrea [bd], M.E. Mattson [bm], P. Mazzanti [e], K.S. McFarland [bb],

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R. McNulty [af,10], A. Mehta [af], P. Mehtala [v], A. Menzione [av], C. Mesropian [bc], T. Miao [p], D. Mietlicki [aj], A. Mitra [a], H. Miyake [bi], S. Moed [u], N. Moggi [e], M.N. Mondragon [p,12], C.S. Moon [y,z,aa,ab,ac,ad], R. Moore [p], M.J. Morello [p], P. Movilla Fernandez [p], A. Mukherjee [p], M. Mussini [f], J. Nachtman [p,14], Y. Nagai [bi], J. Naganoma [bl], I. Nakano [ap], A. Napier [bj], C. Neu [bk], M.S. Neubauer [w], J. Nielsen [ae,6], O. Norniella [w], E. Nurse [ag], L. Oakes [ar], S.H. Oh [o], Y.D. Oh [y,z,aa,ab,ac,ad], I. Oksuzian [bk], T. Okusawa [aq], R. Orava [v], S. Pagan Griso [at], C. Pagliarone [bg], E. Palencia [i,7], V. Papadimitriou [p], J. Patrick [p], G. Pauletta [bh], C. Paus [ai], D.E. Pellett [g], A. Penzo [bg], T.J. Phillips [o], G. Piacentino [av], J. Pilot [ao], K. Pitts [w], C. Plager [h], L. Pondrom [bn], K. Potamianos [ba], O. Poukhov [n,1], F. Prokoshin [n,26], A. Pronko [p], F. Ptohos [r,*,9], E. Pueschel [j], G. Punzi [aw], J. Pursley [bn], A. Rahaman [az], V. Ramakrishnan [bn], N. Ranjan [ba], I. Redondo [ah], M. Rescigno [bd], T. Riddick [ag], F. Rimondi [f], L. Ristori [av,p], T. Rodrigo [i], E. Rogers [w], S. Rolli [bj], R. Roser [p], M. Rossi [bg], F. Rubbo [p], F. Ruffini [ax], A. Ruiz [i], J. Russ [j], V. Rusu [p], W.K. Sakumoto [bb], Y. Sakurai [bl], L. Santi [bh], L. Sartori [av], K. Sato [bi], V. Saveliev [au,22], A. Savoy-Navarro [au], P. Schlabach [p], E.E. Schmidt [p], M.P. Schmidt [bo,1], M. Schmitt [an], T. Schwarz [g], L. Scodellaro [i], A. Scribano [ax], F. Scuri [av], A. Sedov [ba], S. Seidel [am], Y. Seiya [aq], A. Semenov [n], F. Sforza [aw], A. Sfyrla [w], S.Z. Shalhout [g], T. Shears [af], P.F. Shepard [az], M. Shimojima [bi,21], S. Shiraishi [k], M. Shochet [k], I. Shreyber [al], A. Simonenko [n], A. Sissakian [n,1], K. Sliwa [bj], J.R. Smith [g], F.D. Snider [p], A. Soha [p], S. Somalwar [bf], P. Squillacioti [p], M. Stancari [p], M. Stanitzki [bo], R. St. Denis [t], D. Stentz [an], J. Strologas [am], G.L. Strycker [aj], Y. Sudo [bi], A. Sukhanov [q], I. Suslov [n], K. Takemasa [bi], Y. Takeuchi [bi], J. Tang [k], M. Tecchio [aj], P.K. Teng [a], J. Thom [p,8], J. Thome [j], G.A. Thompson [w], P. Ttito-Guzmán [ah], S. Tkaczyk [p], S. Tokar [l,m], K. Tollefson [ak], T. Tomura [bi], S. Torre [r], D. Torretta [p], P. Totaro [as], M. Trovato [ay], F. Ukegawa [bi], S. Uozumi [y,z,aa,ab,ac,ad], A. Varganov [aj], F. Vázquez [q,12], G. Velev [p], C. Vellidis [c], M. Vidal [ah], I. Vila [i], R. Vilar [i], J. Vizán [i], M. Vogel [am], G. Volpi [aw], R.L. Wagner [p], T. Wakisaka [aq], R. Wallny [h], S.M. Wang [a], D. Waters [ag], B. Whitehouse [bj], A.B. Wicklund [b], E. Wicklund [p], S. Wilbur [k], J.S. Wilson [ao], B.L. Winer [ao], P. Wittich [p,8], S. Wolbers [p], H. Wolfe [ao], T. Wright [aj], X. Wu [s], Z. Wu [d], K. Yamamoto [aq], J. Yamaoka [o], T. Yang [p], U.K. Yang [k,17], Y.C. Yang [y,z,aa,ab,ac,ad], W.-M. Yao [ae], G.P. Yeh [p], K. Yi [p,14], J. Yoh [p], K. Yorita [bl], T. Yoshida [aq,11], G.B. Yu [o], I. Yu [y,z,aa,ab,ac,ad], S.S. Yu [p], J.C. Yun [p], A. Zanetti [bg], Y. Zeng [o], S. Zucchelli [f]

[a] *Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, ROC*
[b] *Argonne National Laboratory, Argonne, IL 60439, USA*
[c] *University of Athens, 157 71 Athens, Greece*
[d] *Baylor University, Waco, TX 76798, USA*
[e] *Istituto Nazionale di Fisica Nucleare, Bologna, Italy*
[f] *University of Bologna, I-40127 Bologna, Italy*
[g] *University of California, Davis, Davis, CA 95616, USA*
[h] *University of California, Los Angeles, Los Angeles, CA 90024, USA*
[i] *Instituto de Fisica de Cantabria, CSIC–University of Cantabria, 39005 Santander, Spain*
[j] *Carnegie Mellon University, Pittsburgh, PA 15213, USA*
[k] *Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[l] *Comenius University, 842 48 Bratislava, Slovakia*
[m] *Institute of Experimental Physics, 040 01 Kosice, Slovakia*
[n] *Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[o] *Duke University, Durham, NC 27708, USA*
[p] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[q] *University of Florida, Gainesville, FL 32611, USA*
[r] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[s] *University of Geneva, CH-1211 Geneva 4, Switzerland*
[t] *Glasgow University, Glasgow G12 8QQ, United Kingdom*
[u] *Harvard University, Cambridge, MA 02138, USA*
[v] *Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
[w] *University of Illinois, Urbana, IL 61801, USA*
[x] *The Johns Hopkins University, Baltimore, MD 21218, USA*
[y] *Center for High Energy Physics, Kyungpook National University, Daegu 702-701, Republic of Korea*
[z] *Seoul National University, Seoul 151-742, Republic of Korea*
[aa] *Sungkyunkwan University, Suwon 440-746, Republic of Korea*
[ab] *Korea Institute of Science and Technology Information, Daejeon 305-806, Republic of Korea*
[ac] *Chonnam National University, Gwangju 500-757, Republic of Korea*
[ad] *Chonbuk National University, Jeonju 561-756, Republic of Korea*
[ae] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[af] *University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[ag] *University College London, London WC1E 6BT, United Kingdom*
[ah] *Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
[ai] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[aj] *University of Michigan, Ann Arbor, MI 48109, USA*
[ak] *Michigan State University, East Lansing, MI 48824, USA*
[al] *Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
[am] *University of New Mexico, Albuquerque, NM 87131, USA*
[an] *Northwestern University, Evanston, IL 60208, USA*

[ao] The Ohio State University, Columbus, OH 43210, USA
[ap] Okayama University, Okayama 700-8530, Japan
[aq] Osaka City University, Osaka 588, Japan
[ar] University of Oxford, Oxford OX1 3RH, United Kingdom
[as] Istituto Nazionale di Fisica Nucleare, Sezione di Padova–Trento, Italy
[at] University of Padova, I-35131 Padova, Italy
[au] LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252, France
[av] Istituto Nazionale di Fisica Nucleare, Pisa, Italy
[aw] University of Pisa, Italy
[ax] University of Siena, Italy
[ay] Scuola Normale Superiore, I-56127 Pisa, Italy
[az] University of Pittsburgh, Pittsburgh, PA 15260, USA
[ba] Purdue University, West Lafayette, IN 47907, USA
[bb] University of Rochester, Rochester, NY 14627, USA
[bc] The Rockefeller University, New York, NY 10065, USA
[bd] Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, Italy
[be] Sapienza Università di Roma, I-00185 Roma, Italy
[bf] Rutgers University, Piscataway, NJ 08855, USA
[bg] Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, Italy
[bh] University of Udine, I-33100 Udine, Italy
[bi] University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[bj] Tufts University, Medford, MA 02155, USA
[bk] University of Virginia, Charlottesville, VA 22906, USA
[bl] Waseda University, Tokyo 169, Japan
[bm] Wayne State University, Detroit, MI 48201, USA
[bn] University of Wisconsin, Madison, WI 53706, USA
[bo] Yale University, New Haven, CT 06520, USA

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A B S T R A C T

We present one additional study of multi-muon events produced at the Fermilab Tevatron collider and recorded by the CDF II detector. We use a data set acquired with a dedicated dimuon trigger and corresponding to an integrated luminosity of 3.9 fb^{-1}. We investigate the distribution of the azimuthal angle between the two trigger muons in events containing at least four additional muon candidates to test the compatibility of these events with originating from known QCD processes. We find that this distribution is markedly different from what is expected from such QCD processes and this observation strongly disfavors the possibility that multi-muon events result from an underestimate of the rate of misidentified muons in ordinary QCD events.

This Letter reports on one additional test on the possible origin of multi-muon events observed at the Tevatron. These events were identified in a previous study [1] of a data set acquired with two central ($|\eta| < 0.7$) primary (or trigger) muons, each with transverse momentum $p_T \geqslant 3$ GeV/c, and with invariant mass larger than 5 GeV/c^2 and smaller than 80 GeV/c^2. That study shows that many long-standing inconsistencies between measured and predicted properties of the correlated $b\bar{b}$ production and semileptonic decay at hadron colliders [2–5] could be explained by the presence of a relevant source of muons which appear to be mostly produced beyond the beam pipe of radius 1.5 cm (this contribution is whimsically referred to as ghost events because they were unnoticed or ignored by previous measurements). Within the large uncertainty of the prediction, mostly based on simulations, the observed rate of ghost events is found to be consistent with being produced by muons arising from in-flight-decays of pions and kaons, or punchthrough of hadronic prongs from K_S^0 or hyperon decays. However, a search in ghost events for additional muons with $p_T \geqslant 2$ GeV/c and $|\eta| \leqslant 1.1$ and contained in a $\cos\theta \geqslant 0.8$ cone around the direction of a primary muon selects a small but significant fraction of events with a large content of muon candidates that appears difficult to account for in terms of known sources with the present understanding of the CDF II detector, trigger, and event reconstruction.

A more recent study by the CDF Collaboration [6] has improved the estimate of the contribution of ordinary sources to ghost events. This study addresses in particular the contribution from pion and kaon in-flight-decays. In 1426 pb^{-1} of data, there

* Corresponding author.
E-mail address: f.ptohos@ucy.ac.cy (F. Ptohos).
[1] Deceased.
[2] Visitor from University of MA Amherst, Amherst, MA 01003, USA.
[3] Visitor from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.
[4] Visitor from University of CA Irvine, Irvine, CA 92697, USA.
[5] Visitor from University of CA Santa Barbara, Santa Barbara, CA 93106, USA.
[6] Visitor from University of CA Santa Cruz, Santa Cruz, CA 95064, USA.
[7] Visitor from CERN, CH-1211 Geneva, Switzerland.
[8] Visitor from Cornell University, Ithaca, NY 14853, USA.
[9] Visitor from University of Cyprus, Nicosia CY-1678, Cyprus.
[10] Visitor from University College Dublin, Dublin 4, Ireland.
[11] Visitor from University of Fukui, Fukui City, Fukui Prefecture, 910-0017, Japan.
[12] Visitor from Universidad Iberoamericana, Mexico D.F., Mexico.
[13] Visitor from Iowa State University, Ames, IA 50011, USA.
[14] Visitor from University of Iowa, Iowa City, IA 52242, USA.
[15] Visitor from Kinki University, Higashi-Osaka City, 577-8502, Japan.
[16] Visitor from Kansas State University, Manhattan, KS 66506, USA.
[17] Visitor from University of Manchester, Manchester M13 9PL, United Kingdom.
[18] Visitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.
[19] Visitor from University of Melbourne, Victoria 3010, Australia.
[20] Visitor from Muons, Inc., Batavia, IL 60510, USA.
[21] Visitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.
[22] Visitor from National Research Nuclear University, Moscow, Russia.
[23] Visitor from University of Notre Dame, Notre Dame, IN 46556, USA.
[24] Visitor from Universidad de Oviedo, E-33007 Oviedo, Spain.
[25] Visitor from Texas Tech University, Lubbock, TX 79609, USA.
[26] Visitor from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.
[27] Visitor from Yarmouk University, Irbid 211-63, Jordan.
[28] On leave from J. Stefan Institute, Ljubljana, Slovenia.

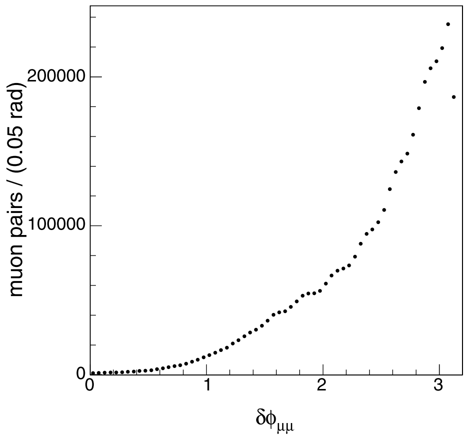

Fig. 1. Distribution of the azimuthal angle $\delta\phi$ between the two trigger muons for all events.

are $54\,437 \pm 14\,171$ ghost events and $12\,169 \pm 1319$ ghost events with three or more muons which cannot yet be accounted for with ordinary sources.

In this Letter, we investigate the distribution of the azimuthal angle ($\delta\phi$) between the two primary muons in events in which both primary muons are accompanied by at least one (or two) additional muon candidates in a $\cos\theta \geqslant 0.8$ cone around their direction, and compare it to those for all QCD sources known to produce dimuon events: $b\bar{b}$, $c\bar{c}$, and Υ production or events in which one trigger muon is due to hadrons misidentified as muons (cosmic rays are removed from the data sample and the contribution of secondary interactions in the detector volume is negligible [1]). As discussed in Ref. [1], known QCD sources produce a handful of events with four and none with six muon candidates. However, if the unaccounted multi-muon events were generated by a gross underestimate of the number of additional muons mimicked by hadrons in ordinary QCD events, the $\delta\phi$ distribution of primary muons in multi-muon events would be similar to that of ordinary QCD events in which the large contribution of next-to-leading order (NLO) terms due to initial and final state radiation results in a broader $\delta\phi$ distribution than that predicted by the Born (LO) approximation. In fact, the $\delta\phi$ distribution of pairs of b hadrons or jets is traditionally used to determine the relative contribution of NLO to LO terms [7]. This type of comparison was also suggested by Ref. [8], in which the excess of multi-muon events is modeled with the decay of two colorless particles produced through the exchange of a heavy object. In such a hypothetical case, their deviation from the back-to-back configuration in the azimuthal angle ($\delta\phi = \pi$) is only caused by initial state radiation of the incoming quarks and is expected to be small.

The study presented here uses a dimuon data set corresponding to an integrated luminosity of 3.9 fb^{-1} and selected with the same requirements used in Ref. [1]. High precision charged particle tracking is provided by a large central drift chamber surrounding a trio of silicon tracking devices composed of eight layers of silicon microstrip detectors ranging in radius from 1.5 to 28 cm in the pseudorapidity region $|\eta| < 1$ [9]. The tracking detectors are inside a 1.4 T solenoid which in turn is surrounded by electromagnetic and hadronic calorimeters. Outside the calorimeters, drift chambers in the region $|\eta| \leqslant 1.1$ provide muon identification. We search events for additional muons using tracks with $p_T \geqslant 2$ GeV/c and $|\eta| \leqslant 1.1$. The rate of additional muons mimicked by hadronic punchthrough is estimated with a probability per track derived by using kaons and pions from $D^{*\pm} \to \pi^\pm D^0$ with $D^0 \to K^+\pi^-$ decays [1,6,10]. The difference between observed additional muons and predicted misidentifications is referred to as real muons.

The $\delta\phi$ distribution for all 3.9 M events is shown in Fig. 1. Fig. 2 compares to the corresponding heavy flavor simulations the $\delta\phi$ distribution of trigger muons due to $b\bar{b}$ and $c\bar{c}$ production. This figure is reproduced from Ref. [10] that has measured $\sigma_{b\to\mu,\bar{b}\to\mu}$ and $\sigma_{c\to\mu,\bar{c}\to\mu}$ in a dimuon data set corresponding to a luminosity of 742 pb^{-1}. In the $b\bar{b}$ case, the distribution has an average of 2.5 with a rms deviation of 0.8 rad. The long and important tail extending to $\delta\phi = 0$ is due to NLO terms and the non-perturbative fragmentation function of b quarks. In $c\bar{c}$ events, because of the smaller quark mass, NLO terms are approximately a factor of three larger and the fragmentation function is much softer. Accordingly, the $\delta\phi$ distribution has a smaller average (2.4 rad) and a larger rms deviation (0.9 rad).

The azimuthal-angle distribution for primary muons produced by $\Upsilon(1S)$ decays is expected to be similar to those for heavy flavors because the final state contains a bleaching gluon recoiling against the Υ meson. This distribution, shown in Fig. 3, is constructed using muon pairs with invariant mass in the range 9.28–9.6 GeV/c^2. As in Ref. [10], the combinatorial background under the $\Upsilon(1S)$ signal is removed with a sideband subtraction technique. A similar $\delta\phi$ distribution is also expected for those cases in which one muon is mimicked by a track in the jet recoiling against a muon due to a heavy-quark semileptonic decay. Fig. 3 shows the $\delta\phi$ distribution of primary muons when one of them is mimicked by pions produced by K^0_S decays. As in

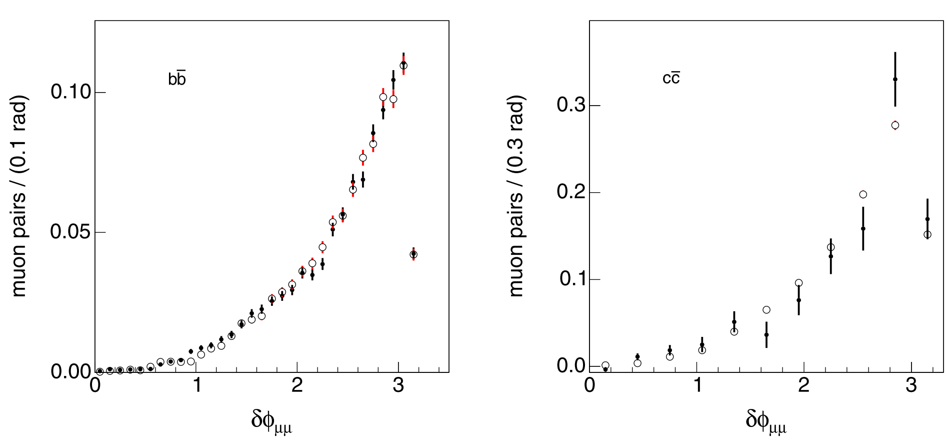

Fig. 2. The distributions (•) of the azimuthal angle $\delta\phi$ between trigger muons due to (left) $b\bar{b}$ and (right) $c\bar{c}$ production are compared to the corresponding heavy flavor simulations (◦). The distributions, reproduced from Ref. [10], are normalized to unit area.

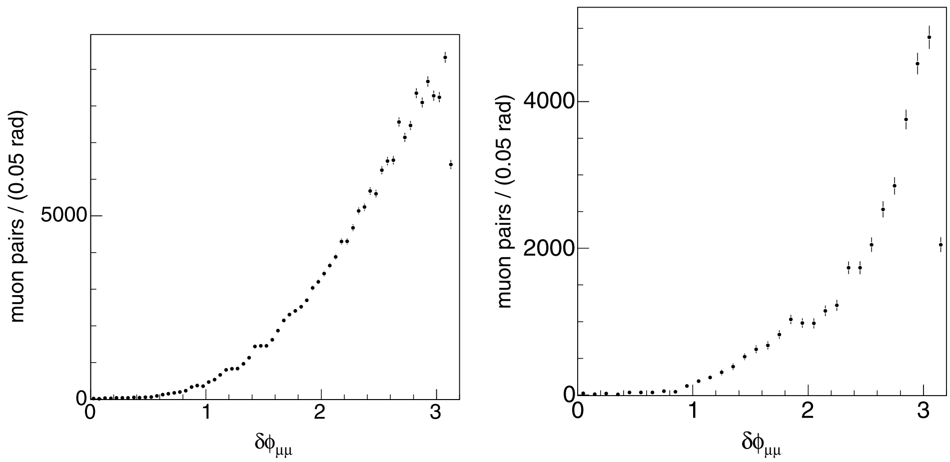

Fig. 3. Distribution of the azimuthal angle $\delta\phi$ between the two trigger muons produced by Υ decays (left) and for events (right) in which one primary muon is mimicked by a pion produced by an identified K^0_S decay. The combinatorial background underneath the Υ and K^0_S signals has been removed with a sideband subtraction method. The data correspond to an integrated luminosity of 3.9 fb^{-1}.

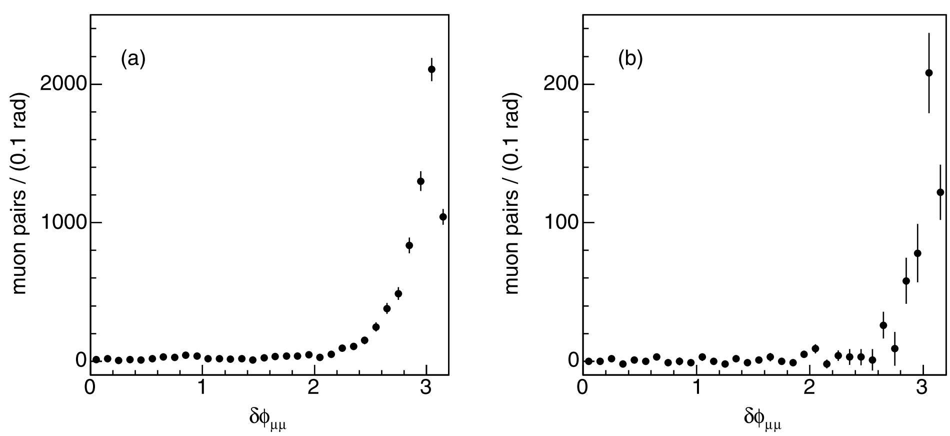

Fig. 4. Distribution of the azimuthal angle $\delta\phi$ between the two trigger muons accompanied by at least (a) one or (b) two additional real muons in a 36.8° cone around their direction.

Ref. [6], we select $K^0_S \to \pi^+\pi^-$ with a $\pi \to \mu$ misidentification by combining primary muons with tracks of opposite charge and $p_T \geqslant 0.5$ GeV/c. We select pairs consistent to those arising from a common three-dimensional vertex. We also take advantage of the K^0_S long lifetime to suppress the combinatorial background. We further require that the distance between the K^0_S vertex and the event primary vertex, corrected by the K^0_S Lorentz boost, corresponds to $ct > 0.1$ cm. We select K^0_S candidates with invariant mass in the range 0.47–0.52 GeV/c^2 (see Fig. 3 of Ref. [6]), and remove the combinatorial background with a sideband subtraction technique.

In summary, the $\delta\phi$ distributions of primary muons produced by known QCD processes peak at $\delta\phi \simeq \pi$, and exhibit a significant tail extending to $\delta\phi = 0$. Depending on the production mechanism, the mean and rms deviation of these distributions are in the range of 2.4–2.5 rad and 0.7–0.9 rad, respectively.

The $\delta\phi$ distributions in the subset of events in which each trigger muon is accompanied by at least one or at least two additional real muons are shown in Fig. 4. These $\delta\phi$ distributions, with mean of 2.9 rad and rms deviation of 0.2 rad and without any tail below $\delta\phi = 2.5$ rad, are different from those of primary muons due to all known QCD sources.

In conclusion, as mentioned earlier, within our present understanding of the CDF-detector response no known sources produce events in which each $\cos\theta \geqslant 0.8$ angular cone around a primary muon contains at least two additional real muons. Had the additional muons been produced by a subtle failure of our method to evaluate the fake-muon contribution, the resulting $\delta\phi$ distribution of primary muons would have been found consistent with those typical of ordinary QCD processes.

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