Evidence for the charmless annihilation decay mode $D^0_s \rightarrow \pi^+\pi^-$

T. Aaltonen,21 B. Álvarez Gonzálezz,9 S. Amerio,40 D. Amidei,32 A. Anastassovv,15 A. Annovi,17 J. Antos,12 G. Apollinari,15 J.A. Appel,15 T. Arisawa,54 A. Artikov,13 J. Asaadi,19 W. Ashmanskas,15 B. Auerbach,57 A. Aurisano,49 F. Azfar,39 W. Badgett,15 T. Bae,25 A. Barbaro-Galtieri,26 V.E. Barnes,44 B.A. Barnett,23 P. Barria,42 P. Bartos,12 M. Bause,40 F. Bedeschi,42 S. Behari,23 G. Bellettini,42 J. Bellinger,56 D. Benjamín,14 A. Beretvas,15 A. Bhatti,46 D. Bisello,40 I. Bizjak,28 K.R. Bland,5 B. Blumenfeld,23 A. Bocci,14 A. Bodek,45 D. Bortoletto,44 J. Boudreau,43 A. Boveia,11 L. Brigliadoric,6 C. Bromberg,33 E. Brucken,21 J. Budagov,13 H.S. Budd,45 K. Burkett,15 G. Busetto,40 P. Bussey,19 A. Buzatu,31 A. Calabara,10 C. Calancha,29 S. Camarda,4 M. Campanelli,28 M. Campbell,32 F. Canelli,11,15 B. Carlh,22 D. Carlsmit,56 R. Carosi,42 S. Carrillo,16 S. Carron,15 B. Casal,9 M. Casarosa,50 A. Castro,6,6 P. Catastini,20 D. Cauz,50 V. Cavaliere,22 M. Cavalli-Sforza,4 A. Cerri,26 L. Cerrito,29 Y.C. Chen,1 M. Chertok,7 G. Chiarelli,42 G. Chiaudichic,15 F. Chlebana,15 K. Cho,25 D. Chokheli,13 W.H. Chun,56 Y.S. Chung,45 M.A. Ciocci/2,42 A. Clark,18 C. Clarke,55 G. Compostellad,40 M.E. Convery,15 J. Conway,7 M. Corbo,15 M. Cordelli,17 C.A. Cox,7 D.J. Cox,4 F. Crescioli,42 J. Cuevas,9 R. Culbertson,15 D. Dagenhart,15 N. d’Ascenzo,15 M. Datta,15 P. de Barbaro,45 M. Dell’Orso,42 L. Demortier,46 M. Deninno,6 F. Devoto,21 M. Di Canto,42 B. Di Ruza,15 J.R. Dittman,5 M. D’Onorio,27 S. Donati,42 P. Dong,15 M. Dorigo,10 K. Ebina,54 A. Eplig,49 A. Erp,32 R. Ebracher,7 S. Errede,22 N. Ershaidat66 R. Eusebi,49 S. Farrington,39 M. Feindt,24 J.P. Fernandez,29 R. Field,16 G. Flanagan,15 R. Forrest,7 M.J. Frank,5 M. Franklin,20 J.C. Freeman,15 Y. Funakoshi,54 I. Furic,16 M. Gallinaro,46 J.E. Garcia,18 A.F. Garfinkel,44 P. Garosi/2,42 H. Gerberich,29 E. Gerchtein,15 V. Giakoumopoulou,3 P. Giannetti,42 K. Gibson,43 C.M. Ginsburg,15 N. Giokaris,3 P. Giorni,17 G. Giurgi,23 V. Glagolev,13 D. Glaenkz,15 M. Gold,35 D. Goldin,9 N. Goldschmidt,16 A. Golossanov,15 G. Gomez,9 G. Gomez-Cabellos,30 M. Goncharov,30 O. González,29 I. Gorelov,35 A.T. Goshaw,14 K. Goulianos,46 S. Grinstein,4 C. Grosso-Pilcher,11 R.C. Group,53,15 J. Guimarães da Costa,20 S.R. Hahn,15 E. Halkiadakis,48 A. Hanaguchi,38 J.Y. Han,45 F. Happpacher,17 K. Hara,51 D. Hare,48 M. Hare,52 R.F. Harr,55 K. Hatakeyama,5 C. Hays,39 M. Heck,24 J. Heinrich,41 M. Herndon,56 S. Hewamanage,5 A. Hocker,15 W. Hopkins/2,15 D. Horn,24 S. Hou,4 R.E. Hughes,36 M. Hurwitz,11 U. Husemann,57 N. Hussain,31 M. Hussein,33 J. Huston,33 G. Intrizio,42 M. Iorbb,17 A. Ivanov,9 E. James,15 D. Jang,10 B. Jayatilaka,14 E.J. Jeon,25 S. Jindariani,15 M. Jones,44 K.K. Joo,25 S.Y. Jun,10 T.R. Junk,15 T. Kamon,25,49 P.E. Karchin,55 A. Kasi,5 Y. Kato/3,38 W. Ketchum,11 J. Keung,41 V. Khotilovich,49 B. Kilminster,15 D.H. Kim,25 H.S. Kim,25 J.E. Kim,25 M.J. Kim,17 S.B. Kim,25 S.H. Kim,51 Y.K. Kim,11 Y.J. Kim,25 N. Kimura,54 M. Kirby,15 S. Klimenko,16 K. Knoepfl,15 K. Kondo,54 D.J. Konc,25 J. Konigsberg,16 A.V. Kotwal,14 M. Kroes,24 J. Kroll,41 D. Krop,11 M. Kruse,14 V. Krutelyov,49 T. Kuhr,24 M. Murata,15 S. Kwang,11 A.T. Laasanen,44 S. Lami,42 S. Lambel,15 M. Lancaster,28 R.L. Lauder,7 K. Lawman,36 A. Lath,48 G. Latino,42 T. LeCo UPte,2 E. Lee,49 H.S. Lee,53 J.S. Lee,25 S.W. Lee,49 S. Lee,42 S. Leone,42 J.D. Lewis,15 A. Limosani,14 C.-J. Lin,26 M. Lindgren,15 E. Lipace,41 A. Lister,18 D.O. Litvinvse,15 C. Liu,43 H. Lii,53 Q. Liu,44 T. Liu,15 S. Lockwitz,57 A. Logvinov,12 D. Lucchese/2,40 J. Lueck,24 P. Lukjan,26 P. Lukens,15 G. Lung,46 J. Lys,26 R. Lyons,12 R. Madrak,15 K. Maeshima,15 P. Maestro,42 S. Malik,46 G. Manca,47 A. Manousakis-Katsikias,3 F. Margaroli,47 C. Marino,24 M. Martínez,4 P. Mastandrea,47 K. Matera,22 M.E. Mattson,35 A. Mazzacone,15 P. Mazzanti,9 K.S. McFarland,45 P. McIntyre,49 R. McNulty,27 A. Mehta,27 P. Mehtala,21 C. Mesropian,46 T. Miao,15 D. Mietlicki,32 A. Mitra,1 H. Miyake,51 S. Moed,15 N. Moggi,6 M.N. Mondragon,15 C.S. Moon,25 R. Moore,15 M.J. Morel,42 J. Morlok,24 M. Movila Fernandez,15 A. Mukherjee,15 Th. Muller,24 P. Murat,15 M. Mussini,26 J. Nachtman,51 Y. Nagai,51 J. Nagarona,54 I. Nakano,37 A. Napier,52 J. Net,49 C. Neu,53 M.S. Neubauer,22 J. Nielsen,26 L. Nodulman,26 S.Y. Noh,39 O. Norniella,21 L. Oakes,39 S.H. Oh,14 Y.D. Oh,25 I. Oksuzian,35 T. Okusawa,38 R. Orava,21 L. Ortolan,4 S. Pagan Griso,44 C. Pagliarone,50 E. Palenciac,9 V. Papadimitriou,15 A.A. Paramonov,2 J. Patrick,15 G. Pauletti,50 M. Paulini,10 C. Paus,30 D.E. Pellett,7 A. Penzo,50 T.J. Phillips,14 G. Piacentino,42 E. Pianori,41 J. Pilot,36 K. Pitts,22 C. Plager,8 L. Pondrom,56 S. Poprockif,15 K. Potamianos,44 F. Prokoshev,13 A. Pranko,26 F. Ptohos,17 G. Punzi,42 A. Rahaman,43 V. Ramakrishnan,56 N. Ranjan,44 I. Redono,29 P. Renton,49 M. Rescigno,47 T. Riddick,28 F. Rimondi,7 L. Ristori,42 A. Robson,49 T. Rodrigo,9 T. Rodriguez,41 E. Rogers,22 S. Rolli,42 R. Roser,15 F. Ruffinif,42 A. Ruiz,9 J. Russ,10 V. Rusi,15 A. Safonov,49 W.K. Sakamoto,45 Y. Sakurai,54 L. Santi,50 K. Sato,51 V. Saveliev,15 A. Savoldo,15 P. Schlabach,15 A. Schmidt,24 E.E. Schmidt,15 T. Schwarz,15 L. Scodellaro,9 A. Scribano,42 F. Scuri,42 S. Seidl,35 Y. Seiya,38 A. Semenov,13 F. Sforza,42 S.Z. Shalhout,7
T. Shears,27 P.F. Shepard,43 M. Shimojima4,51 M. Shochet,11 I. Shreyber-Tecker,34 A. Simonenko,13 P. Sinervo,31 K. Sliwa,52 J.R. Smith,7 F.D. Snider,15 A. Soha,15 V. Sorin,4 H. Song,43 P. Squillacioti12,42 M. Stancari,15 R. St. Denis,19 B. Stelzer,31 O. Stelzer-Chilton,31 D. Stentz,15 J. Strologas,35 G.L. Styrerker,32 Y. Sudo,51 A. Sukhanov,15 I. Suslov,13 K. Takemasa,51 Y. Takeuchi,51 J. Tang,11 M. Tecchio,32 P.K. Teng,1 J. Thom,15 J. Thome,10 G.A. Thompson,22 E. Thomson,41 D. Toback,49 S. Tokar,12 K. Tollefson,33 T. Tomura,51 D. Tonelli,15 S. Torre,17 D. Torretta,15 B.L. Winer,36

Institut de Fisica d'Altes Energies, ICREA, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain

A. Sukhanov,15 K. Sliwa, R. St. Denis, D. Whiteson

G. Velev,12 k T. Yoshida

Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia

D. Torretta,15 B.L. Winer,36

Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany

G.A. Thompson, P.F. Shepard,36

17 Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00014 Frascati, Italy

18 University of Geneva, CH-1211 Geneva 4, Switzerland

19 Glasgow University, Glasgow G12 8QQ, United Kingdom

20 Harvard University, Cambridge, Massachusetts 02138, USA

21 Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland

22 University of Illinois, Urbana, Illinois 61801, USA

23 The Johns Hopkins University, Baltimore, Maryland 21218, USA

24 Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany

25 Center for High Energy Physics: Kyungpook National University, Daegu 702-701, Korea; Seoul National University, Seoul 151-742, Korea; Sungkyunkwan University, Suwon 440-746, Korea; Korea Institute of Science and Technology Information, Daejeon 305-806, Korea; Chonnam National University, Gwangju 500-757, Korea; Chonbuk National University, Jeonju 561-756, Korea

26 Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

27 University of Liverpool, Liverpool L69 7ZE, United Kingdom

28 University College London, London WC1E 6BT, United Kingdom

29 Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, E-28040 Madrid, Spain

30 Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

31 Institute of Particle Physics: McGill University, Montréal, Québec, Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6; University of Toronto, Toronto, Ontario, Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3

32 University of Michigan, Ann Arbor, Michigan 48109, USA

33 Michigan State University, East Lansing, Michigan 48824, USA

34 Foundation for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia

35 University of New Mexico, Albuquerque, New Mexico 87131, USA

36 The Ohio State University, Columbus, Ohio 43210, USA

37 Okayama University, Okayama 700-8530, Japan

38 Osaka City University, Osaka 558, Japan

(CDF Collaboration)
We search for annihilation decay modes of neutral $b$ mesons into pairs of charmless charged hadrons with the upgraded Collider Detector at the Fermilab Tevatron. Using a data sample corresponding to 6 fb$^{-1}$ of integrated luminosity, we obtain the first evidence for the $B^0 \rightarrow \pi^+\pi^-$ decay, with a significance of $3.7\sigma$, and a measured branching ratio $B(B^0 \rightarrow \pi^+\pi^-) = (0.57 \pm 0.15 (\text{stat}) \pm 0.10 (\text{syst})) \times 10^{-6}$. A search for the $B^0 \rightarrow K^+K^-$ mode in the same sample yields a significance of $2.0\sigma$, and a central value estimate $B(B^0 \rightarrow K^+K^-) = (0.23 \pm 0.10 (\text{stat}) \pm 0.10 (\text{syst})) \times 10^{-6}$.

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Our understanding of the dynamics of hadrons containing heavy quarks has made great progress in recent years. The development of effective theories has allowed increasingly accurate predictions for the partial decay widths of such hadrons. An ability to make accurate predictions for these processes is not only important in itself, but is a tool to uncover possible additional contributions due to interactions beyond the standard model. In spite of the general progress of the field, a specific class of decay amplitudes (annihilation topologies) has resisted attempts at quantitative prediction up to the present, and is often simply neglected in calculations. Predictions for these amplitudes vary greatly between approaches, and even within the same approach. Estimates based on the QCD factorization (QCDF) approach are affected by significant uncertainties, due to end-point singularities [1, 2]. More recent perturbative QCD calculations (pQCD) provide more precise predictions, but they tend to be significantly larger than the predictions coming from QCDF [3, 4]. No calculations are yet available within the soft collinear effective theory (SCET) [5]. The lack of knowledge of the size of annihilation-type amplitudes introduces irreducible uncertainties in the predictions for several decays of great interest in the search for new physics effects, such as $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$ [3, 5]. Experimental investigation of the issue is therefore very desirable, and has the potential to enable a significant advancement of the field. The $B_s \rightarrow \pi^+\pi^-$ and $B^0 \rightarrow K^+K^-$ decay modes are ideal for this investigation, because all quarks...
in the final state are different from those in the initial state, so they can be mediated solely by amplitudes with penguin-annihilation (PA) and W-exchange (E) topologies (see Fig. 1). However, they have not yet been observed, the best upper limits at 90% CL being respectively $1.2 \times 10^{-6}$ and $0.41 \times 10^{-6}$. A simultaneous measurement of branching fractions of both modes would be especially useful, as it would allow a better constraint on the strength of PA and E amplitudes.

In this Letter we report the results of a simultaneous search for the two decays $B_s^0 \rightarrow \pi^+\pi^-$ and $B^0 \rightarrow K^+K^-$ [12], using data corresponding to 6 fb$^{-1}$ integrated luminosity of $pp$ collisions at $\sqrt{s} = 1.96$ TeV, collected by the upgraded Collider Detector (CDF II) at the Fermilab Tevatron.

The CDF II detector is described in detail in Ref. [13] with the detector subsystems relevant for this analysis discussed in Ref. [14]. The data are collected by a three-level online event-selection system (trigger). At level 1, tracks are reconstructed in the transverse plane [13].

Two opposite-charge particles are required, with reconstructed transverse momenta $p_{T1}, p_{T2} > 2$ GeV/c, the scalar sum $p_{T1} + p_{T2} > 5.5$ GeV/c, and an azimuthal opening angle $\Delta \phi < 135^\circ$. At level 2, tracks are combined with silicon-tracking-detector hits and their impact parameter $d$ (transverse distance of closest approach to the beam line) is determined with 45 $\mu$m resolution (including the beam spread) and required to be $0.1 < d < 1.0$ mm. A tighter opening-angle requirement, $20^\circ < \Delta \phi < 135^\circ$, is also applied. Each track pair is then used to form a $B$ candidate, which is required to have an impact parameter $d_B < 140$ $\mu$m and to have traveled a distance $L_T > 200$ $\mu$m in the transverse plane. At level 3, a cluster of computers confirms the selection with a full event reconstruction.

The offline selection is based on a more accurate determination of the same quantities used in the trigger, with the addition of two further observables: the isolation ($I_B$) of the $B$ candidate [10], and the quality of the three-dimensional fit ($\chi^2$ with 1$^\circ$ degree of freedom) of the decay vertex of the $B$ candidate. Requiring isolated candidates further reduces the background from light-quark jets, and a low $\chi^2$ reduces the background from decays of different long-lived particles within the event, owing to the good resolution of the silicon-tracking detector in the $z$ direction. We use the same final selection originally devised for the $B_s^0 \rightarrow K^-\pi^+$ search [10], whose simulation has proven to be nearly optimal also for detection of $B^0 \rightarrow \pi^+\pi^-$. This includes the following criteria: $I_B > 0.525$, $\chi^2 < 5$, $d > 120$ $\mu$m, $d_B < 60$ $\mu$m, and $L_T > 350$ $\mu$m.

At most one $B$ candidate per event is found after this selection, and a mass ($m_{\pi^+\pi^-}$) is assigned to each, using a charged pion mass assignment for both decay products. The resulting mass distribution is shown in Fig. 2, and is dominated by the overlapping contributions of the $B^0 \rightarrow K^+\pi^-$, $B^0 \rightarrow \pi^+\pi^-$, and $B_s^0 \rightarrow K^+K^-$ modes [14, 17], with backgrounds coming from misreconstructed multibody $b$–hadron decays (physics background) and random pairs of charged particles (combinatorial background). A $B^0 \rightarrow K^+K^-$ signal would appear in this distribution as an enhancement around 5.18 GeV/c$^2$, while a $B^0 \rightarrow \pi^+\pi^-$ signal is expected at the nominal $B^0$ mass of 5.3663 GeV/c$^2$, where other more abundant modes also contribute [10].

We used an extended unbinned likelihood fit, incorporating kinematic (kin) and particle-identification (PID) information, to determine the fraction of each individual mode in the sample. The likelihood is defined as

$$L = \frac{N}{N^0 \nu} \cdot \prod_{i=1}^{N} \mathcal{L}_i$$

where $N$ is the total number of observed candidates, $\nu$ is the estimator of $N$ to be determined by the fit, and the likelihood for the $i$th event is

$$\mathcal{L}_i = (1 - b) \sum_j f_j \mathcal{L}_{j}^{\text{kin}} \mathcal{L}_{j}^{\text{PID}} + b \left( f_p \mathcal{L}_{p}^{\text{kin}} \mathcal{L}_{p}^{\text{PID}} + (1 - f_p) \mathcal{L}_{c}^{\text{kin}} \mathcal{L}_{c}^{\text{PID}} \right),$$

where the index $j$ runs over all signal modes, and the index ‘p’ (‘c’) labels the physics (combinatorial) background terms. The $f_j$ are the signal fractions to be determined by the fit, together with the background fraction parameters $b$ and $f_p$.

For each charged hadron pair, the kinematic information is summarized by three loosely correlated observables: the squared mass $m_{\pi^+\pi^-}^2$; the charged momentum asymmetry $\beta = (p_+ - p_-)/(p_+ + p_-)$, where $p_+$ ($p_-$) is the momentum of the positive (negative) particle; and the scalar sum of particle momenta $p_{\text{tot}} = p_+ + p_-$. The above variables allow evaluation of the squared invariant mass $m_{a+b}^2$ of a candidate for any mass assignment of the positive and negative decay products ($m_{a+}$,$m_{b-}$), using the equation

$$m_{a+b}^2 = m_{a+b}^2 - m_{a+}^2 - m_{a-}^2 + m_{b+}^2 + m_{b-}^2 + 2\sqrt{p_{a+}^2 + 2m_{a+}^2 + p_{a-}^2 + 2m_{a-}^2 + p_{b+}^2 + 2m_{b+}^2} \times \left(p_{a+} + p_{a-} - p_{b+} \right),$$

where $p_+ = p_{\text{tot}}^{1+\beta/2}$, $p_- = p_{\text{tot}}^{1-\beta}$. 

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**FIG. 1:** PA (left panel) and E (right panel) diagrams contributing to $B^0 \rightarrow K^+K^-$ and $B_s^0 \rightarrow \pi^+\pi^-$ decays.
The solution, while ARGUS function \[19\] convoluted with a Gaussian resolv- ing detail. Momentum dependence and non–Gaussian distributions assigned to each signal have been modeled in the vicinity of larger peaks, the shapes of the mass of the fit and its parameters can be found in Ref. \[18, 20\].

The same distributions for the combinatorial background L\(\text{ing}\) from a common vertex. The likelihood term cut except for vertex quality, replaced by an antiselection containing events passing all requirements of final selections an enriched sample of two generic random tracks, con-

| Mode | \(N_i\) | Significance |
|------|--------|-------------|
| \(B^0 \rightarrow K^+K^-\) | 120 ± 49 ± 42 | 2.8σ |
| \(B^0 \rightarrow \pi^+\pi^-\) | 94 ± 28 ± 11 | 3.7σ |

The likelihood terms \(L^{\text{kin}}_j\) describe the kinematic distributions of \(m^2_{\pi^+\pi^-}\), \(\beta\), and \(p_{\text{tot}}\) variables for the physics signals and are obtained from Monte Carlo simulations. The same distributions for the combinatorial background are instead extracted from real data \[18\], and are inserted into the likelihood through the \(L^{\text{kin}}_j\) term. In particular, the squared-mass distribution of the combinatorial background is parametrized by an exponential function. The slope is fixed in the fit to the value extracted from an enriched sample of two generic random tracks, containing events passing all requirements of final selections except for vertex quality, replaced by an antiselection cut \(\chi^2 > 40\), which strongly rejects track pairs originating from a common vertex. The likelihood term \(L^{\text{kin}}_p\) describes the kinematic distributions of the background from partially reconstructed decays of generic \(B\) hadrons. The \(m^2_{\pi^+\pi^-}\) distribution is, in this case, modeled by an ARGUS function \[19\] convoluted with a Gaussian resolution, while \(\beta\) and \(p_{\text{tot}}\) distributions are obtained from Monte Carlo simulation.

The fit has 28 free parameters. A detailed description of the fit and its parameters can be found in Ref. \[18, 20\].

To ensure the reliability of the search for small signals in the vicinity of larger peaks, the shapes of the mass distributions assigned to each signal have been modeled in detail. Momentum dependence and non–Gaussian resolution tails are accounted for by a full simulation of the detector, while the effects of soft photon radiation in the final state are simulated by PHOTOS \[21\]. This resolution model was accurately checked against the observed shape of the \(3.2 \times 10^6 \ D^0 \rightarrow K^-\pi^+\) and \(140 \times 10^3 \ D^0 \rightarrow \pi^+\pi^-\) signals in a sample of \(D^{*+} \rightarrow D^0\pi^+\) decays, collected with a similar trigger selection. As a result, the systematic uncertainty related to the signal mass shapes is negligible with respect to other uncertainties.

The \(D^{*+} \rightarrow D^0\pi^+\) sample was also used to calibrate the \(dE/dx\) response of the drift chamber to kaons and pions, using the charge of the \(D^{*+}\) to identify the \(D^0\) decay products. The \(dE/dx\) response of protons was determined from a sample of about 167,000 \(\Lambda \rightarrow p\pi^-\) decays, where the kinematic properties and the momentum threshold of the trigger allow unambiguous identiﬁcation of the decay products \[20\]. PID information is summarized by a single observable \(\kappa\), defined as:

\[
\kappa \equiv \frac{dE/dx - dE/dx(\pi)}{dE/dx(K) - dE/dx(\pi)}
\]

where \(dE/dx(\pi)\) and \(dE/dx(K)\) are the expected \(dE/dx\) depositions for those particle assignments. The average values of \(\kappa\) expected for pions and kaons are by construction 0 and 1. Statistical separation between kaons and pions is about 1.4σ, while the ionization rates of protons and kaons are quite similar in the momentum range of interest. The PID likelihood term, which is similar for physics signals and backgrounds, depends only on \(\kappa\) and on its expectation value \(\langle \kappa \rangle\) (given a mass hypothesis) of the decay products. In particular the physics signals model is described by the likelihood term \(L^{\text{PID}}_j\), where the index \(j\) uniquely identiﬁes the final state, while the background model is described by the two terms \(L^{\text{PID}}_p\) and \(L^{\text{PID}}_c\), respectively for the physics and combinatorial background, that account for all possible pairs that can be formed combining only pions and kaons. In fact muons are indistinguishable from pions with the available \(dE/dx\) resolution, and are therefore included within the nominal pion component. For similar reasons, the small proton component in the background has been included within the nominal kaon component. Thus the physics background model allows for independent, charge-averaged contributions of pions and kaons, whose fractions are determined by the fit; while the combinatorial background model, instead, allows for more contributions, since independent fractions of positively and negatively charged pions and kaons are determined by the fit.

The signal fractions returned by the fit are in agreement with those obtained in the previous iteration of this analysis \[10\]. The yields for the \(B^0 \rightarrow \pi^+\pi^-\) and \(B^0 \rightarrow K^+K^-\) modes, obtained from those fractions, are shown in Table 1. The significance is evaluated as the ratio of the yield observed in data to its total uncertainty (statistical and systematic uncertainties added in
that are measured from data: the momentum-averaged
erelative isolation efficiency between $B^0_s$ and $B^0$, and
the difference in efficiency for triggering on kaons and pions
due to the different specific ionization in the drift cham-
er. The former is determined as $1.00 \pm 0.03$ from fully-
reconstructed samples of $B^0_s \rightarrow J/\psi \phi$, and $B^0 \rightarrow J/\psi K^{*0}$
decays \cite{20}. The latter is determined from samples of
$D^0$ mesons decaying into pairs of charged hadrons \cite{18}.
We measure the relative branching fractions $B(D^0 \rightarrow$
$\pi^+ \pi^-)/B(D^0 \rightarrow K^- \pi^0)$ and $B(D^0 \rightarrow K^+ K^-)/B(D^0 \rightarrow$
$K^- \pi^+)$). The numbers of events are extracted from the
available samples of tagged $D^0 \rightarrow \pi^+ \pi^-$, $D^0 \rightarrow K^- \pi^+$
and $D^0 \rightarrow K^+ K^-$ decays, fitting the invariant $D^* \pi$
mass spectrum \cite{18}, while reconstruction efficiencies are
determined from the same simulation used for the mea-
surements described in this Letter. Comparison of these
numbers with world measurement averages \cite{23} allows us
to extract the correction needed to compensate for the
different efficiency of the tracking trigger for kaons and
pions. The final corrections applied to our result do not
exceed 5% and are independent of particle momentum.

The dominant contribution to the systematic uncer-
tainty on both branching fractions is due to the $dE/dx$
model, which derives from the statistical uncertainty on
the 48 parameters used for the analytical description of
the correlated $dE/dx$ response of the two decay prod-
ts \cite{20}. This uncertainty is evaluated by repeating the
likelihood fit 200 times with different sets of those pa-
rameters, randomly extracted from a multidimensional
sphere, centered on the central value of the parametriza-
tion, with a radius corresponding to $1\sigma$ of statistical un-
certainty. The correlations between the parameters are
neglected because their total effect, known from Ref. \cite{24},
where they have been accounted for in detail, brings a re-
duction of the final systematic uncertainty because most
correlations are negative. The $dE/dx$-induced systematic uncertainty on each observable is then obtained as the
standard deviation of the distribution of that observable,
over the ensemble of likelihood fits performed with dif-
ferent sets of parameters. This approach is adequate for
our purposes since the statistical uncertainty is greater
than or of the same order of the systematic uncertainty.

The second dominant contribution to the systematic uncer-
tainty for $B^0_s \rightarrow \pi^+ \pi^-$ comes from the uncer-
tainty on the relative efficiency correction, while for $B^0 \rightarrow$
$K^+ K^-$ it comes from the uncertainty in the background
model, which includes a sizeable component of partially
reconstructed decays with poorly known branching frac-
tions. The latter systematic uncertainty is conservatively
assessed by performing extreme variations of the assumed
relative contributions of the various modes in the simul-
ation; the resulting uncertainty is still a factor of 2 lower
than the uncertainty associated to the $dE/dx$ model.

Other contributions come from trigger efficiencies, $b$-
hadron masses, $b$-hadron lifetimes and $\Delta \Gamma_s/\Gamma_s$, and
transverse momentum distribution of the $A^0_0$ baryon. A

![FIG. 3: Distribution of the relative signal likelihood, $L_s/(L_s + L_{other})$, in the region $5.25 < m_{\pi^+\pi^-} < 5.50$ GeV/c$^2$
for $B^0_s \rightarrow \pi^+ \pi^-$ and $5.10 < m_{\pi^+\pi^-} < 5.35$ GeV/c$^2$
for $B^0 \rightarrow K^+ K^-$. For each event, $L_s$ is the likelihood for the
$B^0_s \rightarrow \pi^+ \pi^-$ (top panel) and $B^0 \rightarrow K^+ K^-$ (bottom
panel) signal hypotheses, and $L_{other}$ is the likelihood for every-
thing but the chosen signal, i.e., the weighted combination
of all other components according to their measured fractions.
Points with error bars show the distributions of data and his-
tograms show the distributions predicted from the measured
fractions. Zoom of the region of interest is shown in the inset.

$\frac{d\sigma}{dx}$, where the statistical uncertainty is deter-
mined from a simulation where the size of that signal is
set to zero. This evaluation assumes a Gaussian distribu-
tion of yield estimates, supported by the results obtained
from repeated fits to simulated samples. This procedure
yields a more accurate measure of significance than the
purely statistical estimate obtained from $\sqrt{-2\Delta \ln(L)}$.

We obtain a $3.7\sigma$ significant signal for the $B^0_s \rightarrow 
\pi^+\pi^-$ mode, and we observe an excess at the $2.0\sigma$
level for the $B^0 \rightarrow K^+ K^-$ mode. As a check on the method, Fig. 3
shows relative likelihood distributions for these modes,
which are in good agreement with our model.

As a further check an alternate fit was performed, using
kinematic information only. Removal of $dE/dx$ informa-
tion leads to results in agreement with the main fit, but
with a loss in resolution of a factor 2 for $B^0_s \rightarrow \pi^+\pi^-$
and 3 for $B^0 \rightarrow K^+ K^-$, confirming the importance of
this information.

To avoid large uncertainties associated with produc-
tion cross sections and absolute reconstruction effici-
cy, we measure all branching fractions relative to the $B^0 \rightarrow
K^+ \pi^-$ mode. A frequentist limit \cite{22} at the 90% C.L.
is quoted for the $B^0 \rightarrow K^+ K^-$ mode. The raw frac-
tions returned by the fit are corrected for the differences
in selection efficiencies among different modes, which do
not exceed 10%. These corrections are determined from
detailed detector simulation, with only two exceptions
In summary, we have searched in CDF data for as-yet-unmeasured charmless decay modes of neutral $B$ mesons into pairs of charged mesons. We report an updated upper limit for the $B^0 \rightarrow K^+ K^-$ mode, which is somewhat unexpected for instance in agreement with predictions obtained with the pQCD approach [3, 4], but it is higher than most other theoretical predictions [1, 2, 26]. The central value for $B(B^0 \rightarrow K^+ K^-)$ is the most precise determination of this quantity to date, and is in agreement with previous experimental results [11, 26] and theoretical predictions [1, 2]. It supersedes the previous CDF limit [10], based on a subsample of the current data. The present measurements represent a significant step in reducing a source of uncertainty in many theoretical predictions for charmless $B$-decays. The results favor a large annihilation scenario, which is somewhat unexpected for instance in QCD [27].

In summary, we have searched in CDF data for as-yet-unmeasured charmless decay modes of neutral $B$ mesons into pairs of charged mesons. We report an updated upper limit for the $B^0 \rightarrow K^+ K^-$ mode, and the first evidence for the $B_s^0 \rightarrow \pi^+ \pi^-$ mode and a measurement of its branching fraction.

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### Table II: Measured relative branching fractions of rare modes.

| Mode                  | Relative $\mathcal{B}$ | Absolute $\mathcal{B} (10^{-6})$ | Limit (10^{-6}) |
|-----------------------|------------------------|----------------------------------|-----------------|
| $B^0 \rightarrow K^+ K^-$ | $B(B^0 \rightarrow K^+ K^-)$ = 0.012 ± 0.005 ± 0.005 | 0.23 ± 0.10 ± 0.10 | [0.05, 0.46] at 90% C.L. |
| $B_s^0 \rightarrow \pi^+ \pi^-$ | $f(B_s^0 \rightarrow \pi^+ \pi^-)$ = 0.008 ± 0.002 ± 0.001 | 0.57 ± 0.15 ± 0.10 | – |

Further systematic uncertainty of the order of 10% is included for the $B^0 \rightarrow K^+ K^-$ mode to account for a small bias of the fitting procedure observed in simulated samples.

The final results are listed in Table II. Absolute branching fractions are also quoted, by normalizing to world-average values of production fractions and $B(B^0 \rightarrow K^+ K^-)$ [23]. The branching fraction measured for the $B_s^0 \rightarrow \pi^+ \pi^-$ mode is consistent with and supersedes the previous upper limit ($< 1.2 \times 10^{-6}$ at 90% C.L.), based on a subsample of the current data [10]. It is in agreement with predictions obtained with the pQCD approach [3, 4], but it is higher than most other theoretical predictions [1, 2, 26]. The central value for $B(B^0 \rightarrow K^+ K^-)$ is the most precise determination of this quantity to date, and is in agreement with previous experimental results [11, 26] and theoretical predictions [1, 2]. It supersedes the previous CDF limit [10], based on a subsample of the current data. The present measurements represent a significant step in reducing a source of uncertainty in many theoretical predictions for charmless $B$-decays. The results favor a large annihilation scenario, which is somewhat unexpected for instance in QCD [27].

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[16] Isolation is defined as $I_B = p_T(B)/[p_T(B) + \sum_i p_{T_i}]$, where $p_T(B)$ is the transverse momentum of the $B$ candidate, and the sum runs over all other tracks within a cone of radius 1, in $\eta$-$\phi$ space around the $B$ flight-direction.

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