Physics

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Measurement of the ratios of branching fractions B (B-s(0)-> D-s(-) pi(+) pi(+) pi(-))/B(B-0 -> D- pi(+) pi(+) pi(-)) and B(B-s(0) -> D-s(-) pi(+))/B(B-0 -> D- pi(+))

A. Abulencia, J. Adelman, T. Affolder, T. Akimoto, M. G. Albrow, D. Ambrose, S. Amerio, D. Amidei, A. Anastassov, K. Anikeev, A. Annovi, J. Antos, M. Aoki, G. Apollinari, J. F. Arguin, T. Arisawa, A. Artikov, W. Ashmanskas, A. Attal, F. Azfar, P. Azzi-Bacchetta, P. Azzurri, N. Bacchetta, W. Badgett, A. Barbaro-Galtieri, V. E. Barnes, B. A. Barnett, S. Baroiant, V. Bartsch, G. Bauer, F. Bedeschi, S. Behari, S. Belforte, G. Bellettini, J. Bellinger, A. Belloni, D. Benjamin, A. Beretvas, J. Beringer, T. Berry, A. Bhatti, M. Binkley, D. Bisello, R. E. Blair, C. Blocker, B. Blumenfeld, A. Bocci, A. Bodek, V. Boisvert, G. Bolla, A. Bolshov, D. Bortoletto, J. Boudreau, A. Boveia, B. Brau, L. Brigliadori, C. Bromberg, E. Brubaker, J. Budagov, H. S. Budd, S. Budd, S. Budroni, K. Burkett, G. Busetto, P. Bussey, K. L. Byrum, S. Cabrera, M. Campanelli, M. Campbell, F. Canelli, A. Canepa, S. Carillo, D. Carlsmith, R. Carosi, M. Casarsa, A. Castro, P. Catastini, D. Cauz, M. Cavalli-Sforza, A. Cerri, L. Cerrito, S. H. Chang, Y. C. Chen, M. Chertok, G. Chiarelli, G. Chlachidze, F. Chlebana, I. Cho, K. Cho, D. Chokheli, J. P. Chou, G. Choudalakis, S. H. Chuang, K. Chung, W. H. Chung, Y. S. Chung, M. Ciljak, C. I. Ciobanu, M. A. Ciocci, A. Clark, D. Clark, M. Coca, G. Compostella, M. E. Convery, J. Conway, B. Cooper, K. Copic, M. Cordelli, G. Cortiana, F. Crescioli, C. C. Almenar, J. Cuevas, R. Culbertson, J. C. Cully, D. Cyr, S. DaRonco, S. D'Auria, T. Davies, D'Onofrio, D. Dagenhart, P. de Barbaro, S. De Cecco, A. Deisher, G. De Lentdecker, Dell'Orso, F. D. Paoli, L. Demortier, J. Deng, M. Deninno, D. De Pedis, P. F. Derwent, G. P. Di Giovanni, C. Dionisi, B. Di Ruzza, J. R. Dittmann, P. DiTuro, C. Dorr, S. Donati, M. Donega, P. Dong, J. Donini, T. Dorigo, S. Dube, J. Efron, R. Erbacher, D. Errede, S. Errede, R. Eusebi, H. C. Fang, S. Farrington, I. Fedorko, W. T. Fedorko, R. G. Feild, M. Feindt, J.

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Measurement of the Ratios of Branching Fractions $\mathcal{B}(B_s^0 \to D_s^- \pi^+ \pi^+ \pi^-)/\mathcal{B}(B^0 \to D^- \pi^+ \pi^+ \pi^-)$ and $\mathcal{B}(B_s^0 \to D_s^- \pi^+)/\mathcal{B}(B^0 \to D^- \pi^+)$

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Using 355 pb^{-1} of data collected by the CDF II detector in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron, we study the fully reconstructed hadronic decays $B^0_{(s)} \to D^-_{(s)}\pi^+$ and $B^0_{(s)} \to D^-_{(s)}\pi^+\pi^+\pi^-$. We present the first measurement of the ratio of branching fractions $\mathcal{B}(B^0_s \to D^-_s\pi^+\pi^+\pi^-)/\mathcal{B}(B^0 \to D^-\pi^+\pi^+\pi^-) = 1.05 \pm 0.10(\mathrm{stat}) \pm 0.22(\mathrm{syst})$. We also update our measurement of $\mathcal{B}(B^0_s \to D^-_s\pi^+)/\mathcal{B}(B^0 \to D^-\pi^+)$ to $1.13 \pm 0.08(\mathrm{stat}) \pm 0.23(\mathrm{syst})$, improving the statistical uncertainty by more than a factor of 2. We find $\mathcal{B}(B^0_s \to D^-_s\pi^+) = [3.8 \pm 0.3(\mathrm{stat}) \pm 1.3(\mathrm{syst})] \times 10^{-3}$ and $\mathcal{B}(B^0_s \to D^-_s\pi^+\pi^+\pi^-) = [8.4 \pm 0.8(\mathrm{stat}) \pm 3.2(\mathrm{syst})] \times 10^{-3}$.

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Hadronic B meson decays provide important information on both weak and hadronic interactions of heavy flavored mesons. The dominant hadronic decay modes of the B meson involve tree-level diagrams where the $b \to c$ transition leads to a charmed meson and a virtual W boson, which often emerges as a charged π, ρ, or $a_1(1260)$ meson [1]. The measurement of the ratios of branching fractions $\mathcal{B}(B^0_s \to D^-_s\pi^+[\pi^+\pi^-])/\mathcal{B}(B^0 \to D^-\pi^+[\pi^+\pi^-])$ [2] reveals information about B decay mechanisms. One can attempt to separate the contributions of various processes in $B^0 \to D^-\pi^+$ decay and then predict the $B^0_s \to D^-_s\pi^+$ branching fraction using $SU(3)$ [3,4] and further estimate flavor $SU(3)$ symmetry breaking effects [5], which can be sizable [6]. The ratios of branching fractions are expected to be close to 1 if the flavor $SU(3)$ is a valid approximation and the contribution of the subleading diagram in the $B^0 \to D^-\pi^+[\pi^+\pi^-]$ decay is small.

In this Letter, we present the first measurement of the ratio of branching fractions $R(D3\pi) = \mathcal{B}(B_s^0 \to D_s^-\pi^+\pi^+\pi^-)/\mathcal{B}(B^0 \to D^-\pi^+\pi^+\pi^-)$ using D_s^- decays to $\phi\pi^-$, $K^{*0}K^-$, and $\pi^-\pi^-\pi^+$ and D^- decays to $K^+\pi^-\pi^-$. We also update our previous [7] measurement of the ratio $R(D\pi) = \mathcal{B}(B_s^0 \to D_s^-\pi^+)/\mathcal{B}(B^0 \to D^-\pi^+)$. We measure the ratios of branching fractions because most of the systematic uncertainties cancel due to the similarity of final state kinematics. The measurement is performed using a sample of inclusive heavy flavor decays, corresponding to an integrated luminosity of 355 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

The components of the CDF II detector relevant for this analysis are briefly described below. A more complete description can be found elsewhere [8]. Charged particle tracks are reconstructed in the pseudorapidity range $|\eta| \lesssim 1.0$, where η is defined as $-\ln\tan(\theta/2)$, and θ represents the angle between the particle and the proton beam direction [9]. Tracks are reconstructed from hits in the silicon microstrip detector (SVX) and the central outer tracker (COT). Both detectors are inside a 1.4 T solenoidal magnetic field. The SVX detector is composed of L00 (a single layer of silicon placed close to the beam pipe), SVX II (five cylindrical layers of double-sided sensors), and ISL (outermost layer of silicon), providing up to 8 coordinate measurements in the r-ϕ view [10]. Surrounding the SVX is the COT, an open cell drift chamber with 96 layers of sense wires [11]. A sample rich in charm and beauty hadrons is selected by a three-level displaced track trigger. At level 1, tracks are reconstructed in the COT by the track trigger processor (XFT) [12]. The trigger requires two tracks with transverse momenta $p_T > 2$ GeV$/c$ and the scalar sum $p_{T1} + p_{T2} > 4.0$ GeV$/c$. The level 2 silicon vertex tracker [13] associates SVX II r-ϕ position measurements with XFT tracks, providing a precise measurement of the track impact parameter (d_0), i.e., the distance of closest approach of the track helix to the beam axis in the transverse plane. Decays of heavy flavor particles are identified by requiring two tracks with $0.12\ \text{mm} < d_0 < 1\ \text{mm}$ and an opening angle in the transverse plane $2° < |\Delta\phi| < 90°$. A requirement $L_{xy} > 0.2$ mm is also applied, where L_{xy} is defined as the distance in the transverse plane from the beam line to the two-track vertex projected onto the two-track momentum vector. The level 3 trigger performs a full event reconstruction applying selection similar to levels 1 and 2 on offline quality quantities.

B candidate reconstruction starts with a collection of tracks. No particle identification is explicitly used, and tracks are assumed to be either a pion or a kaon to match the reconstruction hypothesis. A set of unique track combinations making the ϕ, K^{*0}, D^-, D_s^-, and B candidates is formed. The track combinations reconstructed in 3 dimensions must be consistent with forming a vertex, and combinations that fall outside a wide mass window around the mass of the respective meson are rejected.

The Monte Carlo simulation is an essential part of this analysis. It is used to optimize the selection cuts, model signal, and background and to study the trigger and reconstruction efficiency. We generate single B hadrons with the program BGENERATOR [14]. The B-hadron decays are simulated with EVTGEN [15]. This package has been extensively tuned by experiments at the $\Upsilon(4S)$ resonance and reflects the measured properties of B and D meson decays.

The selection requirements used to reject combinatorial background are optimized by maximizing $\mathcal{S}/\sqrt{\mathcal{S}+\mathcal{B}}$ for each mode individually. The number of signal events ($\mathcal{S}$) is derived from a Monte Carlo simulation of the CDF II detector and trigger. The number of background events ($\mathcal{B}$) is estimated using data in the high-mass sideband interval $m(B) + 10\sigma(B)$ to $m(B) + 16\sigma(B)$, where $m(B)$ is the fitted mass and $\sigma(B) \approx 15\ \text{MeV}/c^2$ is the width of the signal peak. This sideband represents the combinatoric background underneath the signal peak. Selection requirements include cuts on the impact parameter of the B meson, the $\chi^2_{r-\phi}$ [16] of the B vertex fit in the transverse plane, the p_T of the pion from the B decay in $B^0_{(s)} \to D^-_{(s)}\pi^+$, and a minimum p_T requirement of the tracks for decays with 6 tracks in the final state. We exploit the narrow $\phi \to K^+K^-$ resonance and $K^{*0} \to K^+\pi^-$ resonance to suppress background by requiring $1010\ \text{MeV}/c^2 < m(\phi) < 1029\ \text{MeV}/c^2$ and $840\ \text{MeV}/c^2 < m(K^{*0}) < 940\ \text{MeV}/c^2$. There are also requirements on $L_{xy}/\sigma(L_{xy})$—the significance of the measurement of L_{xy} for B and D vertices.

The assumptions on the relative contributions of resonant a_1 and $\rho\pi$ and nonresonant $\pi^+\pi^+\pi^-$ in the $B^0 \to D^-\pi^+\pi^+\pi^-$ signal affect $R(D3\pi)$ because Monte Carlo simulation shows that their reconstruction efficiencies differ by as much as 5%. We find that the contributions of the $\rho\pi$ and nonresonant $\pi^+\pi^+\pi^-$ decays are small. The $\pi^+\pi^+\pi^-$ mass distributions were compared in data between B^0 and B_s^0 mesons and are compatible within statistics, as shown in Fig. 1. The resonant fractions in $B_s^0 \to D_s^-\pi^+\pi^+\pi^-$ and $B^0 \to D^-\pi^+\pi^+\pi^-$ decays are assumed to be identical.

To extract $R(D3\pi)$ [or, equivalently, $R(D\pi)$], we use the following formula:

$$R(D3\pi) = \frac{f_d}{f_s}\frac{\epsilon(B^0)}{\epsilon(B_s^0)}\frac{\mathcal{B}(D^-)}{\mathcal{B}(D_s^-)}\frac{N(B_s^0)}{N(B^0)}, \qquad (1)$$

where $N(B_s^0)$ and $N(B^0)$ are the measured signal yields, $\epsilon(B^0)/\epsilon(B_s^0)$ is the ratio of trigger and reconstruction efficiencies extracted from Monte Carlo simulation, f_d/f_s is the ratio of b quark fragmentation fractions into B^0 and B_s^0 mesons, and $\mathcal{B}(D^-)/\mathcal{B}(D_s^-)$ is the ratio of the world average values for branching fractions of D^- and D_s^- mesons into the reconstructed final states [17].

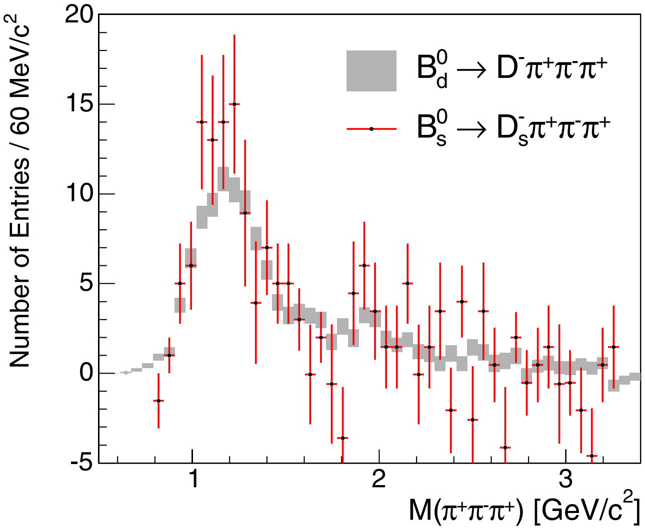

FIG. 1 (color online). Comparison of the sideband subtracted mass spectrum of $\pi^+\pi^+\pi^-$ from B^0 and B_s^0 decays. Only the $D_s^- \to \phi\pi$ channel is used for B_s^0. The B^0 histogram is normalized to B_s^0.

The yields $N(B_s^0)$ and $N(B^0)$ are extracted from the mass spectra in Fig. 2 using a binned likelihood fit and are summarized in Table I. In the normalization modes $B^0 \to D^-\pi^+$ and $B^0 \to D^-\pi^+\pi^+\pi^-$, we observe 8098 ± 114(stat) and 3288 ± 76(stat) signal candidates, respectively. The signal peaks are modeled with a sum of two Gaussians with the same mean values but different widths. The combinatorial background is modeled with a sum of an exponential function and a constant. The shapes of other physics backgrounds are modeled using Monte Carlo simulation, and their parametrization is fixed in the fits to the mass spectra.

There are several backgrounds whose mass distributions peak near the signal region and must be subtracted. They are the Cabibbo-suppressed decays $B_{(s)}^0 \to D_{(s)}^- K^+$ and $B_{(s)}^0 \to D_{(s)}^- K^+\pi^-\pi^+$ and misreconstructed baryon decays $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^+\pi^-$. The ratio of Cabibbo-suppressed $B_{(s)}^0 \to D_{(s)}^- K^+$ background to the corresponding signal was fixed to the world average ratio of branching fractions [17]. The ratio of Cabibbo-suppressed $B_{(s)}^0 \to D_{(s)}^- K^+\pi^-\pi^+$ decay to the signal is fixed to $|V_{us}|^2/|V_{ud}|^2 \approx 0.05$. The fraction of Λ_b background was fixed using the recent CDF measurement of $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)/\mathcal{B}(B^0 \to D^-\pi^+)$ [18]. In all of the cases, the ratios are corrected for the relative trigger and reconstruction efficiencies.

In the case of the $B_s^0 \to D_s^-\pi^+\pi^+\pi^-$ decay, there is a reflection from $B^0 \to D^-\pi^+\pi^+\pi^-$. If one of the pions from a $D^- \to K^+\pi^-\pi^-$ decay is reconstructed as a kaon, a peak is produced under the B_s^0 signal region. These events contribute in the $B_s^0 \to D_s^-\pi^+\pi^+\pi^-$, $D_s^- \to K^{*0}K^-$ decay because the K^{*0} resonance is broad. The fraction of $B^0 \to D^-\pi^+\pi^+\pi^-$ events under $B_s^0 \to D_s^-\pi^+\pi^+\pi^-$ peaks is calculated from the observed number of B^0 mesons. The number of $B^0 \to D^-\pi^+\pi^+\pi^-$ events under the $B_s^0 \to D_s^-(K^{*0}K^-)\pi^+\pi^+\pi^-$ mass distribution is estimated to be 141 ± 6(stat). The systematic uncertainty assigned due to the $B^0 \to D^-\pi^+\pi^+\pi^-$ back-

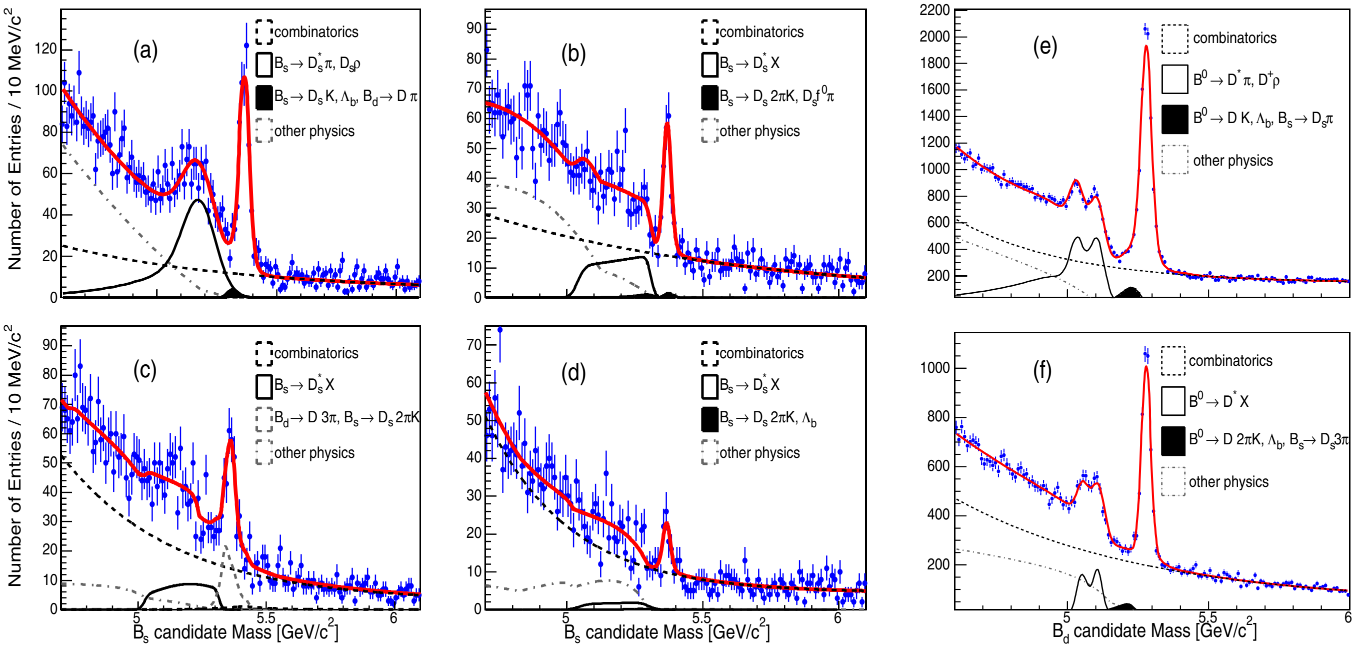

FIG. 2 (color online). Mass spectra for (a) $B_s^0 \to D_s^-\pi^+$, (b) $B_s^0 \to D_s^-(\phi\pi^-)\pi^+\pi^+\pi^-$, (c) $B_s^0 \to D_s^-(K^{*0}K^-)\pi^+\pi^+\pi^-$, (d) $B_s^0 \to D_s^-(\pi^-\pi^-\pi^+)\pi^+\pi^+\pi^-$, (e) $B^0 \to D^-\pi^+$, and (f) $B^0 \to D^-\pi^+\pi^+\pi^-$. The "other physics" category corresponds to the inclusive $B \to D_s^- X$ and $B \to D^- X$ decays.

TABLE I. Summary of event yields, ratios of efficiencies, and individual branching ratio measurements. The uncertainties listed on the yield and the ratio of efficiencies are statistical only. $\mathcal{B}(D^-)/\mathcal{B}(D_s^-)$ is the ratio of $\mathcal{B}(D^- \to K^+\pi^-\pi^-)$ to the corresponding branching fraction of the D_s^- meson [$\mathcal{B}(D_s^- \to \phi\pi^-, \phi \to K^-K^+)$, $\mathcal{B}(D_s^- \to K^{*0}K^-, K^{*0} \to K^-\pi^+)$, or $\mathcal{B}(D_s^- \to \pi^-\pi^+\pi^-)$].

Decay	Yield	$\epsilon(B_s^0)/\epsilon(B^0)$	$\mathcal{B}(D^-)/\mathcal{B}(D_s^-)$	$f_s/f_d \times BR(B_s^0)/BR(B^0)$
$D_s^-(\phi\pi^-)\pi^+$	494 ± 28	0.913 ± 0.004	4.40 ± 0.59	0.292 ± 0.020(stat) ± 0.012(syst)
$D_s^-(\phi\pi^-)\pi^+\pi^+\pi^-$	160 ± 17	0.814 ± 0.010	4.40 ± 0.59	0.263 ± 0.029(stat) ± 0.018(syst)
$D_s^-(K^*K^-)\pi^+\pi^+\pi^-$	90 ± 17	0.352 ± 0.009	3.80 ± 0.77	0.274 ± 0.053(stat) ± 0.030(syst)
$D_s^-(\pi^-\pi^+\pi^-)\pi^+\pi^+\pi^-$	49 ± 11	0.397 ± 0.009	7.80 ± 1.50	0.293 ± 0.067(stat) ± 0.021(syst)

ground subtraction is dominant in this channel and is a part of the "B_s^0 fit model" (see Table II). For $B_s^0 \to D_s^-\pi^+\pi^+\pi^-$ with $D_s^- \to \phi\pi^-$, the corresponding B^0 background fraction is very small due to the narrow width of the ϕ. The contamination of the double charm $B^0 \to D^-D_s^+$, with $D_s^+ \to \pi^+\pi^-\pi^+$, is estimated to be ≈ 1% of the $B^0 \to D^-\pi^+\pi^+\pi^-$ signal and is subtracted from the measured yield. The contamination of $B_s^0 \to D_s^-D_s^+$ in the B_s^0 signal is found to be negligible. Applying a cut on the mass of three pions in the $B_s^0 \to D_s^-\pi^+\pi^+\pi^-$ decay around the mass of the D_s^- meson does not change the measured yields.

The systematic uncertainty on the ratio of efficiencies $\epsilon(B_s^0)/\epsilon(B^0)$ comes from various physics sources. In all cases, the systematics were estimated by observing the change in the ratio of efficiencies when the effect was considered. The effect of the choice of B meson spectrum used by Monte Carlo simulation was determined by reweighting the Monte Carlo events with p_T spectrum based on next-to-leading order calculations [14] to match the p_T spectrum measured at CDF [19]. To estimate the systematic uncertainty due to B and D lifetimes, we varied the assumed lifetime of B and D meson in signal Monte Carlo simulation within world average values [17]. The composition systematic applies to the decay $B_s^0 \to D_s^-(\pi^-\pi^+\pi^-)\pi^+\pi^+\pi^-$ only and is due to the limited knowledge of the resonances in $D_s^- \to \pi^-\pi^+\pi^-$ decay. We assign a systematic uncertainty due to the unknown resonance structure of the $\pi^+\pi^+\pi^-$ system in $B_{(s)}^0 \to D_{(s)}^-\pi^+\pi^+\pi^-$ decay by varying the fraction of the a_1 component in both B^0 and B_s^0 signal Monte Carlo simulation in a range consistent with the observed shape. Systematic uncertainties due to the fit model are estimated by comparing the fitted yields after changing the mass range in which the fit is performed and also by varying the parameters of functions describing the backgrounds. The systematic uncertainties are summarized in Table II.

The results of the measurements for $R(D3\pi)$ are summarized in Table I. To average the results of the measurements by the expected yield, we use Eq. (1), where $N(B_s^0)$ is a sum of the yields in three B_s^0 channels and $\epsilon(B_s^0)$ is a linear combination of Monte Carlo efficiencies multiplied by the ratio of the branching fraction of D_s^- decay in a given channel and $\mathcal{B}(D_s^- \to \phi\pi^-)$. In the averaging procedure, small interference in the Dalitz plot between $D_s^- \to \phi\pi^-$ and $D_s^- \to K^{*0}K^-$ contributions was ignored. Using $f_s/f_d = 0.259 \pm 0.038$ [17], we obtain:

$$R(D3\pi) = 1.05 \pm 0.10(\text{stat}) \pm 0.07(\text{syst}) \pm 0.14(\text{br}) \pm 0.15(\text{pr}).$$

The (br) and (pr) uncertainties refer to the uncertainty on the D meson branching fractions and the ratio of fragmentation fractions f_s/f_d, respectively.

Using Eq. (1) and the input from Table I, we obtain:

$$R(D\pi) = 1.13 \pm 0.08(\text{stat}) \pm 0.05(\text{syst}) \pm 0.15(\text{br}) \pm 0.17(\text{pr}).$$

The measurement of $R(D\pi)$ is consistent with the previous CDF measurement [7] and supersedes that result with a statistical uncertainty reduced by a factor of 2. This measurement is consistent within uncertainties with the theoretical prediction of 1.05 ± 0.24 [3]. The agreement indicates the smallness of the flavor $SU(3)$ breaking terms and limits the amplitude and phase difference of the subleading diagram (W-exchange) with respect to the tree diagram in the $B^0 \to D^-\pi^+$ decay.

In conclusion, we have presented the first measurement of the ratio of branching fractions $R(D3\pi)$. We also have measured the ratio of branching fractions $R(D\pi)$, improving the statistical uncertainty by more than a factor of 2.

TABLE II. Summary of the relative systematics uncertainties on $R(D\pi)$ and $R(D3\pi)$. The range of values appearing in the second column reflects the differences in the fit systematic of the three B_s^0 decays.

	Syst. uncertainty[%]	
Effect	$B \to D\pi$	$B \to D3\pi$
B p_T spectrum	±3.0	±3.0
B_s^0 lifetime	±2.1	±2.1
3π resonance structure	⋯	±2.5
$D_s^- \to 3\pi$ composition	⋯	±3.0
Trigger simulation	±1.2	±1.1
B^0 fit model	±0.5	±1.3
B_s^0 fit model	±1.5	±(3.6–9.3)
Total	±4.2	±(6.7–10.9)

Using the world average values for $\mathcal{B}(B^0 \to D^- \pi^+)$ and $\mathcal{B}(B^0 \to D^- \pi^+ \pi^+ \pi^-)$ [17], we find $\mathcal{B}(B_s^0 \to D_s^- \pi^+) = [3.8 \pm 0.3(\text{stat}) \pm 1.3(\text{syst})] \times 10^{-3}$ and $\mathcal{B}(B_s^0 \to D_s^- \pi^+ \pi^+ \pi^-) = [8.4 \pm 0.8(\text{stat}) \pm 3.2(\text{syst})] \times 10^{-3}$.

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