Observation of the $D_1(2420) \to D \pi^+ \pi^-$ Decays


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0031-9007/05/94(22)/221805(6)$23.00 221805-1 © 2005 The American Physical Society
We report on the first observation of $D_1^0(2420) \rightarrow D^0 \pi^- \pi^+$ and $D_1^+(2420) \rightarrow D^+ \pi^- \pi^+$ decays (where the contribution from the dominant known $D_1 \rightarrow D^* \pi$ decay mode is excluded) in the $B^- \rightarrow D_1^0 \pi^- \pi^+$ and $\bar{B}^0 \rightarrow D_1^+ \pi^-$ decays, respectively. The observation is based on 15.2 $\times$ 10$^7$ $B\bar{B}$ events collected with the Belle detector at the KEKB collider. We also set 90% confidence level upper limits for the branching fractions of the four following decays: $B^- \rightarrow D_1^0 \pi^-$, $D_1^+ \rightarrow D^0 \pi^- \pi^+$, $\bar{B}^0 \rightarrow D_1^+ \pi^-$, $D_1^0 \rightarrow D^+ \pi^- \pi^+$, $B^- \rightarrow D_1^0(2460)\pi^-$, $D_2^- \rightarrow D^0 \pi^- \pi^+$, $\bar{B}^0 \rightarrow D_2^+(2460)\pi^-$, $D_2^+ \rightarrow D^+ \pi^- \pi^+$.

DOI: 10.1103/PhysRevLett.94.221805 PACS numbers: 13.25.Ft, 12.39.Hg, 13.25.Hw, 14.40.Lb

The ground states of heavy-light quark $c\bar{q}$ system, $D$ and $D^*$ mesons, are well studied. For the $D_1$ orbital $P$-wave excitation of the $c\bar{q}$ system only one decay mode $D_1 \rightarrow D^* \pi$ is currently known [1]. Measurements of other modes are important to the study of heavy-light quark systems and the production of excited $D$ mesons in $B$ decays. In particular, there is a significant discrepancy in the branching ratio $R = \mathcal{B}(B^- \rightarrow D_1^0 \pi^-)/\mathcal{B}(B^- \rightarrow D^0 \pi^-)$ between theoretical predictions and current data, if $D_1 \rightarrow D^* \pi$ is assumed to saturate the $D_1(2420)$ width.

Calculations based on the heavy quark effective theory (HQET) and the factorization approach [2–4] predict a value $R \sim 0.35$ [4], assuming nonfactorizable corrections are small. Experimental estimates of $R$ are significantly larger. Based on measurements of the ratio $\mathcal{B}(D_2^0 \rightarrow D^+ \pi^-)/\mathcal{B}(D_2^0 \rightarrow D^+ \pi^-)$ [5,6] and a $B^- \rightarrow D^{*+} \pi^- \pi^-$ study [7], the CLEO collaboration obtained $R = 1.8 \pm 0.8$. Recently the branching fractions for the decays $B \rightarrow D^{*+} \pi \rightarrow D^{(*)} \pi \pi$ have been measured with better accuracy [8], resulting in $R = 0.77 \pm 0.15$. [We use $D^{*+}$ to denote $P$-wave excitations of the $D$ meson, including $D_1(2420)$ and $D_2^+(2460)$.] These experimental determinations assume that $D_1$ and $D_2^+$ decays are saturated by the two-body $D \pi$ and $D^{(*)} \pi$ modes, respectively. The existence of $D_{1,2}$ decay channels other than $D_{1,2} \rightarrow D^{(*)} \pi$ would modify the $R$ value, possibly lifting the 2.8$\sigma$ discrepancy between the prediction of Ref. [4] and the experimental results. Measurements of subleading $D^{*+}$ decays are also valuable for understanding heavy-light quark systems, given recent unexpected results in the charmed-strange sector [9].

In this Letter we report the first observation of the $D_1^+ \rightarrow D^+ \pi^- \pi^+$ and $D_1^0 \rightarrow D^0 \pi^- \pi^+$ decays, and the results of a search for the $D_2^+ \rightarrow D^{(*)} \pi^\pm \pi^\mp$ and $D_1 \rightarrow D^* \pi^- \pi^+$ decay modes. The $D_1$ mesons were reconstructed from the $B^0 \rightarrow D_1^+ \pi^-$ and $B^- \rightarrow D_1^0 \pi^-$ decays, respectively. The results are based on a sample of 15.2 $\times$ 10$^7$ $B\bar{B}$ pairs produced at the KEKB asymmetric-energy $e^+e^-$ collider [10]. The inclusion of charge conjugate states is implied throughout this Letter.

The Belle detector has been described elsewhere [11]. Charged tracks are selected with a set of requirements based on the average number of hits in the central drift chamber (CDC) and on the distance of the closest approach to the interaction point. Track momentum transverse to the beam axis of at least 0.05 GeV/c is required for all tracks in order to reduce the combinatorial background. For charged particle identification (PID), the combined information from specific ionization in the CDC $(dE/dx)$, time-of-flight scintillation counters, and aerogel Čerenkov counters is used. Charged kaons are selected with PID criteria that have an efficiency of 88%, a pion misidentification probability of 8%, and negligible contamination from protons. All charged tracks with PID responses consistent with a pion hypothesis that are not positively identified as electrons are considered as pion candidates. Photon candidates are selected from calorimeter showers not associated with charged tracks. An energy deposition of at least 30 MeV and a photonlike shape are required for each candidate. Pairs of photons with an invariant mass within 12 MeV/c$^2$ ($\sim 2.5\sigma$) of the $\pi^0$ nominal mass [1] are considered as $\pi^0$ candidates. These cuts are commonly
used in analyses of data collected with the Belle detector to
achieve a good signal to background ratio in the selection
of these particles.

We reconstruct \( D^0 \) (\( D^+ \)) mesons in the \( K^- \pi^+ \)
(\( K^- \pi^+ \pi^+ \)) decay channel and require the invariant mass
to be within 15 MeV/\( c^2 \) (\( \sim 3\sigma \)) of the \( D^0 \) (\( D^+ \)) mass. The
\( D^{*0} \) (\( D^{*+} \)) mesons are reconstructed in the \( D^0 \pi^0 \) (\( D^0 \pi^+ \))
decay mode. The calculated mass difference between \( D^{*0} \)
(\( D^{*+} \)) and \( D^0 \) candidates is required to be within
2.1 MeV/\( c^2 \) (\( \sim 2.5\sigma \)) of the expected value [1]. For
\( D^* \rightarrow D^0 \pi \) decays the \( D^0 \rightarrow K^- \pi^+ \pi^- \pi^+ \) mode is also
included (the same \( D^* \) selection criteria were used as
above).

We combine \( D^{(*)} \) candidates with \( \pi^- \pi^- \pi^+ \) to form \( B \)
mesons. Candidate events are identified by their center-of-
mass (c.m.) energy difference, \( \Delta E = (\overline{\Sigma}E_i) - E_{\text{beam}} \), and
the beam constrained mass, \( M_{bc} = \sqrt{E^2_{\text{beam}} - (\overline{\Sigma}p_i)^2} \),
where \( E_{\text{beam}} \) is the beam energy and \( \overline{p}_i \) and \( E_i \) are the
momenta and energies of the decay products of the \( B \)
meson in the c.m. frame. We define the signal region as
\( 5.273 < M_{bc} < 5.285 \) GeV/\( c^2 \) and \( |\Delta E| < 25 \) MeV. The
sidebands are defined as \( 5.273 < M_{bc} < 5.285 \) GeV/\( c^2 \)
and 25 MeV < \( |\Delta E| \) < 50 MeV. If there is more than
one \( B \) candidate (this occurs in 12\% of the events), the
one with the \( D^{(*)} \) mass closest to the nominal value and the
best \( \pi^- \pi^- \pi^+ \) vertex is chosen. We use Monte Carlo (MC)
simulation to model the detector response and determine
the acceptance [12]. A range of \( D_1 \rightarrow D \pi \pi \) decay models
was used for this simulation (see below), and the resulting
variation in efficiency was included in the systematic
uncertainty.

Variables that characterize the event topology calculated
in the c.m. frame are used to suppress the background from
the two-jet-like \( e^+e^- \rightarrow q\bar{q} \) continuum process. We re-
quire \( |\cos\theta_{\text{th}}| < 0.80 \), where \( \theta_{\text{th}} \) is the angle between
the thrust axis of the \( B \) candidate and that of the rest
of the event; this eliminates 77\% of the continuum back-
ground while retaining 78\% of the signal events. We also
define a Fisher discriminant, \( F \), which is based on the
production angle of the \( B \) candidate, the angle of the thrust
axis with respect to the beam axis, and nine parameters that
classify the momentum flow in the event [13]. We
impose a requirement on \( F \) that rejects 67\% of the remaining
continuum background and retains 83\% of the signal.

To suppress the large contribution from the dominant
\( D_1 \rightarrow D^* \pi \rightarrow D \pi \pi \) decay mode, we apply a requirement
on the invariant mass of the relevant \( D \pi \) combination
\( |(m_{D^*} - m_D) - (m_{D_{1S}} - m_{D_{10}})| > 6 \) MeV/\( c^2 \) (10\sigma) [1].

The \( \Delta E \) and \( M_{D^{(*)}\pi\pi} \) distributions for the selected \( B \rightarrow
D_1 \pi, D_1 \rightarrow D^{(*)}\pi \pi \) candidates are shown in Fig. 1. (To
improve the \( m_{D^{(*)}\pi\pi} \) mass resolution, we replace it with
\( m_{D^{(*)\pi}} = m_{D^{(*)}\pi\pi} - m_{D_{1S}} + m_{D_{10}} \) [1].) To plot the \( \Delta E \) dis-
tributions, we require \( M_{bc} \) to lie in the signal region with
an additional requirement \( |M_{D^{(*)\pi\pi}} - M_{D_1}| < 25 \) MeV/\( c^2 \),
where \( M_{D_1} \) is the ground average mass value; for the
\( M_{D^{(*)\pi\pi}} \) distributions we select events from the \( \Delta E \) signal
region. (Although there are two \( D^{\pi\pi} \) combinations, they are kinematically separated in the \( D_1 \) mass region.)

Clear signals are observed for \( B \rightarrow D_0^0 \pi^- \), \( D_1^0 \rightarrow
D^0 \pi^- \pi^+ \) and \( B^0 \rightarrow D^+_1 \pi^- \), \( D_1^+ \rightarrow D^+ \pi^- \pi^+ \) decays.
For branching fraction calculations we use signal yields
determined from the fit to \( M_{D^{(*)\pi\pi}} \) distributions as it allows
us to directly estimate a possible contribution from the
\( B \rightarrow D_3 \pi, D_2 \rightarrow D \pi \pi \) decay. The signal shape dis-
tribution is parametrized by a convolution of a resolution
Gaussian (\( \sigma = 2.5 \pm 0.6 \) MeV/\( c^2 \), set from MC simu-
larations.)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{(color online). \( \Delta E \) (left) and \( M_{D^{(*)\pi\pi}} \) (right) distributions for the \( D_1^0 \rightarrow D^0 \pi^- \pi^+ \) (first row), \( D_1^+ \rightarrow D^+ \pi^- \pi^+ \) (second
row), \( D_1^0 \rightarrow D^{*0} \pi^- \pi^+ \) (third row), \( D_1^+ \rightarrow D^{*+} \pi^- \pi^+ \) (fourth row). Open histograms represent the data from the signal area,
solid histograms show the \( M_{D^{(*)\pi\pi}} \) (where applicable) and \( \Delta E \)
sidebands, the curves are the fit results—for the signal area and
sidebands.}
\end{figure}
tion) with a signal Breit-Wigner function; the background is represented by a linear function. (The $D^{*+}$ width in data was used to validate the MC estimate of detector resolution.) The $D_1$ mass and width determined from the fit are $M_{D_1} = 2426 \pm 3 \pm 1$ MeV/$c^2$ (statistical and systematic error, respectively), $\Gamma_{D_1} = 24 \pm 7 \pm 8$ MeV/$c^2$ for $D_1^0$ and $M_{D_1} = 2421 \pm 2 \pm 1$ MeV/$c^2$, $\Gamma_{D_1} = 21 \pm 5 \pm 8$ MeV/$c^2$ for $D_1^+$; these are consistent with the world average values [1]. The signal yields are given in Table I: the first and second errors on the branching fraction products are statistical and systematic, and the third is a model uncertainty due to other possible sources of $D_1$ production, and contributions from $D_2^*$, discussed below. For the $B \to D_1 \pi \to D^* \pi^+ \pi^- \pi^+$ decay channels, we do not observe statistically significant signals and thus determine 90% C.L. upper limits [14] for their branching fractions. In the fit to the $M_{D^* \pi \pi}$ distribution, we fix the $D_1$ mass and width at their world average values. The statistical significance of signals quoted in Table I is defined as $\sqrt{-2 \ln (L_0/L_{\text{max}})}$, where $L_{\text{max}}$ and $L_0$ denote the maximum likelihood with the nominal signal yield and with the signal yield fixed at zero, respectively.

To account for contamination from other possible $D_1$ production mechanisms (such as $e^+e^- \to c\bar{c}$ continuum production or semileptonic $B \to D_1 \ell \nu$ decays), we fit the $M_{D^* \pi \pi}$ distribution for events in the $\Delta E$ sidebands. In this fit, we fix the $D_1$ mass and width at their world average values. The fits give $-6 \pm 8$ events for the $D_1^0$ and $10 \pm 11$ events for the $D_1^+$. The resulting uncertainties in the $D_1$ yields are $+0.00 \%$ for the $D_1^0$ and $+0.00 \%$ for the $D_1^+$. The $B \to D_2^*(2460) \pi$, $D_2^* \to D^{\pi^+} \pi^-$ decay may also contribute to the $B \to D^\pi^- \pi^- \pi^+$ final state. To check for a possible effect, we perform a simultaneous fit to the $M(D_2^*(2460) \pi)$ and $M(D_1^+ \pi^- \pi^+)$ distributions, where we assume isospin invariance and require the ratio $N(D_2^*)/N(D_1)$ to be the same for both charge combinations. The fit finds the ratio $N(D_2^*)/N(D_1) = 0.30 \pm 0.14$ and signal yields of $N(D_2^*) = 120 \pm 17$, $N(D_1^0) = 137 \pm 16$. While an excess can be seen near the $D_2^*(2460)$ mass in $D_1^0 \to D^0 \pi^- \pi^+$, there is no evidence of an enhancement in the $D_1^+ \to D^+ \pi^- \pi^+$ mode (see Fig. 1); we set a 90% C.L. upper limit on the $D_2^*$ contribution of $B(B \to D_2^*(2460) \pi) \times B(D_2^* \to D^{\pi^+} \pi^-) < 0.51B(B \to D_1 \pi^-) \times B(D_1 \to D^{\pi^+} \pi^-)$ [15], and determine the $D_1(2420)$ yield from the fit without $D_2^*(2460)$. Fixing the $\Gamma_{D_2^*/D_1}$ ratio to 0.47 results in a change of $-21\%$ in the $D_1$ yield: this is combined in quadrature with the uncertainty from other possible $D_1$ sources, to obtain the “model” uncertainty in Table I.

The signal yields extracted from the $\Delta E$ distributions are used only to verify that there is no significant contribution to the signal from the non-$D_1$ peak region. The $\Delta E$ signal shape is parametrized by a Gaussian with parameters determined from signal MC simulation. The $\Delta E$ background shape is described by a linear function. We restrict the fit to the range $-0.1 < \Delta E < 0.2$ GeV to avoid contributions from other $B$ decays, where an additional pion is not reconstructed. Signal yields obtained from the fits to $\Delta E$ distributions are $106 \pm 12$ for $D_1^0 \pi^- \pi^-$ and $96 \pm 13$ for $D^+ \pi^+ \pi^-$, while the corresponding reconstruction efficiencies are 10.8% and 7.6%, respectively. Thus, the event yields obtained from the two methods are consistent.

In order to determine the $D_1 \to D^\pi \pi$ partial width, an analysis of final states with neutral pions is required. With only the $D_1 \to D^\pi^- \pi^-$ branching fraction measurement, an analysis of the decay dynamics could also be useful to determine the total $D_1 \to D^\pi \pi$ width. As the limited statistics do not allow us to perform a full amplitude analysis, we consider the one-dimensional projections of several variables: $M_{D^* \pi}$, $M_{\pi^- \pi^+}$, $\cos\theta(\pi^- \pi^+)$, $\cos\theta(\pi^- \pi^+$), and $\cos\theta(\pi^- D)$ (where all angles are calculated in the $D^{**}$ rest frame). Although these variables are not independent, they highlight each model’s features. For instance, the helicity angle distributions differentiate between the $D_1 \to D(\pi \pi)$ and $D_1 \to (D \pi)\pi$ models. We select events from the $B$ signal region with the additional requirement $|M(D(\pi \pi)) - M(D_1)| < 25$ MeV/$c^2$. Decays through the following quasi-two-body intermediate states are considered: $D_1 \to D^0 \to D^{*+} \pi^-$, $D_1 \to D_1(2308) \pi$, and $D_1 \to D_1(600) \to D^{*+} \pi^-$ (we set $M_f = 0.8$ GeV/$c^2$ and $\Gamma_f = 0.8$ GeV/$c^2$; the $D_{1e}(2308)$ parameters are taken from Ref. [8]). We use the simplest nontrivial Lorentz-invariant expressions for the corresponding matrix elements in MC simulation [16]. We fit the experimental data with different models. For each variable we plot two distributions: one from the signal region and the other from the $\Delta E$ sideband. We perform a simultaneous fit to these distributions, assuming a Poisson-like profile in each bin whose mean is the sum of the

### Table I. Number of events, efficiencies and branching fraction products of $B \to D^{*+} \pi, D^{*+} \to D^{(*)+} \pi^+ \pi^-$ decays.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{sig}$</th>
<th>$\varepsilon(10^{-2})$</th>
<th>$B(B \to D^{(<em>)+} \pi) \times B(D^{(</em>)+} \to D^{(*)+} \pi)(10^{-4})$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \to D_1^0 \pi^-$, $D_1^0 \to D^0 \pi^- \pi^+$</td>
<td>151 $\pm$ 24</td>
<td>14.1</td>
<td>(1.85 $\pm$ 0.29 $\pm$ 0.35$^{+0.04}_{-0.04}$)</td>
<td>8.7$\sigma$</td>
</tr>
<tr>
<td>$B^0 \to D_1^+ \pi^-$, $D_1^+ \to D^{*+} \pi^+ \pi^-$</td>
<td>124 $\pm$ 20</td>
<td>9.9</td>
<td>(0.89 $\pm$ 0.15 $\pm$ 0.17$^{+0.02}_{-0.02}$)</td>
<td>10$\sigma$</td>
</tr>
<tr>
<td>$B^- \to D_1^0 \pi^-$, $D_1^0 \to D^{*+} \pi^- \pi^+$</td>
<td>&lt;1.2</td>
<td>2.2</td>
<td>&lt;0.06</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$B^0 \to D_1^+ \pi^-$, $D_1^+ \to D^{*+} \pi^+ \pi^-$</td>
<td>&lt;12.0</td>
<td>3.4</td>
<td>&lt;0.33</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$B^- \to D_2^* \pi^-$, $D_2^* \to D^{*+} \pi^+ \pi^-$</td>
<td>&lt;4.4</td>
<td>2.2</td>
<td>&lt;0.22</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$B^0 \to D_2^* \pi^+$, $D_2^* \to D^{*+} \pi^+ \pi^-$</td>
<td>&lt;9.0</td>
<td>3.4</td>
<td>&lt;0.24</td>
<td>$\cdots$</td>
</tr>
</tbody>
</table>
background and signal (for a given model) in the signal region or the background only in the sideband. The obtained differences of likelihood values for all variables are listed in Table II. Figure 2 shows the $M_{\pi^+\pi^-}$ and $\cos\theta(\pi_0^B D)$ distributions along with expectations based on different $D_1 \to D^0 \pi \pi^-$ decay models [17]. Although the $D_1 \to D^0 \pi \pi^-$ decay mechanism describes the data best, some contribution from other mechanisms cannot be excluded completely.

It is interesting to examine the dependence of the $R$ value on the decay mechanism. The expression for $R$ can be written as $s_1 \times B(B^- \to D_2^0 \pi^-, D_2^0 \to D^{+\pi^0})/(s_2 \times B(B^- \to D_1^0 \pi^-, D_1^0 \to D^{+\pi^-}) + s_2 \times B(B^- \to D_1^0 \pi^-, D_1^0 \to D^{+\pi^-}))$ where $s_j$ is a scale factor that recovers the full width from the single decay channel. (These scale factors include the branching fractions of all relevant $D^{*+}$, $D^+$, and $D$ subdecays; the $s_j$ factors are calculated from Clebsch-Gordan coefficients for each of the three models, without accounting for any possible interference effects.) Following the procedure used in Ref. [8] and fixing $s_1$ at 3/2, we can calculate scale factors for different models: $s_2(D^{*0} \to D_0^\pi \pi^-) = 9/4$ (disregarding possible interference effects in $D_0^\pi \pi^0$ decays), $s_2(D^{*0} \to D^0 \rho) = 3$, $s_3(D^{*0} \to D^0 f_0) = 3/2$. Using the branching fractions measured in Ref. [8] and here, the central value for $R$ depends on the decay model in the following way: 0.50 for $D \rho$, 0.60 for $D f_0$, and 0.54 for $D_0 \pi$. The following sources of systematic errors are considered: tracking efficiency (8% overall, integrated over particle momenta), kaon identification efficiency (2% overall), $\pi^0$ reconstruction efficiency (8%), $D$ branching fraction uncertainties (2%–7%), MC statistics (2%), model uncertainty in MC efficiency (10%), uncertainty caused by variation of cuts (5%), background shape uncertainty (10%). The uncertainty in the tracking efficiency is estimated using partially reconstructed $D^{+} \to D^0[K_0^\pi ^\pi^-] \pi^+$ decays. The kaon identification uncertainty is determined from $D^{+} \to D^0[K^- \pi^+] \pi^+$ decays. The $\pi^0$ reconstruction uncertainty is obtained using $D^0$ decays to $K^- \pi^+$ and $K^- \pi^- \pi^0$. To determine the systematic uncertainty in the signal yield extraction, we use different parametrizations for the background events. The overall systematic uncertainty is 19% for $B \to D \pi \pi$ and 21% for $B \to D^* \pi \pi$. We assume equal production rates for $B^+ B^-$ and $B^0 \bar{B}^0$ pairs and do not include the corresponding uncertainty in the total systematic error.

The $B^- \to D^{*+} \pi^- \pi^-$ final state also includes the $D^{*+} \pi^- \pi^-$ intermediate state with $D^{*+} \to D^0 \pi^-$. We reverse the $D^*$ veto requirement to select $D^{*+} \pi^- \pi^-$ events and measure the branching ratio $B(B^- \to D^{*+} \pi^- \pi^-) = (1.27 \pm 0.07) \times 10^{-4}$ (based on a sample of 85 $\times 10^6 BB$ events), which agrees well with the value of $B(B^- \to D^{*+} \pi^- \pi^-) = (1.25 \pm 0.07) \times 10^{-4}$ measured earlier [8].

In summary, we report the first observation of $D_1(2420) \to D^{\pi^+ \pi^-}$ decays (with the dominant $D_1 \to D^* \pi$ contribution excluded). The measured branching ratios of the $B^- \to D_2^{\pi^-}$, $D_1^0 \to D^0 \pi^- \pi^-$ and $B^0 \to D_1^+ \pi^-$, $D_1^- \to D^+ \pi^- \pi^+$ decays with the corresponding statistical significances and systematic uncertainties are presented in Table I. We find the upper limit for the possible $D_2^\pi$ contribution to these results: $B(B^- \to D_2^{\pi^-}) \times B(D_2^0 \to D^\pi \pi^-) < 0.51 B(B^- \to D_1 \pi^-) \times B(D_1 \to D^* \pi^- \pi^-)$.

No statistically significant signal has been observed for the $D^{*+} \to D^{*+} \pi^- \pi^-$ decays. The corresponding 90% C.L. upper limits are listed in Table I. Analysis of the $D_1 \to D^{\pi^+ \pi^-}$ dynamics shows that the decay model $D_1 \to D^0 \pi$ gives the best description of the data. The $R = B(B^- \to D_2^{\pi^-})/B(B^- \to D_1^{\pi^-})$ value calculated assuming $D_1 \to D^0 \pi$ dominates is 0.54 ± 0.18; this is $\sim 2\sigma$ lower than the previously published one and is consistent with the expectation for $R$ from HQET and factorization [4].

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the NII for the computing network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC (Contract No. 10175071, China); DST (India); the BK21 program of MOEHRD and the CHEP SRC program of

![FIG. 2 (color online). $M_{\pi^+\pi^-}$ (left) and $\cos\theta(\pi_0^B D)$ (right) distributions for the $D_1^0 \to D^+ \pi^- \pi^+$ and $D_1^+ \to D^+ \pi^- \pi^+$, respectively. Points with error bars represent the experimental data, solid line—$D_1^0 \pi$, dashed—$D \rho$, chain—$D f_0$ models with the expected background added. The hatched histogram corresponds to expected background (from $\Delta E$ sidebands).](image-url)
KOSEF (Korea); KBN (Contract No. 2P03B 01324, Poland); MIST (Russia); MESS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

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[15] We use the mean \( +1.28\sigma \) construction to set the limit. As most of the systematic uncertainties cancel in the ratio of the branching fractions, the systematic uncertainty is negligible.

[16] We use the following expressions for matrix elements for the \( D_1 \rightarrow D \pi \pi \) decay:

\[
F^\pi\eta(B^0, \pi^+\eta) F_{\mu\nu}(D^-_1, \pi^-_1) P(D^-_1, \eta) P(D^-_1, \eta),
\]

\[
F^\phi\eta(B^0, \pi^+\eta) F_{\mu\nu}(f^0, D^-) P(D^-_1, \eta) P(D^-_1, \eta),
\]

\[
F^\eta\eta(B^0, \pi^+\eta) F_{\mu\nu}(f^0, \pi^-) P(D^-_1, \eta) P(D^-_1, \eta),
\]

where the following notation is used: \( F^{\mu\nu}(A, B) = P^A_\mu P^B_\nu - P^A_\nu P^B_\mu \), \( P(B - C) = P(B) - P(C) \), and \( P \) stands for a 4-momentum.

[17] In the case of the \( D f_0 \) model the key \( \cos \theta(\pi^- D) \) distribution is practically independent of the \( f_0 \) mass and width.