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Measurement of the branching fractions for $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}\rho^+$

The *BABAR* Collaboration

Abstract

Using 5.2 fb^{-1} of e^+e^- annihilation data recorded with the *BABAR* detector at the PEP-II storage ring while operating on the $\Upsilon(4S)$ resonance, a sample of fully reconstructed B^0 decays in the hadronic modes $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}\rho^+$ have been reconstructed. In this paper, a study of these events is reported, including preliminary measurements of the absolute branching fractions for these modes, which are found to be $\mathcal{B}(B^0 \to D^{*-}\pi^+) = (2.9 \pm 0.3 \pm 0.3) \times 10^{-3}$ and $\mathcal{B}(B^0 \to D^{*-}\rho^+) = (11.2 \pm 1.1 \pm 2.5) \times 10^{-3}$.

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1 Introduction

The dominant hadronic decay modes of the B meson leading to open charm in the final state involve tree-level diagrams where the $b \to c$ transition leads to a charmed meson and an external W, which often emerges as a charged π, ρ, or a_1. In this study, we report a new measurement of the branching fractions for $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}\rho^+$ [1]. The former is known to about 10% from previous measurements, while the latter has proven more difficult to determine due to the helicity of the ρ [1, 2, 3].

2 The *BABAR* detector and dataset

The data used in this analysis were collected with the *BABAR* detector while operating in the PEP-II storage ring at the Stanford Linear Accelerator Center. For this analysis, we use a sample equivalent to 5.22 ± 0.16 fb^{-1} of integrated luminosity, collected while running on the $\Upsilon(4S)$ resonance. This corresponds to $(5.93 \pm 0.21) \times 10^6$ $B\overline{B}$ pairs, assuming the $\Upsilon(4S)$ decays only to B mesons.

The *BABAR* detector is described in detail elsewhere [4]. Charged particle tracking is provided by a 5-layer silicon microstrip detector, capable of stand-alone pattern recognition, and a 40-layer cylindrical drift chamber. This is followed outward in radius by a specialized particle identification system, based on detection of Cherenkov light generated in quartz. A calorimeter consisting of thallium-doped cesium iodide crystals provides detection for photons, and particle identification for electrons. These devices sit inside the superconducting coil, which provides a 1.5 T field with 3% uniformity over the tracking volume. The flux return for the magnet is finely segmented and instrumented with resistive-plate chambers to provide both muon identification and crude hadronic calorimetry for the detection of K_L^0 mesons.

3 *B* reconstruction method

Hadronic events for this study are selected by a set of simple requirements designed to minimize systematic errors in B counting. We require more than three charged tracks forming a primary vertex within 0.5 cm of the beam spot in both transverse directions, a sum of charged and neutral energy greater than 5 GeV, and the normalized second Fox-Wolfram moment for the event, R_2, calculated from charged tracks and neutrals in the $\Upsilon(4S)$ frame, less than 0.5. Neutrals are clusters in the calorimeter with no associated tracks, more than 30 MeV in energy, and a lateral moment of the shower distribution less than 0.8. The R_2 requirement is designed to reject the jet-like continuum events over the more uniformly distributed $\Upsilon(4S)$ decays. A fiducial requirement of $0.410 < \theta_{Lab} < 2.540$ for charged tracks and $0.410 < \theta_{Lab} < 2.409$ for neutrals, where θ_{Lab} is the polar angle to the beam line, is made in calculating these quantities and in the subsequent steps of the study.

B^0 candidates in the channels $D^{*-}\pi^+$ and $D^{*-}\rho^+$ are reconstructed using the mode $D^{*-} \to \overline{D}^0\pi^-$, followed by $\overline{D}^0 \to K^+\pi^-$. The ρ^+ is seen in its decay to $\pi^+\pi^0$. All charged tracks are required to originate close to the beam spot; the distance of closest approach in the transverse plane, is required to be less than 1.5 cm and along the beam line to be less than 3 cm. The daughters of the $\overline{D}^0$ must have a transverse momentum, p_T, greater than 100 MeV/c, and include

[1] Here, and throughout this document, we use the convention that a particular candidate state also implies the charge conjugate state is included.

at least 20 drift chamber hits. The soft pion track is only required to have p_T greater than 70 MeV/c, taking advantage of stand-alone track finding in the silicon detector to improve acceptance. No particle identification is used for this analysis. Neutral pions are formed from pairs of photons with energy greater than 30 MeV and having a lateral shower moment less than 0.8. The invariant mass of the candidate must lie within ± 25 MeV/c^2 of the nominal π^0 mass.

$\overline{D}^0$ candidates are formed from $K^+\pi^-$ combinations, where the kaon and pion are required to have a minimum momentum of 200 MeV/c, and the invariant mass of the candidate must be within $\pm 2.5\sigma$ of the nominal $\overline{D}^0$ mass [5]. All $\overline{D}^0$ candidates are required to have momentum greater than 1.3 GeV/c in the $\Upsilon(4S)$ frame. A vertex constraint fit is performed, for which the χ^2 probability must be greater than 0.1%.

The reconstructed $\overline{D}^0$ is then combined with a soft pion having charge opposite to the kaon to form D^{*-} candidates. A vertex constraint fit is applied to improve the angular resolution for the soft pion, using a fixed effective vertical beam spot size of 40 μm. In those cases where the fit converges, D^{*-} candidates are selected by the requirement that $\Delta m = m(\overline{D}^0\pi^-) - m(\overline{D}^0)$ lies within $\pm 2.5\sigma$ of the nominal mass difference [5]. The width is taken from a weighted average of the two-Gaussian distribution that is required to fit the Δm distribution.

$B^0 \to D^{*-}\pi^+$ candidates are reconstructed by combining a D^{*-} and a π^+ with momentum greater than 500 MeV/c. The decay $B^0 \to D^{*-}\pi^+$ involves a pseudoscalar initial-state particle decaying into a vector and pseudoscalar, so that the final-state D^{*-} is polarized. Therefore, the helicity angle θ_H between the soft pion direction and the D^{*-} direction in the D^{*-} rest frame should be distributed as $\cos^2\theta_H$. In contrast, combinatorial background is uniform in $\cos\theta_H$. Therefore, B meson candidates are selected with the additional requirement $|\cos\theta_H| > 0.4$. This requirement removes 40% of the background and only 5% of signal events.

For the $B^0 \to D^{*-}\rho^+$ mode, ρ^+ candidates are formed by combining a π^0 meson and a charged pion with momentum greater than 200 MeV/c. We require the momentum of the ρ^+ to be greater than 1 GeV/c and the $\pi^+\pi^0$ mass to lie within 150 MeV/c^2 of the ρ^+ mass. Finally, the opening angle, θ_T, between the thrust angle of the B candidate and the thrust axis of the remaining charged and neutrals in the event is required to satisfy $|\cos\theta_T| < 0.9$ in order to remove continuum backgrounds.

In the case of a correctly reconstructed B meson produced by the decay of an $\Upsilon(4S)$, within the experimental resolution, the measured sum of neutral and charged energies, E^*_m, must be equal to the beam energy, E^*_b, both evaluated in the $\Upsilon(4S)$ frame. We define ΔE to be the difference between the measured B candidate energy and beam energy in the $\Upsilon(4S)$ frame, $\Delta E = E^*_m - E^*_b$. The resolution on $\sigma_{\Delta E}$ is predicted to be 16.0 ± 0.6 MeV for $D^{*-}\pi^+$ and 28 MeV for $D^{*-}\rho^+$. The beam-energy substituted mass, $m_{\rm ES}$, is defined as $m^2_{ES} = (E^*_b)^2 - (\sum_i \boldsymbol{p}_i)^2$, where the $\boldsymbol{p}_i$ is the momentum of the ith daughter of the B candidate. The predicted resolution in $m_{\rm ES}$ is typically about 2.5 MeV/c^2 for $D^{*-}\pi^+$ and 3.1 MeV/c^2 for $D^{*-}\rho^+$. This is about a factor of 10 better than the resolution in the reconstructed invariant mass. The resolution for $m_{\rm ES}$ is dominated by the beam energy spread rather than by the detector resolution. It is largely uncorrelated with the error on ΔE.

The variables ΔE and $m_{\rm ES}$ are used to define a signal region and also sideband regions for background studies. For all modes, the region between 5.2 and 5.3 GeV/c^2 in $m_{\rm ES}$ and between ± 300 MeV in ΔE is used to study the B candidates. The peak position, m^0_B, which should be the nominal B mass, and the resolution $\sigma_{m_{\rm ES}}$ are extracted from the distribution of $m_{\rm ES}$ after requiring ΔE be consistent with zero to within $\pm 2.5\sigma$. The resolution in ΔE is extracted from the ΔE distribution obtained by requiring that $m_{\rm ES}$ lie within $\pm 2.5\sigma_{m_{\rm ES}}$ of m^0_B.

The signal region in the two dimensional plane $m_{\rm ES}$ versus ΔE is defined as a area $\pm 2.5\sigma$ wide centered at the nominal B mass, m_B^0, and at $\Delta E = 0$. By staying below $|\Delta E| = m_\pi$, we avoid correlated background from B decays where a real final-state charged pion is either not included in the reconstruction or a random soft pion from the recoil B is added to the observed state.

Only one candidate per event is allowed to appear in the $m_{\rm ES}$ versus ΔE distribution. The criteria selected is to consider only the entry with the smallest absolute value for ΔE. The resulting two dimensional distribution of candidate events in ΔE and $m_{\rm ES}$ is shown in Fig. 1.

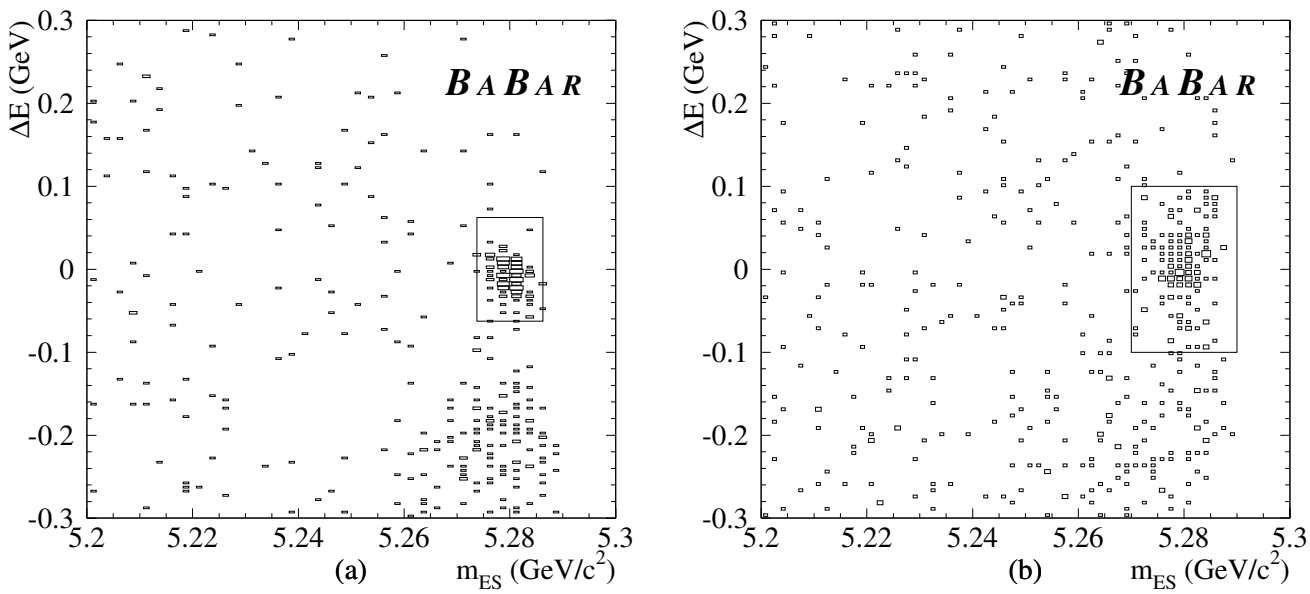

Figure 1: Distribution in data of ΔE versus $m_{\rm ES}$ for B candidates in the channels (a) $B^0 \to D^{*-}\pi^+$ and (b) $B^0 \to D^{*-}\rho^+$.

4 Branching fraction measurements

The measurement of branching fractions requires an estimate of the combinatorial background in the $m_{\rm ES}$ distribution near the nominal B mass. For the channel $B^0 \to D^{*-}\pi^+$, the $m_{\rm ES}$ distribution, shown in Fig. 2, is fitted with a background function [3] which parameterizes how the phase space approaches zero as the energy approaches E_b^*:

$$f_{BG}(\xi) \quad = \quad N\xi\sqrt{1-\xi^2}\,\exp(\kappa(1-\xi^2)) \tag{1}$$

where $\xi = m_{\rm ES}/E_b^*$, and the normalization and the shape are determined by the parameters N and κ. The signal is characterized by a Gaussian distribution with free mass, m_B, and width, $\sigma m_{\rm ES}$. The projection of the signal as a function of ΔE, also shown in Fig. 2, is fitted using a linear background function plus a single Gaussian distribution with free mean and width, $\sigma_{\Delta E}$. The region $-0.3 < \Delta E < -0.13\,$GeV, containing feeddown from $D^{*-}\rho$ where a pion is left out of the reconstruction, is excluded from the fit. The observed width of the signal in $m_{\rm ES}$ is $2.45 \pm 0.18\,{\rm MeV}/c^2$ while the

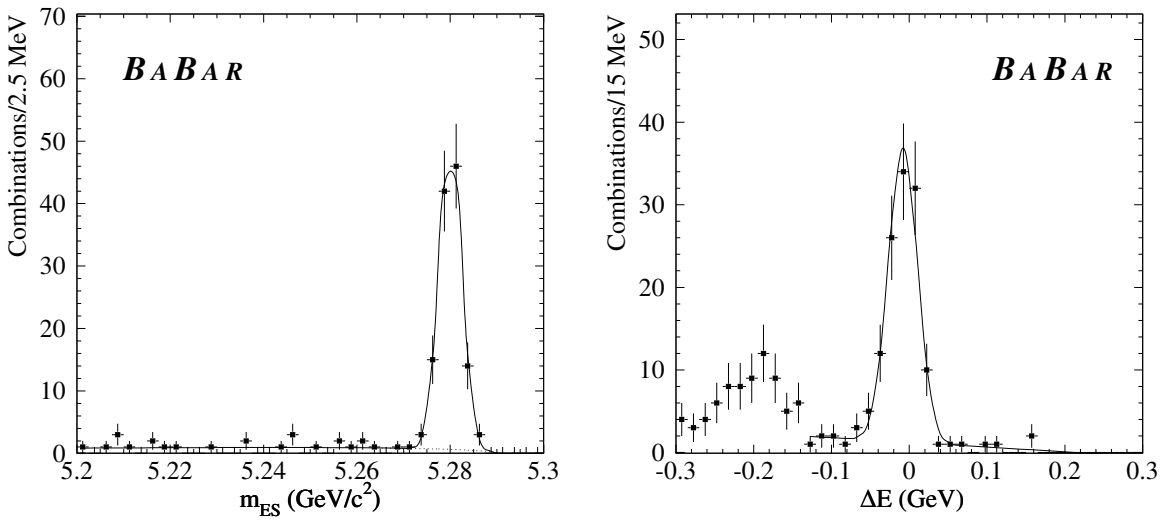

Figure 2: Distribution of $m_{\rm ES}$ for $|\Delta E\ | < 2.5\sigma_{\Delta E}$ (left), and ΔE for $|m_{\rm ES} - m_B^0| < 2.5\sigma m_{\rm ES}$ (right) in the channel $B^0 \to D^{*-}\pi^+$. The fits are described in the text.

Table 1: Observed and expected yields and efficiencies for B^0 decay modes.

B^0 mode	Observed yield	Efficiency (%)
$D^{*-}\pi^+$	119 ± 11	27.0 ± 1.0
$D^{*-}\rho^+$	131 ± 13	7.6 ± 0.6

ΔE resolution is observed to be 18.8 ± 0.9 MeV. Acceptances are calculated in terms of the fitted widths observed in data and Monte Carlo simulation.

For the channel, $B^0 \to D^{*-}\rho^+$ the observed $m_{\rm ES}$ distribution is shown in Fig. 3. This has been fitted with the same background function and signal function described above. The projection of the signal as a function of ΔE, also shown in Fig. 3, is fitted using a linear background function plus a single Gaussian distribution with free mean and width, $\sigma_{\Delta E}$, with the region $-0.3 < \Delta E < -0.13$ GeV once more excluded. The width of the signal in $m_{\rm ES}$ is $3.5 \pm 0.3\,{\rm MeV}/c^2$ while the ΔE resolution is observed to be 39.5 ± 4.7 MeV.

A detailed Monte Carlo simulation is used to determine the acceptance for the signal events. Control samples are used to determine the uncertainties on crucial performance characteristics of the simulation. The fitted yields for signal events and estimated efficiencies for each channel are listed in Table 1.

A variety of sources contribute to the systematic errors on the final branching fraction results. The number of produced B mesons is extracted from the ratio of multihadron-to-muon pair events on- and off-resonance, after application of the simple event selection criteria described above. After extrapolation from accepted to produced numbers of $B\overline{B}$ pairs, the estimated uncertainty is 3.6% [4].

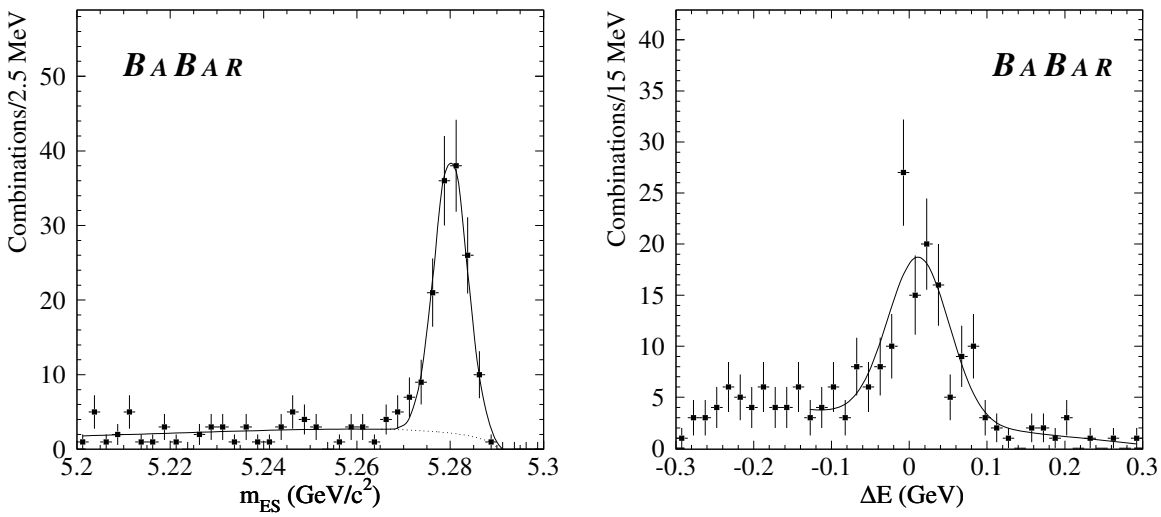

Figure 3: Distribution of $m_{\rm ES}$ for $|\Delta E\ | < 2.5\sigma_{\Delta E}$ (left), and ΔE for $|m_{\rm ES} - m_B^0| < 2.5\sigma m_{\rm ES}$ (right) in the channel $B^0 \to D^{*-}\rho^+$. The fits are described in the text.

The primary check on charged track efficiency is obtained by studying the probability for observing drift chamber versus silicon detector-only tracks in inclusive $D^0 \to K^-\pi^+\pi^+\pi^-$. This is compared with the rate for finding the third track in one-versus-three topology tau-pair decays. A final check is the observed multiplicity distribution in $\Upsilon(4S)$ events. A systematic error of 2.5% per track with $p_T > 1\,\mathrm{GeV}/c$ on the overall efficiency scale is determined by comparing the three methods. The soft pion efficiency is determined from a study of the forward-backward asymmetry in observed D^{*-} decays, and is also constrained to some extent by the same charm and tau-pair studies. The p_T resolution in the Monte Carlo events is adjusted to reproduce the resolution seen in cosmic ray muons. The overall systematic uncertainty in the final result due to tracking efficiency is estimated to be 7.9% for the final states considered in this study. An additional systematic error contribution come from changes in the ratio of observed and predicted efficiencies as the selection requirements are varied within a reasonable range (3%).

In the case of the $B^0 \to D^{*-}\rho^+$ channel, there are additional systematic errors due to the ρ^+ and its polarization. The reconstruction efficiency for the π^0, as modeled in our Monte Carlo simulation, is verified to be accurate to within 5% [4]. The width of the signal in the ΔE projection is modestly larger than predicted by the Monte Carlo simulation. Therefore, we have varied the ΔE requirement for the signal band over a wide range around the nominal 2.5σ, and estimate a further 10% uncertainty due to this requirement. Finally, we have extracted the branching fraction separately in the two hemispheres of the ρ helicity angle, $\theta_H(\rho)$, greater and less than zero. A further 15% systematic error is assigned on the basis of the observed difference in branching fraction. The helicity distributions for the ρ and the D^{*-} are consistent with expectations based on previous measurements [2] and our Monte Carlo efficiency calculation, although we have not yet attempted to determine the polarization from the data.

An additional check of the result for $B^0 \to D^{*-}\pi^+$ is to relax the $\cos\theta_H$ requirement, and extract the fitted signal as a function of $\cos\theta_H$ instead. The distribution of the B candidates

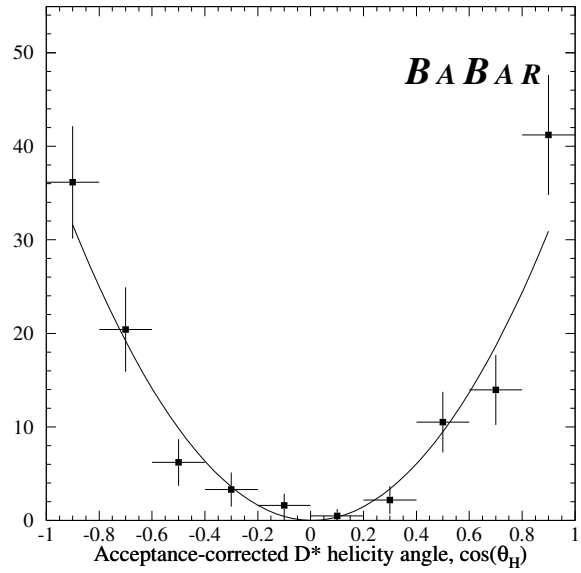

Figure 4: Distribution of $B^0 \to D^{*-}\pi^+$ as a function of the helicity angle of the soft pion, $\cos\theta_H$, in the D^{*-} rest frame after acceptance correction. The vertical axis has arbitrary units.

within $\pm 2.5\sigma_{m_{\rm ES}}$ of the nominal B mass and $\pm 2.5\sigma_{\Delta E}$ of $\Delta E = 0$ exhibits no forward-backward asymmetry after acceptance corrections as can be seen in Figure 4. This confirms our understanding of the soft pion efficiency in the D^{*-} decay. Overlayed on the 126 signal candidates, with an estimated background of 4 events, is a fit with $\cos^2\theta_H$, yielding a χ^2 for goodness-of-fit of 8.6 for 7 degrees of freedom.

The PDG compilation [5] of measured branching fractions for the $D^{*+} \to D^0\pi^+$, $(68.3 \pm 1.4)\%$, and $D^0 \to K^-\pi^+$, $(3.83 \pm 0.09)\%$, are used in computing our final results. The measurement errors on these branching fractions are included in the systematic error on our final result. We also assume the $\Upsilon(4S)$ decays into $B^0\overline{B}^0$ pairs with a 50% fraction; no systematic error is assigned to this value.

Based on fitted yield of signal events, the estimated efficiency, and the number of produced B mesons in our sample, the preliminary results for the branching fractions for $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}\rho^+$ are $(2.9 \pm 0.3 \pm 0.3) \times 10^{-3}$ and $(11.2 \pm 1.1 \pm 2.5) \times 10^{-3}$ respectively. The branching fraction for $B^0 \to D^{*-}\rho^+$ includes all non-resonant and quasi-two-body contributions that lead to a $\pi^+\pi^0$ invariant mass in the ρ band. However, the acceptance for non-resonant $D^{*-}\pi^+\pi^0$ decays is about 15% of $D^{*-}\rho^+$ so that, combined with the known branching fraction for this mode, the non-resonant contribution to our result for $B^0 \to D^{*-}\rho^+$ is expected to be quite small. Both branching fraction results compare well with previous measurements and with the world average [5].

5 Summary

B^0 decays to $D^{*-}\pi^+$ and $D^{*-}\rho^+$ have been studied using the decay chain $D^{*-} \to \overline{D}^0\pi^-$, followed by $\overline{D}^0 \to K^+\pi^-$. The preliminary branching fractions obtained for these channels, $(2.9 \pm 0.3 \pm 0.3) \times$

10^{-3} and $(11.2 \pm 1.1 \pm 2.5) \times 10^{-3}$ respectively, are compatible with previous observations [1, 2, 3].

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