Observation of new resonances decaying to $D\pi$ and $D^*\pi$ in inclusive $e^+e^-$ collisions near $\sqrt{s} = 10.58$ GeV

P. del Amo Sanchez, J. P. Lees, V. Poireau, E. Preciponde, J. Tisserand, J. Garra Tico, E. Grauges, M. Martinelli, A. Palano, M. Pappagallo, G. Eigen, B. Stugu, L. Sun, M. Battaglia, D. N. Brown, B. Hooberman, L. T. Kerth, Y. Guo, Kolomensky, G. Lynch, M. Wisniewski, T. Tanabe, C. M. Hawkes, A. T. Watson, H. Koch, T. Schroeder, J. D. Asgeirsson, C. Hearty, T. S. Mattison, J. A. McKenna, A. Khan, A. R. Ryd, V. E. Blinov, A. R. Buzykaev, V. P. Druzhinin, V. Poireau, J. Yu, I. Skovpen, E. P. Solodov, K. Yu, Todyshev, A. N. Yushkov, M. Bondioli, S. Curry, D. Kirkby, A. J. Lankford, M. Mandelkern, E. C. Martin, D. P. Stoker, H. Afratani, J. W. Gary, F. Liu, O. Long, G. M. Vitug, C. Campagnari, T. M. Hong, D. Kovalsky, J. D. Richman, C. West, M. E. Eisner, C. A. Heuts, J. Kroseberg, W. S. Lockman, A. J. Martinez, T. Schalk, B. A. Schumm, A. Seiden, L. O. Winstead, C. H. Cheng, D. A. Doll, B. Echenard, D. G. Hitlin, P. Ongmongkolkul, F. C. Porter, A. Y. Rakitin, R. Andreassen, M. S. Dubrovin, G. Mancinelli, B. T. Meadows, M. D. Sokoloff, P. C. Bloom, W. T. Ford, A. G. Gaz, M. Nagel, U. Nauenberg, J. G. Smith, S. R. Wagner, W. H. Toki, H. Jasper, T. M. Karbach, J. M. Kivel, Petzold, B. Spaan, K. Wacker, M. J. Kobel, K. R. Schubert, R. Schwartz, D. Bernard, M. Verderi, P. J. Clark, S. Playfer, J. E. Watson, M. Andreotti, D. Bettoni, C. Bozzi, R. Calabrese, A. Cecchi, G. Cibinetto, E. Fioravanti, P. Franchini, E. Luppi, M. Munerato, M. Negrini, A. Petrella, L. Piemontese, R. Baldini-Ferroli, A. Calcetta, R. Sangro, G. Finocchiaro, M. Nicolaci, S. Pacetti, P. Patteri, I. M. Peruzzi, M. Piccolo, R. M. R. Monge, S. Passaggio, C. Patrignani, C. Robutti, T. Sosis, B. Bhuyan, V. Prasad, C. L. Lee, M. Morii, A. Adametz, J. Marks, U. Uwer, F. Bernlochner, M. Ebert, H. M. Lackey, T. Lueck, A. Volk, P. D. Dauncey, M. Tibbetts, P. K. Behera, U. Mallik, J. Chen, J. Cochran, H. B. Cawley, L. Dong, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin, Z. J. Guo, N. Arnaud, M. Davier, D. Derkach, J. Firmino da Costa, G. Grosdidier, F. Le Diberder, A. M. Lutz, B. Malassagna, A. Perez, P. Roudeau, M. H. Schune, J. Serrano, V. Sordini, A. Stocchi, L. Wang, G. Wormser, D. J. Lange, D. M. Wright, J. Bingham, C. A. Chavez, J. P. Coleman, J. R. Frye, E. Gabathuler, R. Gamet, D. E. Hutchcroft, D. J. Payne, C. Touramanis, A. J. Bevan, F. Di Lodovico, R. Sacco, M. Sigamani, G. Cowan, S. Paramesvaran, A. C. W. Crenn, D. N. Brown, C. L. Davis, A. G. Denig, M. Fritsch, W. Gradl, A. Hafner, K. E. Alwyn, D. Bailey, R. J. Barlow, G. Jackson, D. G. Lafferty, J. Anderson, R. Cenci, A. Jawahery, D. A. Roberts, G. Simi, J. M. Tuggle, D. A. M. Tuggle, C. Dallapiccola, E. Salvati, R. Cowan, D. Dujmic, G. Sciolla, M. Zhao, D. Lindemann, P. M. Patel, S. H. Robertson, M. Schram, P. Biassoni, A. Lazaro, V. Lombardo, F. Palombo, S. Stracka, L. Cremaldi, R. Godang, R. Kroeger, P. Sonnek, J. D. Summers, X. Nguyen, M. Simard, P. Taras, G. De Nardo, D. Monorchio, G. Onorato, C. Sciolla, G. Raven, H. L. Snok, C. P. Jessop, K. J. Knoepfel, J. M. LoSecco, W. F. Wang, L. A. Corwin, K. Honscheid, J. J. Krolewski, F. A. Kshaid, R. Kass, J. P. Morris, N. L. Bross, J. Braun, R. Fery, O. Igonkina, J. A. Kolb, R. Rahmat, N. B. Sinev, D. Strom, J. Strube, E. Torrence, G. Castelli, E. Feltresi, N. Gagliardi, M. Maroni, M. Morandin, M. Posocco, F. Simonetto, R. Stroili, E. Ben-Haim, G. R. Bonneau, H. G. Hauffe, G. Calderini, J. Chauveau, H. Hamon, P. Leruste, G. Marchioro, A. Ocari, J. Prendik, S. Sitt, M. Biasini, E. Manoni, A. Ross, C. Angelini, G. Batignani, S. Bettarini, M. Carpinelli, G. Casarosa, A. Cervelli, F. Forti, M. A. Giorgi, A. Luisini, N. Neri, E. Paoloni, G. Rizzo, J. J. Walsh, D. Lopes Pegna, C. Lu, J. Olsen, A. J. S. Smith, A. V. Telnov, E. Baracchini, G. Cavoto, R. Facchini, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Li Gioia, M. A. Mazzone, G. Pireddu, F. Renga, T. Hartmann, T. Ledig, H. Schroder, R. Waldis, T. Adye, B. Franek, O. Olaya, F. F. Wilson, E. S. Emery, G. Hamel de Monchenault, G. Vasseur, Ch. Yêche.
up or a down quark is poorly known. The spectrum of mesons consisting of a charm and an
D and D in a search for new excited
energy collider. We observe, for the first time, candidates for the radial excitations of the
B meson states. We use a dataset, consisting of
= 2 excited states of the
quark-antiquark systems was predicted in 1985 using a relativistic chromodynamic potential model [1]. The low-
mass spectrum of the c¯c or c¯d system is comprised of the ground states (1S), the orbital excitations with angular momentum L=1,2 (1P,1D), and the first radial excitations (2S). In this paper we label the states using the notation D^{(2S+1)}(nL), where J is the total angular momentum of the state, n is the radial quantum number, and L and S are the orbital angular momentum and total spin.

The spectrum of mesons consisting of a charm and an
up or a down quark is poorly known. The spectrum of
of the quarks. Besides the ground states \((D, D^*)\), only two 1P states, known as the \(D_1(2420)\) and \(D_2(2460)\) \([2]\), are well-established experimentally since they have relatively narrow widths (\(\sim 30\) MeV). In contrast, the other two 1P states, known as the \(D_0^*(2400)\) and \(D_1^*(2430)\), are very broad (\(\sim 300\) MeV), making them difficult to detect \([3-5]\).

To search for states not yet observed, we analyze the inclusive production of the \(D^+\pi^-\), \(D^0\pi^+\), and \(D^{*+}\pi^-\) \([6]\) final states in the reaction \(e^+e^- \rightarrow c\bar{c} \rightarrow D^{(*)}\pi X\), where \(X\) is any additional system. We use an event sample consisting of approximately 590 million \(e^+e^- \rightarrow c\bar{c}\) events \((454\) fb\(^{-1}\)) produced at \(e^+e^-\) center-of-mass (CM) energies near \(10.58\) GeV and collected with the BaBar detector at the SLAC PEP-II asymmetric-energy collider. Our signal yield for the \(L = 1\) resonances is more than ten times larger than the best previous study \([7]\), resulting in much greater sensitivity to higher resonances.

The BaBar detector is described in detail in Ref. \([8]\). Charged-particle momenta are measured with a 5-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) inside a 1.5-T superconducting solenoidal magnet. A calorimeter consisting of 6580 CsI(Tl) crystals is used to measure electromagnetic energy. A ring-imaging Cherenkov radiation detector (DIRC), aided by measurements of ionization energy loss, \(dE/dx\), in the SVT and DCH, is used for particle identification (PID) of charged hadrons.

The \(D\pi\) system is reconstructed in the \(D^+\pi^-\) and \(D^0\pi^+\) modes, where \(D^+ \rightarrow K^-\pi^+\pi^+\) and \(D^0 \rightarrow K^-\pi^+\). A PID algorithm is applied to all tracks. Charged kaon identification has an average efficiency of 90% within the acceptance of the detector and an average pion-to-kaon misidentification probability of 1.5%.

For all channels we perform a vertex fit for the \(D^+\) and \(D^0\) daughters. To improve the signal to background ratio for \(D^+ \rightarrow K^-\pi^+\pi^+\), we require that the measured flight distance of the \(D^\pi\) candidate from the \(e^+e^e^-\) interaction region be greater than 5 times its uncertainty. To improve the signal purity for \(D^0 \rightarrow K^-\pi^+\pi^-\) we require \(\cos\theta_K < -0.9\) where \(\theta_K\) is the angle formed by the \(K^-\) in the \(D^0\) candidate rest frame with respect to the prior direction of the \(D^0\) candidate in the CM reference frame. The \(D\pi\) candidates for both \(D^+\) and \(D^0\) are then reconstructed by performing a vertex fit with an additional charged primary pion, which originates from the \(e^+e^-\) interaction region. For all vertex fits we require a \(\chi^2\) probability > 0.1%.

In the \(D^0\pi^+\) sample, we veto \(D^0\) candidates from \(D^{*+}\) or \(D^{*0}\) decays by forming \(D^0\pi^+\) (where the \(\pi^+\) is any additional pion in the event) and \(D^0\pi^0\) combinations, and rejecting the event if the invariant-mass difference between this combination and the \(D^0\) candidate is within \(2\sigma\) of the nominal \(D^*\pi\) mass difference \([2]\), where \(\sigma\) is the detector resolution.

The \(K^-\pi^+\pi^+\) and \(K^-\pi^+\) mass distributions are shown in Figs. 1 a) and 1 b). We fit these distributions to a linear background and a Gaussian signal; the signal widths obtained are \(\sigma_{D^+} = 6.7\) MeV/c\(^2\) and \(\sigma_{D^{*0}} = 7.6\) MeV/c\(^2\). The signal region is defined to be within \(\pm 2.5\)\(\sigma\) of the peak, while sideband regions are defined as the ranges \((\pm 5.0\sigma, \pm 7.5\sigma)\) and \((\pm 4.0\sigma, \pm 6.5\sigma)\) for the \(D^+\) and \(D^0\), respectively. The \(D^+\) signal region has purity \(N_S/(N_S + N_B) = 65\%\), where \(N_S\) (\(N_B\)) is the number of signal (background) events, while the \(D^0\) purity is 83%.

The \(D^{*+}\pi^-\) system is reconstructed using the \(D^0 \rightarrow K^-\pi^+\pi^-\) and \(D^0 \rightarrow K^-\pi^+\pi^-\) decay modes. A \(D^0\) candidate is accepted if its invariant mass is within \(30\) MeV/c\(^2\) of the mean value. A \(D^{*+}\) candidate is reconstructed by requiring an additional slow pion (\(\pi^+_s\)) originating from the \(e^+e^-\) interaction region. We select a \(D^{*+}\) candidate if the mass difference \(\Delta m = m(K^-\pi^+(\pi^+\pi^-)\pi^+_s) - m(K^-\pi^+(\pi^+\pi^-))\) is within \(2.0\) MeV/c\(^2\) of the mean value. The \(D^0\) candidate invariant mass distribution and the \(\Delta m\) distribution are shown in Figs. 1 c) and 1 d). The \(D^+\) signal purity is 89%. Finally, we reconstruct a \(D^{*+}\pi^-\) candidate by combining a \(D^{*+}\) candidate with an additional charged track identified as a \(\pi^-\) and applying a vertex fit.

Background from \(e^+e^- \rightarrow BB\) events, and much of the combinatorial background, are removed by requiring the CM momentum of the \(D^{(*)}\pi\) system to be greater than \(3.0\) GeV/c. In addition, we remove fake primary pion candidates originating mainly from the opposite side of the event by requiring \(\cos\theta_\pi > -0.8\). The angle \(\theta_\pi\) is defined in the \(D^{(*)}\pi\) rest frame as the angle between the primary pion direction and the prior direction of the \(D^{(*)}\pi\) system in the CM frame.

To extract the resonance parameters we define the variables \(M(D^+\pi^-) = m(K^-\pi^+\pi^-) - m(K^-\pi^+\pi^+) + m_{D^+}\) and \(M(D^0\pi^+) = m(K^-\pi^+) - m(K^-\pi^-) + m_{D^{*0}},\) where \(m_{D^+}\) and \(m_{D^{*0}}\) are the values of the \(D^+\) and \(D^0\) mass \([2]\). The use of the mass difference improves the

![FIG. 1: (color online) Mass distribution for a) \(D^+\) and b) \(D^0\) candidates in the \(D^+\pi^-\) and \(D^0\pi^+\) samples. Plots c) and d) correspond to the \(D^{*+}\pi^-\) sample and show the mass distribution for \(D^0\) candidates and the \(\Delta m\) distribution for \(D^{*+}\) candidates. The vertical lines show the signal and, in a) and b), the side-band regions.](image-url)
resolution on the reconstructed mass to about 3 MeV/$c^2$. We remove the contribution due to fake $D^+$ and $D^0$ candidates by subtracting the $M(D\pi)$ distributions obtained by selecting events in the $D^+$ or $D^0$ candidate mass sidebands.

The $D^+\pi^-$ and $D^0\pi^+$ mass spectra are presented in Fig. 2 and show similar features.

- Prominent peaks for $D_2^*(2460)^0$ and $D_2^*(2460)^+$.
- The $D^+\pi^-$ mass spectrum shows a peaking background (feeddown) at about 2.3 GeV/$c^2$ due to decays from the $D_1(2420)^0$ and $D_2^*(2460)^0$ to $D^{*+}\pi^-$. The $D^{*+}$ in these events decays to $D^{*+}\pi^0$ and the $\pi^0$ is missing in the reconstruction. The missing $\pi^0$ has very low momentum because the $D^{*+}$ decay is very close to threshold. Therefore, these decays have a mass resolution of only 5.8 MeV/$c^2$ and a bias of $-143.2$ MeV/$c^2$. Similarly, $D^0\pi^+$ shows peaking backgrounds due to the decays of the $D_1(2420)^+$ and $D_2^*(2460)^+$ to $D^{*0}\pi^+$ where the $D^{*0}$ decays to $D^0\pi^0$.
- Both $D^+\pi^-$ and $D^0\pi^+$ mass distributions show new structures around 2.6 and 2.75 GeV/$c^2$. We call these enhancements $D^*(2600)$ and $D^*(2760)$.

We have compared these mass spectra with those obtained from generic $e^+e^- \rightarrow \bar{c}c$ Monte Carlo (MC) events. These events were generated using JETSET [9] with all the known particle resonances incorporated. The events are then reconstructed using a detailed GEANT4 [10] detector simulation and the event selection procedure used for the data. In addition, we study $D\pi$ mass spectra from the $D^+$ and $D^0$ candidate mass sidebands, as well as mass spectra for wrong-sign $D^{*+}\pi^+$ and $D^{0}\pi^-$ samples. We find no backgrounds or reflections that can cause the structures at 2.6 and 2.76 GeV/$c^2$. In the study of the $D^0\pi^-$ final state we find a peaking background due to events where the $D^0$ candidate is not a true $D^0$, but the $K^-$ candidate and the primary $\pi^+$ candidate are from a true $D^0 \rightarrow K^-\pi^+$ decay. These combinations produce enhancements in $M(D^0\pi^+)$ both in the $D^0$ candidate mass signal region and sidebands. However, this background is linear as a function of the $D^0$ candidate mass, is removed by the sideband subtraction.

The smooth background is modeled using the function:

$$B(x) = P(x) \times \begin{cases} e^{c_1 x + c_2 x^2} & \text{for } x \leq x_0, \\ e^{d_0 x + d_1 x + d_2 x^2} & \text{for } x > x_0, \end{cases}$$  \hspace{1cm} (1)$$

where $P(x) = \frac{1}{\sqrt{\pi}} \frac{1}{\sqrt{x^2 - (m_D + m_x)^2} \sqrt{x^2 - (m_D - m_x)^2}}$ is a two-body phase-space factor and $x = M(D\pi)$. Only four parameters are free in the piece-wise exponential: $c_1$, $c_2$, $d_2$, and $x_0$. The parameters $d_0$ and $d_1$ are fixed by requiring that $B(x)$ be continuous and differentiable at the transition point $x_0$. We account for the feeddown of peaking backgrounds by convolving Breit-Wigner (BW) functions [11] with a function describing the resolution and bias obtained from the simulation of these decays. The mass and width of the $D_1(2420)$ feeddown are fixed to the values obtained in the $D^+\pi^-$ analysis described below, while the parameters of the $D_2^*(2460)$ feeddown are fixed to those of the true $D_2^*(2460)$ in the same $M(D\pi)$ distribution.

The $D_2^*(2460)$ is modeled using a relativistic BW function with the appropriate Blatt-Weisskopf centrifugal barrier factor [2]. The $D^*(2600)$ and $D^*(2760)$ are modeled with relativistic BW functions [2]. Finally, although not visible in the $M(D^+\pi^-)$ mass distribution, we include a BW function to account for the known resonance $D_2^*(2400)$, which is expected to decay to this final state. The $\chi^2$ per number of degrees of freedom (NDF) of the fit decreases from 596/245 to 281/242 when this resonance is included. This resonance is very broad and is present together with the feeddown and $D_2^*(2460)^0$; therefore we restrict its mass and width parameters to be within $2\sigma$ of the known values [5]. The shapes of the signal components are corrected for a small variation of the efficiency as a function of $M(D\pi)$ and are multiplied by the two-body phase-space factor. They are also corrected for the mass resolution by convolving them with the resolution function determined from MC simulation of signal de-
The fit to the $M(D^0\pi^+)$ mass distribution (Fit B) is shown in Fig. 2 (bottom); this fit has $\chi^2$/NDF of 278/224. We find consistent mass values for both $D^*(2600)$ and $D^*(2760)$ in the fits of the $D^+\pi^-$ and $D^0\pi^+$ mass distributions.

We now search for these new states in the $D^{*+}\pi^-$ decay mode. We define the variable $M(D^{*+}\pi^-) = m(K^-\pi^+\pi^-\pi^0\pi^-) - m(K^-\pi^+\pi^-\pi^+\pi^-) + m_{D^{++}}$ where $m_{D^{++}}$ is the value of the $D^{*+}$ mass [2]. The $D^{*+}\pi^-$ mass distribution is shown in Fig. 3 and shows the following features.

- Prominent $D_1(2420)^0$ and $D_2(2460)^0$ peaks.
- Two additional enhancements at $\sim 2.60$ GeV/c$^2$ and $\sim 2.75$ GeV/c$^2$, which we initially denote as $D^*(2600)^0$ and $D^*(2750)^0$.

Studies of the generic MC simulation as well as studies of the $D^{*+}$ sidebands and the wrong-sign sample ($D^{*+}\pi^-$) show no peaking backgrounds in this mass spectrum.

We fit $M(D^{*+}\pi^-)$ by parametrizing the background with the function in Eq. (1). The $D_1(2420)^0$ and $D_2(2460)^0$ resonances are modeled using relativistic BW functions with appropriate Blatt-Weisskopf form factors. The $D^*(2600)^0$ and $D^*(2750)^0$ are modeled with relativistic BW functions. The broad resonance $D_2'(2430)^0$ is known to decay to this final state, however, this fit is insensitive to it due to its large width ($\sim 380$ MeV) [4] and because the background parameters are free.

Due to the vector nature of the $D^{*+}$, the $D^{*+}\pi^-$ final state contains additional information about the spin-parity $(J^P)$ quantum numbers of the resonances. In the rest frame of the $D^{*+}$, we define the helicity angle $\theta_H$ as the angle between the primary pion $\pi^-$ and the slow pion $\pi^+$ from the $D^{*+}$ decay. The distributions in $\cos \theta_H$ for the predicted resonances, assuming parity conservation, are given in Table II. Initially, we have attempted to fit the $M(D^{*+}\pi^-)$ distribution incorporating only two new signals at $\sim 2.6$ GeV/c$^2$ and at $\sim 2.75$ GeV/c$^2$. However, when we extract the yields as a function of $\cos \theta_H$ we find that the mean value of the peak at $\sim 2.6$ GeV/c$^2$ increases by $\sim 70$ MeV/c$^2$ between $\cos \theta_H = -1$ and $\cos \theta_H = 0$, and decreases again as $\cos \theta_H \to +1$. This behaviour suggests two resonances with different helicity-angle distributions are present in this mass region. To proceed we incorporate a new component, which we call $D(2550)^0$, into our model at $\sim 2.55$ GeV/c$^2$. We extract the parameters of this component by requiring $|\cos \theta_H| > 0.75$ in order to suppress the other resonances. In this fit (Fit C), shown in Fig. 3 (top), we fix the parameters of the $D_2(2460)^0$ and $D^*(2600)^0$ to those measured in $D^+\pi^-$. We obtain a $\chi^2$/NDF of 214/205 for this fit. This fit also determines the parameters of the $D_1(2420)^0$. We then perform a complementary fit (Fit D), shown in Fig. 3 (middle), in which we require $|\cos \theta_H| < 0.5$ to discriminate in favor of the $D^*(2600)^0$. We obtain a $\chi^2$/NDF of 210/209 for this fit. To determine the final parameters of the $D(2750)^0$ signal we fit the total $D^{*+}\pi^-$ sample while assuming isospin symmetry.
TABLE I: Summary of the results. The first error is statistical and the second is systematic; “fixed” indicates the parameters were fixed to the values from Fit A or C. The significance is defined as the yield divided by its total error.

| Resonance | Channel (Fit) | Efficiency (%) | Yield (x10^3) | Mass (MeV/c^2) | Width (MeV) | Significance |
|-----------|---------------|----------------|---------------|----------------|-------------|--------------|
| D_1(2420)^0 | D^+π^- (C) | 1.09 ± 0.03 | 102.8±1.3±2.3 | 2420.1±0.1±0.8 | 31.4(4)±13 | 1.0 ± 0.3 |
| D_2(2460)^0 | D^+π^- (E) | 1.29 ± 0.03 | 230.8±1.8±3.4 | 2462.2±0.1±0.8 | 50.5(4)±10 | 1.0 ± 0.3 |
| D(2550)^0 | D^+π^- (C) | 1.12 ± 0.04 | 136±2±13 | 2402.2±0.2±0.5 | 50.5(4)±10 | 1.0 ± 0.3 |
| D^*(2600)^0 | D^+π^- (E) | 1.14 ± 0.04 | 34.3±6.7±9.2 | 2539.4±4.5±6.9 | 130±12±13 | 3.0 ± 0.3 |
| D^*(2600)^+ | D^+π^- (A) | 1.35 ± 0.05 | 26.0±1.4±6.6 | 2608.7±2.4±2.5 | 93±6±13 | 3.9 ± 0.3 |
| D^*(2600)^+ | D^+π^- (D) | 50.2±3.0±6.7 | 2608.7(4) | 93(fixed) | 7.3 ± 0.3 |
| D^*(2600)^+ | D^+π^- (E) | 1.18 ± 0.05 | 71.4±1.7±7.3 | 2608.7±9(4) | 93(fixed) | 7.3 ± 0.3 |
| D(2750)^0 | D^+π^- (E) | 1.23 ± 0.07 | 23.5±2.1±5.2 | 2752.4±1.7±2.7 | 11±6±11 | 4.0 ± 0.3 |
| D(2760)^0 | D^+π^- (A) | 1.41 ± 0.09 | 113±0.8±1.0 | 2763.3±2.3±2.7 | 60.9±5.1±3.6 | 8.9 ± 0.3 |
| D_2(2460)^+ | D^0π^+ (B) | 110.8±1.3±7.5 | 2465±0.2±1.1 | 50.5(4) | 50.5(4) | 50.5(4) |
| D(2600)^+ | D^0π^+ (B) | 110.8±1.3±7.5 | 2465±0.2±1.1 | 50.5(4) | 50.5(4) | 50.5(4) |
| D(2760)^+ | D^0π^+ (B) | 5.7±0.7±1.5 | 2769.7±3.8±1.5 | 60.9(4) | 60.9(4) | 60.9(4) |

The first model for the M(D^+π^-) distribution is used to extract the signal yields as a function of cos θ_H. We divide the data into 10 sub-samples corresponding to cos θ_H intervals of 0.2 between −1 and +1. Each sample is fitted with all shape parameters fixed to the values determined above. The yields extracted from these fits are plotted for each signal in Fig. 4. For the D_1(2420) we measure the helicity parameter h = 5.7±0.2, where the error includes both statistical and systematic uncertainties. This value is consistent with the measurement by ZEUS [12]. The cos θ_H distributions of the D_2(2460) and D^*(2600) are consistent with the expectations for natural parity, defined by P = (−1)^l, and leading to a sin^2 θ_H distribution. This observation supports the assumption that the enhancement assigned to the D^*(2600) in the D^+π^- and D^+π^- belong to the same state; only states with natural parity can decay to both D^+π^- and D^+π^-.

The cos θ_H distribution for the D(2550)^0 is consistent with pure cos^2 θ_H as expected for a J^P = 0^- state.

The ratio of branching fractions B(D^*(2600)^0 → D^+π^-) / B(D^*(2600)^0 → D^+π^-) (where D^+ labels any resonance) can be useful in the identification of the new signals with predicted states. We compute this ratio for the D_2(2460)^0, D^*(2600)^0, and D(2750)^0 using the yields obtained from the fits to the total samples and correcting for the reconstruction efficiency: (N_{D^0π^-}/σ_{D^0π^-})/(N_{D^+π^-}/σ_{D^+π^-}). The efficiencies and yields are shown in Table I. We find the following ratios:

B(D_2(2460)^0 → D^+π^-) = 1.47 ± 0.03 ± 0.16,
B(D(2550)^0 → D^+π^-) = 0.32 ± 0.02 ± 0.09,
B(D^*(2600)^0 → D^+π^-) = 0.42 ± 0.05 ± 0.11.

The first uncertainty is due to the statistical uncertainty on the yields. The second uncertainty includes the systematic uncertainty on the yields, the systematic uncertainty due to differences in PID and tracking efficiency, and the errors from the branching fractions for the de-
FIG. 4: (color online) Distribution in $\cos \theta_H$ for each signal in $D^{\ast+} \pi^-$. The error bars include statistical and correlated systematic uncertainties. The curve is a fit using the function $Y$ shown in the plot; $\varepsilon_H$ is the efficiency as a function of $\cos \theta_H$.

cay chains [2]. Although in the last ratio the signal in the numerator may not be the same as the signal in the denominator, we determine the ratio, as it may help elucidate the nature of this structure.

In summary, we have analyzed the inclusive production of the $D^{\ast+} \pi^-$, $D^0 \pi^+$, and $D^{\ast+} \pi^-$ systems in search of new $D$ meson resonances using 454 $\text{fb}^{-1}$ of data collected by the BABAR experiment. We observe for the first time four signals, which we denote $D(2550)^0$, $D^*(2600)^0$, $D(2750)^0$, and $D^*(2760)^0$. We also observe the isospin partners $D^*(2600)^+$ and $D^*(2760)^+$. The $D(2550)^0$ and $D^*(2600)^0$ have mass values and $\cos \theta_H$ distributions that are consistent with the predicted radial excitations $D^*_1(25)$ and $D^*_1(25)$. The $D^*(2760)^0$ signal observed in $D^{\ast+} \pi^-$ is very close in mass to the $D(2750)^0$ signal observed in $D^{\ast+} \pi^-$; however, their mass and width values differ by 2.6$\sigma$ and 1.5$\sigma$, respectively. Four $L = 2$ states are predicted to lie in this region [1], but only two are expected to decay to $D^+ \pi^-$. This may explain the observed features.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MICIN (Spain), STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union), the A. P. Sloan Foundation (USA) and the Binational Science Foundation (USA-Israel).

[1] S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).
[2] C. Amsler et al. (Particle Data Group), Phys. Lett. B 667, 1 (2008).
[3] A. F. Falk and M. E. Peskin, Phys. Rev. D 49, 3320 (1994).
[4] K. Abe et al. (BELLE collaboration), Phys. Rev. D 69, 112002 (2004).
[5] B. Aubert et al. (BABAR collaboration), Phys. Rev. D 79, 112004 (2009).
[6] Charge conjugates are implied throughout this paper.
[7] A. Abulencia et al. (CDF collaboration), Phys. Rev. D 73, 051104 (2006).
[8] B. Aubert et al. (BABAR collaboration), Nucl. Instrum. Methods in Phys. Res. Sect. A 479, 1 (2002).
[9] T. Sjostrand, Computer Physics Commun. 82, 74 (1994).
[10] S. Agostinelli et al. (GEANT4 collaboration), Nucl. Instrum. Methods in Phys. Res. Sect. A 506, 250 (2003).
[11] G. Breit and E. Wigner, Phys. Rev. 49, 519 (1936).
[12] S. Chekanov et al. (ZEUS collaboration), Eur. Phys. J. C 60, 25 (2009).