Observation of anomalous production of D-mesons in $\sqrt{s} = 4.03$ GeV e^+e^- annihilations

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Abstract

We report a study of inclusive D-meson production in $\sqrt{s} = 4.03$ GeV e^+e^- collisions based on a 22.3 pb^{-1} data sample accumulated in the BES detector. Fits to the inclusive single D-meson momentum spectrum indicate that a substantial component of the observed $D\overline{D}\pi$ and/or $D\overline{D}\gamma$ final states can not be attributed to either $D^*\overline{D}$ or non-resonant production.

1 Introduction

The momentum spectrum of D-mesons produced in e^+e^- collisions at $\sqrt{s} = 4.03$ GeV is characterized by three distinct features, as illustrated in Fig. 1. A peak near $p_D = 0.75$ GeV corresponds to nearly monochromatic D-mesons from two-body pair production $e^+e^- \to D\overline{D}$. The width of this peak is determined by resolution and a small contribution from initial state radiation. At low momentum, in the range $\sim 0.05 < p_D < 0.25$ GeV, there is a broad feature consistent with $e^+e^- \to D\overline{D}\pi\pi$ production. This production is expected to be dominated by $D^*\overline{D^*}$ final states and the momentum of both D-mesons is smeared by the $D^* \to D$ decay process. The third feature, in the "intermediate" momentum region between $p_D \sim 0.4$ and 0.6 GeV corresponds to $e^+e^- \to D\overline{D}\pi$ production. Here $D^*\overline{D}$ final states are expected to dominate, and the shape of the momentum spectrum in this region is a combination of a resolution-broadened monochromatic peak at $p_D = 0.55$ GeV, corresponding to the directly produced "bachelor" $\overline{D}$, with a broad distribution corresponding to "daughter" D-mesons from the $D^* \to D\pi$ and $D\gamma$ decays.

It is also possible to have nonresonant $D\overline{D}\pi$ production. For this case, the most general decay matrix element coupling the $J^P = 1^-$ $\psi(4.03)$ initial state to the $0^-0^-0^-$ $D\overline{D}\pi$ final state is the axial vector combination $\vec{p_D} \times \vec{p_{\overline{D}}}$. This matrix element emphasizes events where the three final state particles have nearly equal momenta and the inclusive D momentum spectrum indicated by the dashed line in Fig. 1. This distribution peaks around $p_D \simeq 0.4$ GeV/c with a preponderance of events in the momentum region between the contributions from $D^*\overline{D^*}$ and $D^*\overline{D}$ production.

The Mark-II [1] and Mark-III [2] experiments have reported determinations of D^* branching ratios based on analyses of events with D mesons in this intermediate momentum region.

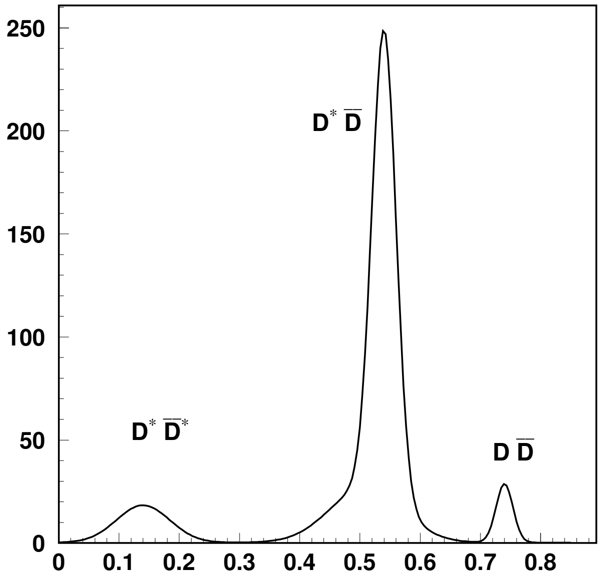

Figure 1: A sketch of D momentum spectrum

In both cases, a $D^{*+} \to D^+\gamma$ branching fraction near 20% is reported, in marked disagreement with the recent direct CLEO measurement of $1.4 \pm 0.5\%$ [3].

In this report we present preliminary results of a study of the inclusive D-meson momentum distribution in the $0.3 < p_D < 0.7$ GeV momentum region using a 22.3pb^{-1} data sample e^+e^- annihilation events accumulated in the BES detector located at the Beijing Electron-Positron Collider. The results are compared to expectations based on $D^*\overline{D}$ and nonresonant $D\overline{D}\pi$ production.

2 Experimental procedure

The BES detector is a large solid-angle magnetic spectrometer that is described in detail in ref. [4]. Charged particle momenta are determined by a resolution of $\sigma_p/p = 2.1\%\sqrt{1+p^2(GeV)}$ in a 40-layer drift chamber. Particle identification is provided by dE/dx measurements in the drift chamber and a surrounding barrel array of time-of-flight (TOF) scintillation counters. For this analysis we use tracks that are well fit to a three-dimensional helix that originates near the interaction region and within the polar angle region $|\cos\theta| < 0.85$. The dE/dx and TOF information for each track is used to determine χ^2 values for the hypotheses that the track is either a charged pion or kaon.

Charged D mesons are identified via the $D^+ \to K^-\pi^+\pi^+$ decay mode.[1] For each track

[1] In this analysis we always include, but do not explicitly indicate, the charge conjugate modes.

combination with the appropriate net charge, we determine an overall particle identification likelihood from the χ^2 values of the individual tracks. The particle assignment with the highest likelihood is used. The invariant mass of all $K^-\pi^+\pi^+$ combinations selected in this way are plotted as data points in Fig. 2, where a pronounced peak at M_{D^+} is evident. Included in the figure is a histogram of the invariant masses of wrong-sign $K^+\pi^+\pi^-$ combinations, normalized to match the right-sign distribution away from the D^+ mass peak. A fit of a single gaussian to the invariant mass distribution with the wrong-sign distribution used as a background shape yields a total number of 2369 ± 144 $D^\pm$ mesons. Of these, 1776 ± 106 are in the $0.3 < p_D < 0.7$ GeV momentum range.

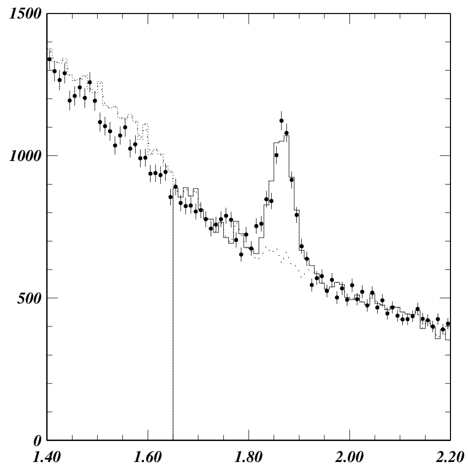

Figure 2: The $K^-\pi^+\pi^+$ mass distribution.

For the inclusive D^0 meson measurement we use the $D^0 \rightarrow K^-\pi^+$ mode. For each opposite-sign track combination we make the most likely particle identification assignment using the individual track χ^2 values. The resulting $K^-\pi^+$ invariant mass distribution is shown as data points in Fig. 3, where there is a strong D^0 signal. Included in the figure as a histogram is the invariant mass distribution of doubly charged $\pi^\pm K^\pm$ pairs, normalized to that of the neutral pairs for masses above the D^0 peak. The doubly charged distribution describes the background well on the high-mass side of the D^0 peak, but fails for low masses because of the presence of neutral $\pi^\pm K^\mp$ pairs from $D \rightarrow K\pi\pi$ decays, a background that is confined to be below $M_{K\pi} < 1.73$ GeV. A fit of a single gaussian to the πK mass distribution of Fig. 3 using the doubly charged distribution for masses above 1.73 GeV as a background shape yields a total number of 4537 ± 176 D^0 and $\overline{D^0}$ mesons, including 2501 ± 125 in the momentum range.$0.3 < p_D < 0.7$ GeV.

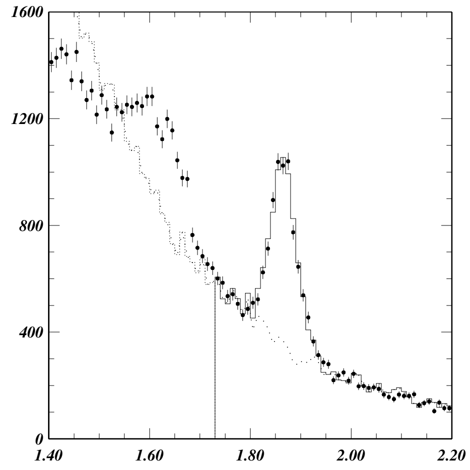

Figure 3: The $K^-\pi^+$ mass distribution.

To determine the inclusive D-meson momentum spectrum, we separate the events shown in Figs. 2 and 3 into 10 MeV/c bins of the $K\pi\pi$ and $K\pi$ momentum, respectively, and fit each individual spectrum using the same procedure as described above. These fits give the inclusive D-meson momentum distributions shown in Figs. 4 and 5, both of which clearly show the three structures illustrated in Fig. 1 above.

3 Fitting the momentum spectra

We fit the momentum spectra using MC-determined shape functions for the bachelor and daughter distributions. Although we focus on the intermediate region, we also fit the low-momentum $D^*\overline{D^*}$ and high momentum $D\overline{D}$ regions as a check of our procedures. Here we only describe in detail the input to the intermediate region fits

There are three components to the intermediate momentum region of the charged D momentum spectrum: bachelors with area $N^{bach}_{D^+}$, and the daughters from $D^{*+} \to D^+\pi^0$ with area $N^{dau}_{D^+\pi^0}$ and from $D^{*+} \to D^+\gamma$ with area $N^{dau}_{D^+\gamma}$. These are related to each other as

$$\begin{aligned} N^{bach}_{D^+} &= N^{D^{*+}D^-}\mathcal{B}^+_{K2\pi}\eta_{K2\pi}, \\ N^{dau}_{D^+\pi^0} &= \mathcal{B}^*_{D^+\pi^0}N^{D^{*+}D^-}\mathcal{B}^+_{K2\pi}\eta_{K2\pi} = \mathcal{B}^*_{D^+\pi^0}N^{bach}_{D^+}, \text{ and} \\ N^{dau}_{D^+\gamma} &= \mathcal{B}^*_{D^+\gamma}N^{D^{*+}D^-}\mathcal{B}^+_{K2\pi}\eta_{K2\pi} = \mathcal{B}^*_{D^+\gamma}N^{bach}_{D^+}, \end{aligned} \quad (1)$$

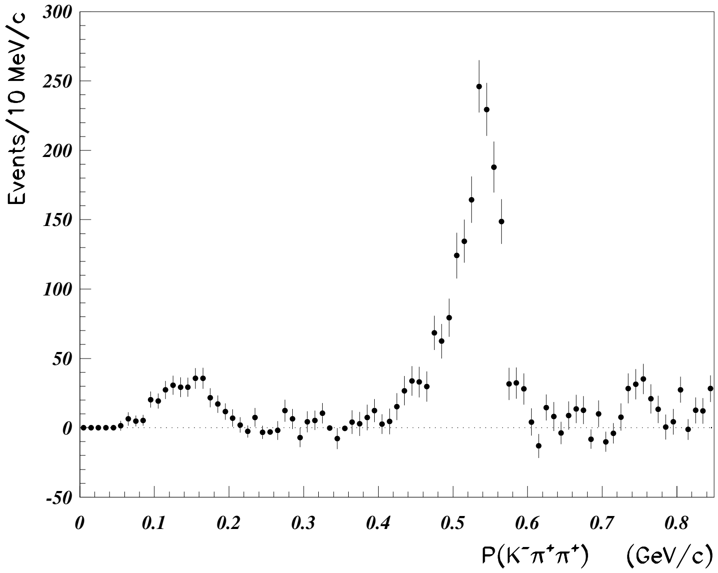

Figure 4: The inclusive D^+ momentum spectrum for the $D^+ \to K^-\pi^+\pi^+$ mode.

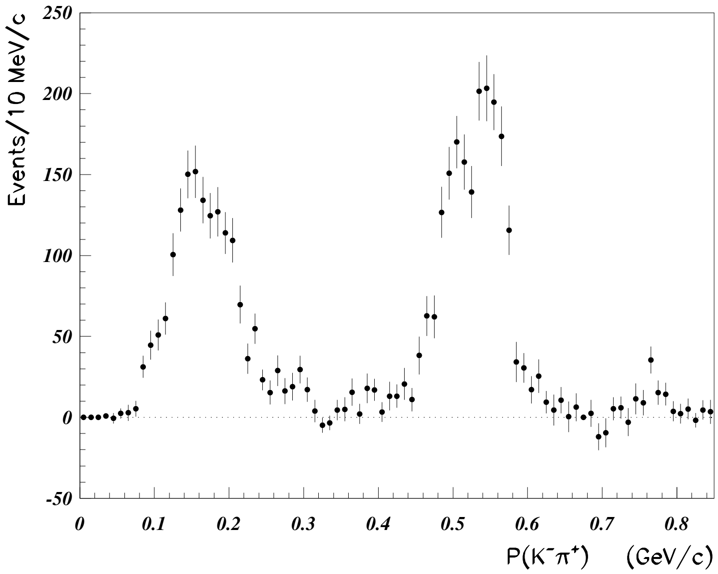

Figure 5: The inclusive D^0 momentum spectrum for the $D^0 \to K^-\pi^+$ mode

where $\eta_{K2\pi}$ is the $D^+ \to K^-\pi^+\pi^+$ acceptance determined from the MC simulation. Since the bachelor and daughter D^+ mesons have slightly different momenta, the acceptances in each case are, in principle, somewhat different. However, MC simulations indicate that these differences are enirely negligible at the level of precision with which they can be determined ($\sim \pm 5\%$). The MC result is $\eta_{K2\pi} = 0.22 \pm 0.01$.

There are four components to the intermediate momentum region of the neutral D momentum spectrum: the bachelors, with area $N_{D^0}^{bach}$, and the daughters from $D^{*0} \to D^0\pi^0$ with area $N_{D^0\pi^0}^{dau}$ and from $D^{*0} \to D^0\gamma$ with area $N_{D^0\gamma}^{dau}$, and daughters from $D^{*+} \to D^0\pi^+$ with $N_{D^0\pi^+}^{dau}$. These are related to each other as

$$\begin{array}{lclcl}
N_{D^0}^{bach} & = & N^{D^{*0}\overline{D^0}}\mathcal{B}_{K\pi}^0\eta_{K\pi}, & & \\
N_{D^0\pi^0}^{dau} & = & \mathcal{B}_{D^0\pi^0}^{*}N^{D^{*0}\overline{D^0}}\mathcal{B}_{K\pi}^0\eta_{K\pi} & = & \mathcal{B}_{D^0\pi^0}^{*}N_{D^0}^{bach}, \\
N_{D^0\gamma}^{dau} & = & \mathcal{B}_{D^0\gamma}^{*}N^{D^{*0}\overline{D^0}}\mathcal{B}_{K\pi}^0\eta_{K\pi} & = & \mathcal{B}_{D^0\gamma}^{*}N_{D^0}^{bach}, \text{ and} \\
N_{D^0\pi^+}^{dau} & = & \mathcal{B}_{D^0\pi^+}^{*}N^{D^{*+}D^-}\mathcal{B}_{K\pi}^0\eta_{K\pi} & = & \mathcal{B}_{D^0\pi^+}^{*}(\mathcal{B}_{K\pi}^0\eta_{K\pi}/\mathcal{B}_{K2\pi}^{+}\eta_{K2\pi})N_{D^+}^{bach},
\end{array} \tag{2}$$

where $\eta_{K\pi}$ $D^0 \to K^-\pi^+$ acceptance, which is equal within errors for the four different sources, and the last relation makes use of the first relation of eqn. (1). The MC simulation gives $\eta_{K\pi} = 0.42 \pm 0.02$.

With CLEO's direct measurement of the $D^{*+} \to D^+\gamma$ mode, all of the branching fractions in the above relations are well known [5]. In addition, I-spin symmetry in the $e^+e^- \to D^*\overline{D}$ process implies

$$\frac{N^{D^{*0}\overline{D^0}}}{N^{D^{*+}D^-}} = \left(\frac{p_{D^0}}{p_{D^+}}\right)^3 = 1.077, \tag{3}$$

which provides the relation

$$N_{D^0}^{bach} = 1.077 N_{D^+}^{bach}\frac{\mathcal{B}_{K\pi}^0\eta_{K\pi}}{\mathcal{B}_{K2\pi}^{+}\eta_{K2\pi}}. \tag{4}$$

Thus, if D-meson production in the $0.3 < p_D < 0.7$ GeV momentum region is all due to I-spin conserving $e^+e^- \to D^*\overline{D}$ processes, both the charged and neutral D-meson momentum spectra can, in principle, be simultaneously fit with a single free parameter, $N_{D^+}^{bach}$, the number of charged bachelor D mesons. In practice, since the relation between $N_{D^+}^{bach}$ and $N_{D^0}^{bach}$ in eqn. (4) depends upon ratios of the $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ acceptance and branching ratios, we use both $N_{D^+}^{bach}$ and $N_{D^0}^{bach}$ as free parameters. In this case, the only component of the fit that depends on knowing the relative acceptance and branching fractions is the $N_{D^0\pi^+}^{dau}$ component of the D^0 spectrum.

3.1 Fit to $D^*\overline{D}$ production with fixed D^* decay branching fractions

Figs. 6a and b show the results of fits to the D^+ and D^0 momentum spectra in the range $0.3 < p_D < 0.7$ GeV assuming only $D^*\overline{D}$ production. Here we fix the D^* branching ratios at the PDG/CLEO values and leave $N^{bach}_{D^+}$ and $N^{bach}_{D^0}$ as free parameters. The fit is poor: it has $\chi^2/d.o.f. = 121/78$ and a confidence level of 0.13%. The relative normalization of the D^0 spectrum disagrees with the I-spin prediction by a factor of 0.64 ± 0.11, where the error includes the uncertainties in acceptance and branching fraction ratios.

For the D^+ spectrum, the fit overshoots the data in the bachelor D^+ region and undershoots it in the daughter D^+ region. For the D^0 spectrum, the fit overshoots the $N^{dau}_{D^0\gamma}$ component and undershoots the $N^{bach}_{D^0}$ and $N^{dau}_{D^0\pi^{+,0}}$ components. Leaving $N^{dau}_{D^0\pi^+}$ as a free parameter, eliminates all dependence on acceptance, but does not improve the quality of the fit. In this case, $N^{dau}_{D^0\pi^+}$ increases, which is opposite to what would be the case if the I-spin discrepancy noted above were due to an acceptance problem.

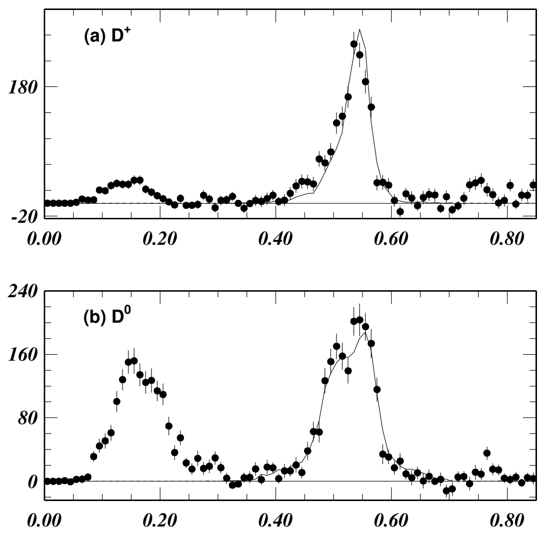

Figure 6: The inclusive **a)** $D^+ \to K^-\pi^+\pi^+$ and **b)** $D^0 \to K^-\pi^+$ momentum spectra fit using the D^* branching fractions fixed at the PDG/CLEO values.

The hypothesis that D meson production in the intermediate momentum region is nearly exclusively due to the $D^*\overline{D}$ process does not work very well. It gives poor fits to both the charged and neutral D momentum spectrum. We examined two different possibilities for this discrepancy. In one case we considered the possibility that the PDG/CLEO branching fraction values are wrong. In the other, we examined the possibility of a substantial contribution from non-resonant $D\overline{D}\pi$ production.

3.2 Fit to $D^*\overline{D}$ with floating D^{*+} branching fractions

The measurements of the $D^{*+} \to D^+\pi^0$ and $D^0\pi^+$ branching fractions listed in the PDG tables are constrained to agree with the p-wave phase-space corrected I-spin relation

$$\frac{\mathcal{B}(D^{*+} \to D^0\pi^+)}{\mathcal{B}(D^{*+} \to D^+\pi^0)} = 2\left(\frac{p_{D^0}}{p_{D^+}}\right)^3 = 2.21 \pm 0.07, \qquad (5)$$

where p_{D^0} (p_{D^+}) is the D^0 (D^+) momentum in the D^{*+} rest frame. In contrast, the recent CLEO measurement of $D^{*+} \to D^+\gamma$ is a direct comparison of the number of $D^+\gamma$ and $D^+\pi^0$ events, with no assumptions. We refit the D^+-meson momentum spectra allowing $B(D^{*+} \to D^+\pi^0 + D^+\gamma)$ to float while keeping the ratio of the $D^+\pi^0$ and $D^+\gamma$ branching fractions fixed at the CLEO value. Here no I-spin constraint is applied; both $N_{D^+}^{bach}$ and $N_{D^0}^{bach}$ are left as free parameters.

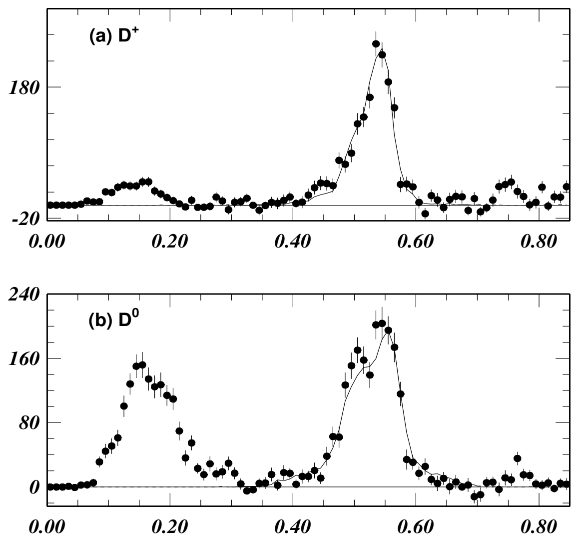

Figure 7: The inclusive **a**) $D^+ \to K^-\pi^+\pi^+$ and **b**) $D^0 \to K^-\pi^+$ momentum spectra fit with D^* branching fractions that are allowed to float. Here no constraints from I-spin symmetry are imposed.

Figures 7a and b show the results of a fit to the D-meson momentum spectra where the fractions of daughters from D^{*+} decays are allowed to float. This fit gives a $\chi^2/d.o.f.$ =

106/77, which has a confidence level of 1.5%. However, the fit gives a very high $D^{*+} \to D^+\pi^0 + D^+\gamma$ branching fraction:

$$\mathcal{B}(D^{*+} \to D^+\pi^0 + D^+\gamma) = 0.665 \pm 0.080; \tag{6}$$

a result that is a factor of two above the PDG/CLEO value of 0.320 ± 0.025, a 4σ discrepancy. Moreover, this is not compensated by a commensurate reduction in the $D^{*+} \to D^0\pi^+$ branching fraction: the fit results correspond to

$$\mathcal{B}(D^{*+} \to D^0\pi^+) = 0.681 \pm 0.090, \tag{7}$$

and a sum of D^{*+} branching fractions that exceeds unity by 3 standard deviations, i.e.

$$\mathcal{B}(D^{*+} \to D^0\pi^+) + \mathcal{B}(D^{*+} \to D^+\pi^0) + \mathcal{B}(D^{*+} \to D^+\gamma) = 1.35 \pm 0.12. \tag{8}$$

3.3 Fit including non-resonant $D\overline{D}\pi$ production

We considered the possibility of non-resonant $D\overline{D}\pi$ production as the source of the discrepancy in the fit to the D meson momentum spectra. As discussed in the introduction above, this mechanism produces D mesons with a momentum spectrum that peaks around $p_D \simeq 0.4$ GeV/c with a preponderance of events between the $D^*\overline{D^*}$ and the $D^*\overline{D}$ region, where the measured D-meson momentum spectra are nearly zero. Since we do not observe a substantial signal in this region, especially in the D^+ spectrum, we do not expect that the data can accommodate a significant amount of non-resonant $D\overline{D}\pi$ production.

Figures 8 shows the results of a fit the D^+ momentum spectra in the range $0.3 < p_D < 0.7$ GeV/c with bachelor-daughter ratios fixed at the PDG values and non-resonant $D^+\overline{D}\pi$ included. No constraints from I-spin symmetry for $D^*\overline{D}$ production are imposed. The additional free parameter does not improve the χ^2, and the confidence level of the fit is worse. At the 90% CL, the number of $D^\pm$-mesons from non-resonant $D\overline{D}\pi$ production is less than 56 out of a total of 1607 ± 62 $D^\pm$ mesons in the $0.3 < p_D < 0.7$ GeV/c momentum region. This gives a limit on non-resonant D^+ to all D^+ production in the intermediate momentum range of less than 4%.

4 Discussion

We are unable to fit the shape of the momentum spectrum of D mesons produced in e^+e^- collisions at $\sqrt{s} = 4.03$ using conventional mechanisms. Allowing the D^{*+} branching fractions to vary does not provide a consistent description of the data. There is a component of $D\overline{D}\pi$ and/or $D\overline{D}\gamma$ that is neither $D^*\overline{D}$, nonresonant $D\overline{D}\pi$, nor initial-state radiation $D\overline{D}\gamma$ production. The effect is a $\sim 30\%$ excess of events in the daughter momentum in both

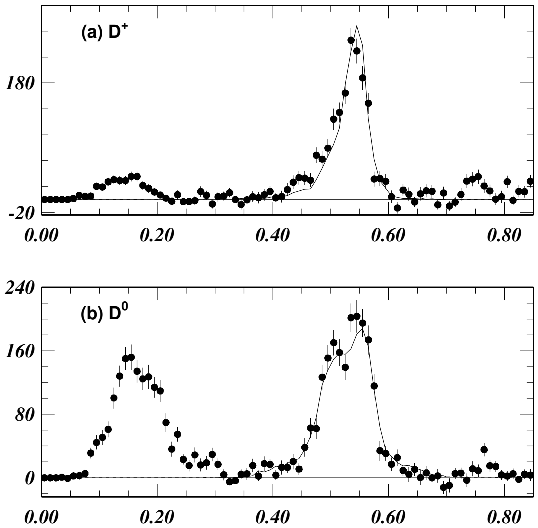

Figure 8: The inclusive **a)** $D^+ \to K^-\pi^+\pi^+$ and **b)** $D^0 \to K^-\pi^+$ momentum spectra fit using D^* branching fractions fixed at PDG/CLEO values and with a component from nonresonant $D\overline{D}\pi$ production included. No constraints from I-spin symmetry for $D^*\overline{D}$ production are imposed.

the charged and neutral spectrum over the expectations from the number of events in the bachelor peak.

The momentum spectrum of D mesons produced at similar energies was first studied by the Mark-I group [6] and later, with higher statistics by the Mark-II [1] and Mark-III [2] groups. The D^+ spectra in both of the latter two reports (Fig. 11b in ref. [1] and Fig. 2a in ref. [2]) show some excess of daughters compared to bachelors. This excess is possibly the source of the large $D^{*+} \to D^+\gamma$ branching fractions that both groups reported.

5 Acknowledgements

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