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# First Evidence for a Radially Excited $D^{*'}$ Meson

Preliminary

DELPHI Collaboration

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**Abstract**

Using $D^{*+}$ mesons exclusively reconstructed in the DELPHI experiment at LEP, an excess of $62 \pm 14$(stat.) events is observed in the $D^{*+}\pi^+\pi^-$ invariant mass distribution. This signal is compatible with the expected decay of a radially excited $D^{*'}$ ($J^P = 1^-$) meson. The measured mass is $2637 \pm 2$(stat.) $\pm\, 6$(syst.) MeV/$c^2$.

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# 1 Introduction

For mesons containing heavy and light quarks ($Q\bar{q}$) and in the limit where the heavy quark mass is much larger than the typical QCD scale ($m_{\rm Q} \gg \Lambda_{\rm QCD}$), the spin $\vec{s}_{\rm Q}$ of the heavy quark and the total (spin+orbital) angular momentum $\vec{j}_{\rm q} = \vec{s}_{\rm q} + \vec{L}$ of the light component are separately conserved. Heavy quark symmetry [1], together with the knowledge of lower mass mesons, allow to predict the mass and decay widths of heavy mesons [2] of total spin $\vec{J} = \vec{s}_{\rm Q} + \vec{j}_{\rm q}$.

In the charm sector, the lowest $L = 0$ states of D and D$^*$ mesons are well identified. Only the narrow orbital excitations ($L = 1$, $j_{\rm q} = 3/2$) of charmed mesons have been clearly observed so far [3]. Broad states are expected but they are not seen yet (see Table 1 for non-strange charmed mesons) [4] [5]. Orbitally excited beauty mesons present a similar scheme.

| | $J^P$ $j_{\rm q}$ | Mass (MeV/$c^2$) | Width (MeV/$c^2$) | Decay modes |
|---|---|---|---|---|
| $\rm D_0^*$ | $0^+$ $1/2$ | $\sim 2360$ | $\geq 170$ | ($\rm D\pi$) |
| $\rm D_1^*$ | $1^+$ $1/2$ | $\sim 2420$ | $\geq 250$ | ($\rm D^*\pi$) |
| $\rm D_1^+$ | $1^+$ $3/2$ | $\sim 2422$ | $\sim 19$ | ($\rm D^*\pi$, $\rm D\rho$) |
| $\rm D_1^0$ | $1^+$ $3/2$ | $2422.2 \pm 1.8$ | $18.9^{+4.6}_{-3.5}$ | $\rm D^{*+}\pi^-$ ($\rm D^{*0}\pi^0$, $\rm D\rho$) |
| $\rm D_2^{*+}$ | $2^+$ $3/2$ | $2459 \pm 4$ | $25^{+8}_{-7}$ | $\rm D^0\pi^+$, $\rm D^{*0}\pi^+$ ($\rm D^{(*)+}\pi^0$, $\rm D^*\rho$) |
| $\rm D_2^{*0}$ | $2^+$ $3/2$ | $2458.9 \pm 2.0$ | $23 \pm 5$ | $\rm D^+\pi^-$, $\rm D^{*+}\pi^-$ ($\rm D^{(*)0}\pi^0$, $\rm D^*\rho$) |

Table 1: Expected and observed orbital excitations of $\rm D^0$ and $\rm D^+$ mesons. The broad $L = 1$ D mesons ($j_{\rm q} = 1/2$) states are estimated [1]. The narrow $j_{\rm q} = 3/2$ states are all measured [3], except the $\rm D_1^+$ state. In the last column, those predicted decay modes which are not yet observed are indicated within parentheses.

Together with these orbital excitations, radial excitations of heavy mesons are also foreseen [4]: based on a relativistic quark model with QCD, $\rm D'$ ($J^P = 0^-$) and $\rm D^{*\prime}$ ($J^P = 1^-$) are expected with a mass of 2.58 GeV/$c^2$ and 2.64 GeV/$c^2$ , respectively. The uncertainty on the mass values is of the order of 10-25 MeV/$c^2$. The dominant decay modes are $\rm D\pi\pi$ and $\rm D^*\pi\pi$, respectively, but decays into $\rm D^{(*)}\rho$ or through an intermediate orbital excitation are not excluded. On Figure 1 the spectrum of the various D mesons is displayed with their decay modes involving an S-wave, or a P- or D-wave transition.

In the B sector, a narrow resonance compatible with the expectation of a $\rm B^{(*)\prime}$ decaying into $\rm B^{(*)}\pi^+\pi^-$ has been reported recently by the DELPHI experiment [6]. The purpose of the present paper is to search for a narrow $\rm D^{*+}\pi^+\pi^-$ resonance. The $\rm D^{*+}$ candidates are selected in the exclusive decay channels $\rm D^{*+} \to D^0\pi_*^+$ followed by $\rm D^0 \to K^-\pi^+$ or $\rm D^0 \to K^-\pi^+\pi^+\pi^-$ using DELPHI data collected from 1992 to 1995 [1]. Then the known $\rm D_1^0$ and $\rm D_2^{*0}$ decaying into $\rm D^{*+}\pi^-$ are looked for in order to control the vertex finding procedure and the invariant mass estimate. Finally $\rm D^{*+}\pi^+\pi^-$ final states are considered.

[1]Throughout the paper charge-conjugate states are implicitly included and the pion from the $\rm D^{*+}$ decay is denoted $\pi_*^+$.

# 2 The DELPHI detector

The DELPHI detector has been described in detail elsewhere [7], only those components relevant for the present analysis are discussed here.

The tracking of charged particles is accomplished in the barrel region with a set of cylindrical tracking detectors whose axes are oriented along the 1.23 T magnetic field and the direction of the beam.

The time projection chamber (TPC), the main tracking device, is a cylinder of 30 cm inner radius, 122 cm outer radius and length 2.7 m. For polar angles between 39° and 141° it provides up to 16 space points along the charged particle trajectory.

The microvertex detector (VD), located nearest the LEP interaction region, has an intrinsic R$\phi$ resolution of 5–6 $\mu$m and consists of three concentric layers of silicon microstrip detectors at average radii of 6.3 cm, 9.0 cm, and 10.9 cm. The layers surround the beam pipe, a beryllium cylinder of inner radius 5.3 cm and wall thickness 1.45 mm. In the earlier runs all the VD layers were single-sided with strips parallel to the beam direction. In 1994 and 1995 runs the innermost and the outermost layers were replaced by double-sided silicon microstrip modules.

The VD, the inner detector (ID), the TPC and the outer detector (OD), measure the charged particle tracks at polar angles $\theta$ between 30° and 150°. Combining the information from these detectors, a resolution $\sigma(p)/p$ of $\pm 3.0$ % has been obtained for muons of 45 GeV/$c$ momentum.

Hadrons are identified using the specific ionization ($dE/dx$) in the TPC and the Cherenkov radiation in the barrel Ring Imaging CHerenkov detector (RICH) placed between the TPC and the OD detectors. The tracking in the forward ($11° < \theta < 33°$) and backward ($147° < \theta < 169°$) regions is improved by two pairs of Forward drift Chambers (FCA and FCB) in the end-caps.

# 3 The event sample and the simulation

Charged particles were selected as follows: the momentum had to be between 0.1 GeV/$c$ and 50 GeV/$c$, the relative error on momentum measurement less than 100%, the track length in the TPC had to be larger than 30 cm, the projection of their impact parameter relative to the interaction point had to be below 4 cm in the plane transverse to the beam direction and the distance to the interaction point along the beam direction below 10 cm.

Hadronic events were selected by requiring five or more charged particles (of momentum larger than 0.4 GeV/$c$) and a total energy in charged particles larger than 12% of the collision energy, assuming all charged particles to be pions. A total of 1.4 (2.0) million hadronic events was obtained from the 1992-1993 (1994-1995) data at centre-of-mass energies between 88.2 GeV and 94.2 GeV in 1993 and 1995, and at the $Z^0$ peak energy in 1992 and 1994.

Simulated hadronic events have been generated with the JETSET 7.3 Parton Shower program [8]. The generated events were followed through the detailed detector simulation DELSIM [9] which included simulation of secondary interactions and digitization of all electronic signals. The simulated data were then processed through the same analysis chain as the real data. The hadronic event selection efficiency was thus estimated to be $(95 \pm 1)$% [7].

For the purpose of the present analysis, a special event sample containing a $D_2^{*+}$ decaying into $D^{*+}\pi^+\pi^-$ through a S-wave transition was simulated in both modes $D^{*+} \to D^0\pi_*^+$ followed by $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^+\pi^-$. The $D_2^{*+}$ mass was arbitrarily fixed to 2640 MeV/$c^2$.

# 4 $D^{*+}$ meson reconstruction

The primary interaction vertex was computed in space for each event using an iterative procedure based on the $\chi^2$ of the fit. The average transverse position of the interaction point, known for each fill, was included as a constraint during the primary vertex fit.

For the $D^0$ from $D^{*+}$ decay, a $K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-$ combination was selected to compute a secondary vertex in space. The $D^0$ momentum was calculated by the sum of the momenta of the decay products from this secondary vertex. Kaon candidates were considered if they had a momentum larger than 1 GeV/$c$. Pion candidates were considered if they had a momentum larger than 1 GeV/$c$ in the $K^-\pi^+$ channel and 0.5 GeV/$c$ in the $K^-\pi^+\pi^+\pi^-$ channel. At least two tracks from the $D^0$ decay were asked to be seen in the microvertex detector. A distance $\Delta L$ was computed between the primary and secondary vertices in the plane transverse to the beam axis. This distance was given the same sign as the scalar product of the $D^0$ momentum with the vector joining the primary to the secondary vertices.

To reduce the combinatorial background in the $K^-\pi^+$ channel where no K identification was applied, the angle $\theta^*$ between the $D^0$ flight direction and the kaon direction in the $D^0$ rest frame was required to satisfy the condition $\cos\theta^* > -0.8$. For genuine $D^0$ candidates an isotropic distribution in $\cos\theta^*$ is expected whereas the background is strongly peaked in the backward direction.

In the $K^-\pi^+\pi^+\pi^-$ channel further selections were required to reduce the important combinatorial background: an impact parameter, computed in the plane transverse to the beam direction, of each charged particle track relative to their common $D^0$ vertex smaller than 200 $\mu$m, a kaon candidate compatible with the expectation according to the combined RICH and $dE/dx$ identification and a positive distance $\Delta L$.

Then all charged particles with momentum between 0.4 GeV/$c$ and 4.5 GeV/$c$ and charge opposite to that of the kaon candidate of the $D^0$ were used as pion candidates for the $D^{*+} \to D^0\pi_*^+$ decay. The $D^{*+}$ were selected if their energy fraction $X_E(D^{*+}) = E(D^{*+})/E_{\mathrm{beam}}$ was larger than 0.25.

In the $K^-\pi^+$ channel, the reconstructed mass difference $M(K^-\pi^+\pi_*^+) - M(K^-\pi^+)$ was selected within $\pm 2$ MeV/$c^2$ of the nominal ($D^{*+}-D^0$) mass difference of 145.4 MeV/$c^2$ [3]. In order to reduce the combinatorial background in the $K^-\pi^+\pi^+\pi^-$ channel, the corresponding mass difference $M(K^-\pi^+\pi^+\pi^-\pi_*^+) - M(K^-\pi^+\pi^+\pi^-)$ had to lie within $\pm 1$ MeV/$c^2$ of the nominal value.

The invariant mass distributions $M(K^-\pi^+)$ and $M(K^-\pi^+\pi^+\pi^-)$ are shown on Figure 2. The ($K^-\pi^+$) mass distribution was fitted by using the following contributions: the exponential of a second order polynomial function for the combinatorial background, a parametrization of the $D^0 \to K^-\pi^+\pi^0$ reflection with free normalization and the sum of two Gaussian functions (of common mean) for the $D^0 \to K^-\pi^+$ candidates. The measured ($K^-\pi^+$) mass is $1868 \pm 1(\mathrm{stat.})$ MeV/$c^2$ and the observed $\sigma$ width of the narrower Gaussian is $22 \pm 1(\mathrm{stat.})$ MeV/$c^2$.

The ($K^-\pi^+\pi^+\pi^-$) mass distribution was fitted by using the following contributions: a second order polynomial function for the combinatorial background and a Gaussian function for the $D^0 \to K^-\pi^+\pi^+\pi^-$ candidates. The measured ($K^-\pi^+\pi^+\pi^-$) mass is $1869 \pm 1$(stat.) MeV/$c^2$ and the observed $\sigma$ width is $13 \pm 1$(stat.) MeV/$c^2$. In both decay modes, the measured $D^0$ mass was found about 4 MeV/$c^2$ above the expectation of $1864.5 \pm 0.5$ MeV/$c^2$ [3].

In the following, for the $K^-\pi^+$ (or $K^-\pi^+\pi^+\pi^-$) channel, the mass difference will be required to lie within $\pm 2$ ($\pm 1$) MeV/$c^2$ of the nominal ($D^{*+}-D^0$) mass difference and the reconstructed $D^0$ invariant mass to lie within $\pm 40$ ($\pm 30$) MeV/$c^2$ of the nominal $D^0$ mass. These selections correspond to $4700 \pm 100$(stat.) and $3250 \pm 90$(stat.) reconstructed $D^{*\pm}$ in both channels, respectively.

# 5 Search for orbitally excited D mesons

In this section a search for orbitally excited $D_1^0$ and $D_2^{*0}$ decaying into $D^{*+}\pi^-$ is presented. Using the pion from the $D^{*+} \to D^0\pi_*^+$ decay, a $D^0\pi_*^+\pi^-$ vertex can be fitted. In the next section a search for $D^{*+}\pi^+\pi^-$ final states will be presented, where a $D^0\pi^+\pi^-$ vertex will be also fitted. However in the latter case the two additional pions will not be taken from the $D^{*+}$ decay. The kinematical characteristics of both vertices are rather similar and allow the search of the well known $D_1^0$ and $D_2^{*0}$ states to be used as a test of the method.

In the $D^{*+}\pi^-$ final state, all pion candidates of charge opposite to the $D^{*+}$ and momentum greater than 1.5 GeV/$c$ were considered. Those pion candidates compatible with a kaon according to the combined RICH and $dE/dx$ identification were rejected.

Then, as explained above, the pion from $D^{*+} \to D^0\pi_*^+$ decay was used to fit a $D^0\pi_*^+\pi^-$ vertex. At least one pion had to be detected in the microvertex detector. In the $D^0 \to K^-\pi^+$ channel, the additional pion $\pi^-$ (or $\pi_*^+$) was selected if its impact parameter with respect to the common $D^0\pi_*^+\pi^-$ vertex was less than 50 (or 150) $\mu$m. This requirement was less stringent for the pion from the $D^{*+}$ decay, because this $\pi_*^+$ has a lower momentum and suffers more from multiple scattering in the detector. In the $D^0 \to K^-\pi^+\pi^+\pi^-$ channel, the $\chi^2$ probability of the $D^0\pi_*^+\pi^-$ vertex had to be larger than 0.001. These different vertex conditions were justified because the $D^0$ decay vertex was better defined in the case of the $K^-\pi^+\pi^+\pi^-$ channel.

In order to reduce further the combinatorial background, two different samples were defined by using the decay length significance $\Delta L/\sigma_L$ between the secondary $D^0\pi_*^+\pi^-$ vertex and the primary vertex, where $\Delta L$ with its error $\sigma_L$ was computed as in section 4, and by using a B-tagging algorithm [10]:

- A $b\bar{b}$ enriched sample: the decay length significance had to be larger than 2 and the B-tagging probability had to be smaller than 0.1 ;
- A $c\bar{c}$ enriched sample: the decay length significance had to fulfill $|\Delta L/\sigma_L| < 2$ and either the B-tagging probability was larger than 0.1 or the overall energy fraction $X_E(D^{*+}\pi^-)$ was larger than 0.4 .

Those events not selected as $b\bar{b}$ or $c\bar{c}$ according to these criteria were removed.

To estimate the $M(D^{*+}\pi^-)$ invariant mass, the following mass difference was computed: $M(D^{*+}\pi^-) = M(D^0\pi_*^+\pi^-) - M(D^0\pi_*^+) + m_{D^*}$ where $m_{D^*}$ is the nominal $D^{*+}$ mass [3]. This gives a resolution $\sigma$ of about 6 MeV/$c^2$ on $M(D^{*+}\pi^-)$, according to the simulation.

This invariant mass distribution is presented on Figure 3 for the selected events. An excess of ($D^{*+}\pi^-$) pairs is observed between 2.4 and 2.5 GeV/$c^2$ , but not in the ($D^{*+}\pi^+$) sample. The $M(D^{*+}\pi^-)$ distribution was fitted as the sum of two contributions: a function of the form $\alpha(M(D^*\pi) - m_{D^*} - m_\pi)^\beta \cdot \exp(-\gamma(M(D^*\pi) - m_{D^*} - m_\pi))$ for the background, where $m_\pi$ is the pion mass, and two Breit-Wigner functions describing both $D_1^0$ and $D_2^{*0}$ resonances. The overall number and relative proportions of these states and their average masses were left free in the fit, whereas both full widths were fixed to their world average value [3] (see Table 1). A total number of $264 \pm 49$ $D_1^0$ and $D_2^{*0}$ was observed, $(62 \pm 9)\%$ being associated to the $D_1^0$ resonance. The obtained $D_1^0$ mass was $2420 \pm 2$ MeV/$c^2$, in good agreement with the nominal value of $2422 \pm 2$ MeV/$c^2$. The fitted $D_2^{*0}$ mass of $2472 \pm 6$ MeV/$c^2$ is slightly larger than the nominal value of $2459 \pm 2$ MeV/$c^2$ [3]. All fitted errors are statistical only.

# 6 Search for a radially excited D meson

Repeating a similar procedure as in the previous section, all remaining opposite charge $\pi^+\pi^-$ pairs produced in the same direction as the $D^{*+}$ candidates were used to fit a $D^0\pi^+\pi^-$ vertex. The pion from the $D^{*+} \to D^0\pi_*^+$ decay had its momentum computed at this new secondary vertex. Only events selected as $b\overline{b}$ or $c\overline{c}$ candidates were retained.

In the $K^-\pi^+$ channel, each pion was selected if its momentum was larger than 0.6 GeV/$c$ and if its impact parameter relative to the common $D^0\pi^+\pi^-$ vertex was smaller than 50 $\mu$m. In order to reduce further the combinatorial background in the $K3\pi$ channel, while benefiting from a better $D^0$ vertex, the following selections were applied: the momentum of each pion had to be larger than 1 GeV/$c$ and the $D^0\pi^+\pi^-$ vertex probability had to be larger than 0.01.

The reconstructed invariant mass was computed as above:
$M(D^{*+}\pi^+\pi^-) = M(D^0\pi_*^+\pi^+\pi^-) - M(D^0\pi_*^+) + m_{D^*}$ with a resolution $\sigma$ of about 6 MeV/$c^2$, according to the simulation. The invariant mass distribution of all $D^{*+}\pi^+\pi^-$ candidates is presented on Figure 4. A narrow peak is observed whereas the wrong charge combinations $D^{*+}\pi^-\pi^-$ do not show any excess. A binned maximum likelihood fit was performed on this $M(D^{*+}\pi^+\pi^-)$ distribution by taking into account two contributions: a function of the form $\alpha(M(D^*\pi\pi) - m_{D^*} - m_{\pi\pi})^\beta \cdot \exp(-\gamma(M(D^*\pi\pi) - m_{D^*} - m_{\pi\pi}))$ for the background, with $m_{\pi\pi}$ set to 340 MeV/$c^2$, and a Gaussian function with free parameters to describe the narrow peak. The $\chi^2$ per degree of freedom is 65/62. The fitted number of events is $62 \pm 14$, the fitted $\sigma$ width is $8 \pm 2$ MeV/$c^2$, in agreement with the expected resolution, and the average mass is found to be $2637 \pm 2$ MeV/$c^2$. Only statistical errors are quoted.

This 4 standard deviations signal is likely to come from the expected $D^{*'}$ radial excitation (see Figure 1) [4]. A systematic uncertainty of $\pm 6$ MeV/$c^2$ on its mass can be inferred by comparing the fitted invariant mass of the $D^0$ , $D_1^0$ and $D_2^{*0}$ in sections 4 and 5 to their world average values.

No signal was found for the decay $D_2^{*+}(2459) \to D^{*+}\rho^0$ which is kinematically disfavoured [2].

# 7 Conclusion

Using about 8000 exclusively reconstructed $D^{*\pm}$, a search for $D^{*+}\pi^+\pi^-$ decay vertices was performed. A narrow peak has been observed in the invariant mass distribution, whose width is compatible with the detector resolution. A signal of $62 \pm 14$(stat.) events was fitted. The observed mass is $2637 \pm 2$(stat.) $\pm$ 6(syst.) MeV/$c^2$. This is the first evidence for a radially excited $D^{*'}$ ($J^P = 1^-$) meson, as predicted by S. Godfrey and N. Isgur [4].

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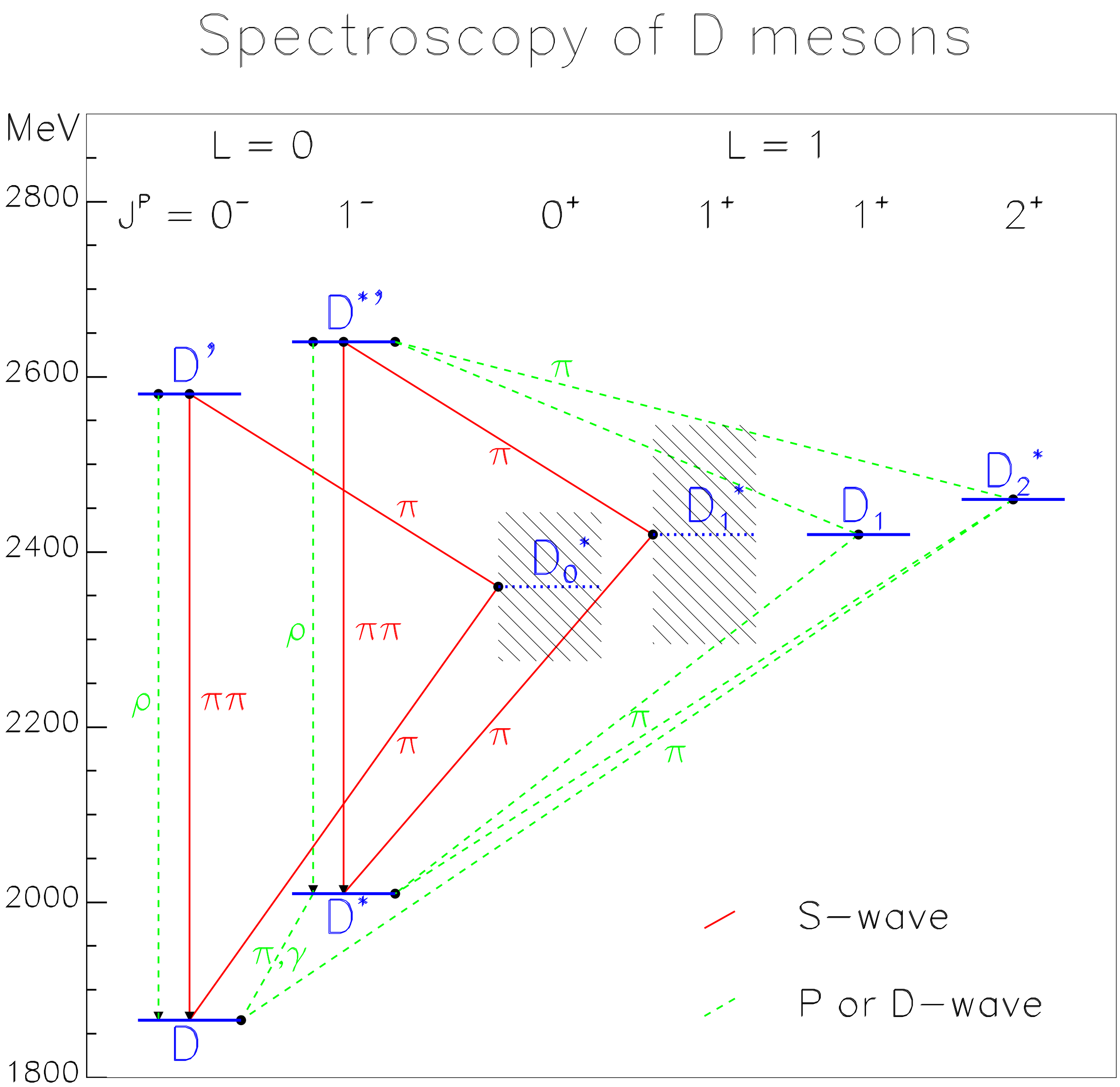


Figure 1: Spectroscopy of non-strange D mesons. For clarity the foreseen $D_1$ and $D_2^*$ decays involving a $\rho$ meson are not shown (see also Table 1).

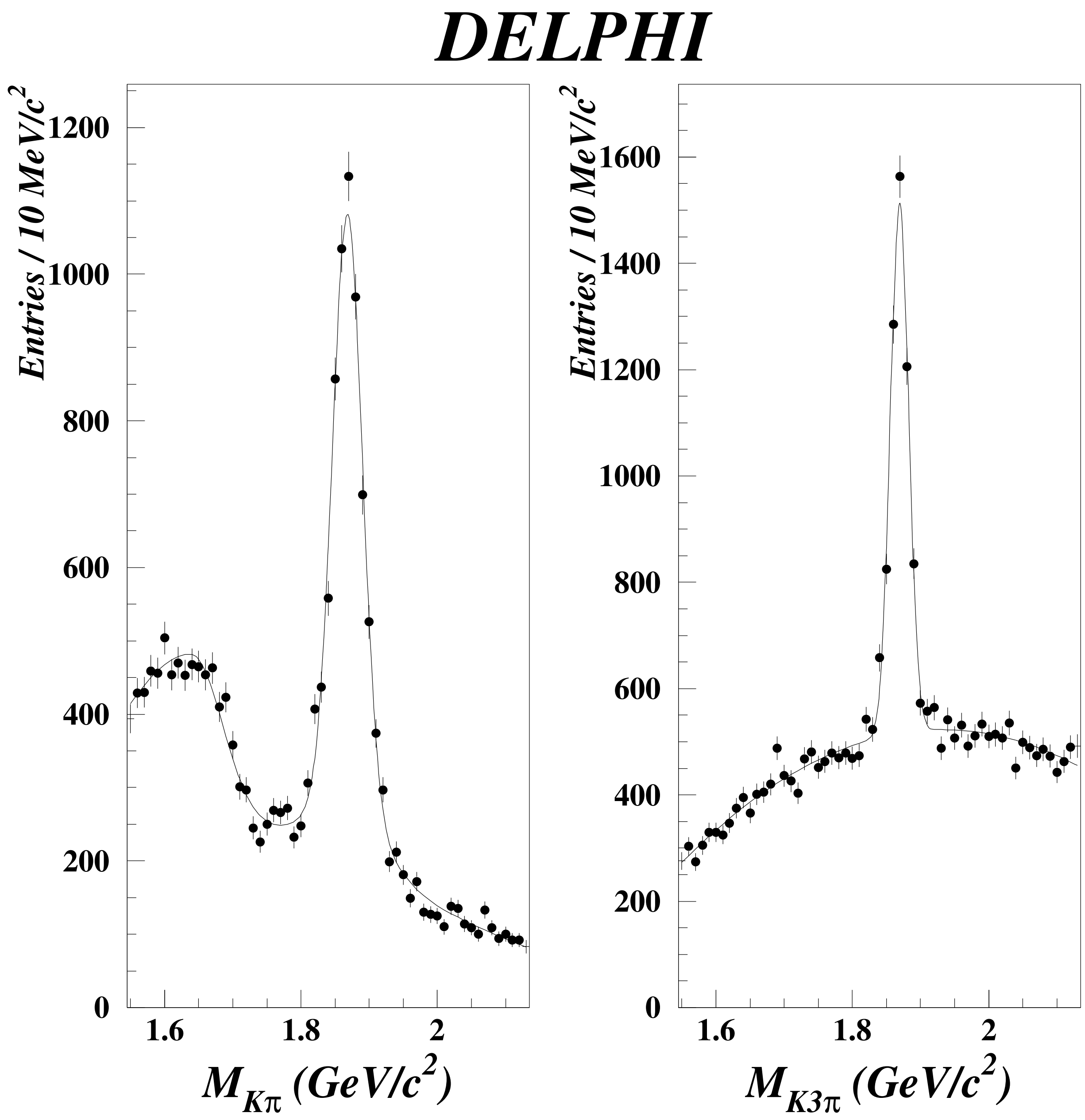


Figure 2: Invariant mass distributions in the $D^{*+} \rightarrow (K^-\pi^+)\pi^+_*$ and $D^{*+} \rightarrow (K^-\pi^+\pi^+\pi^-)\pi^+_*$ decay channels. The fitted curves are explained in the text.

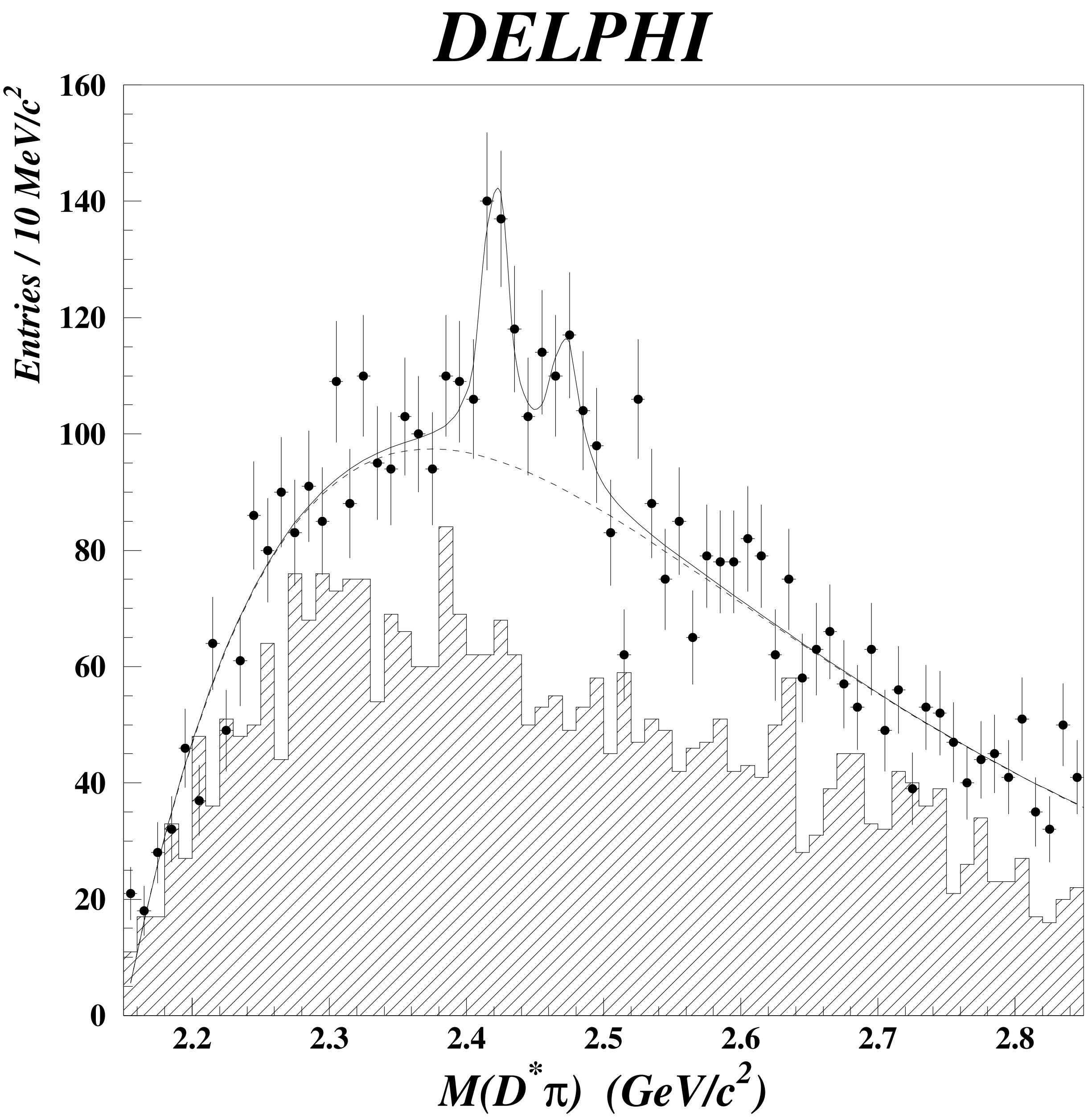


Figure 3: Invariant mass distributions ($D^{*+}\pi^-$) (dots) and ($D^{*+}\pi^+$) (hatched histogram). The mass computation and the fitted curves are explained in the text.

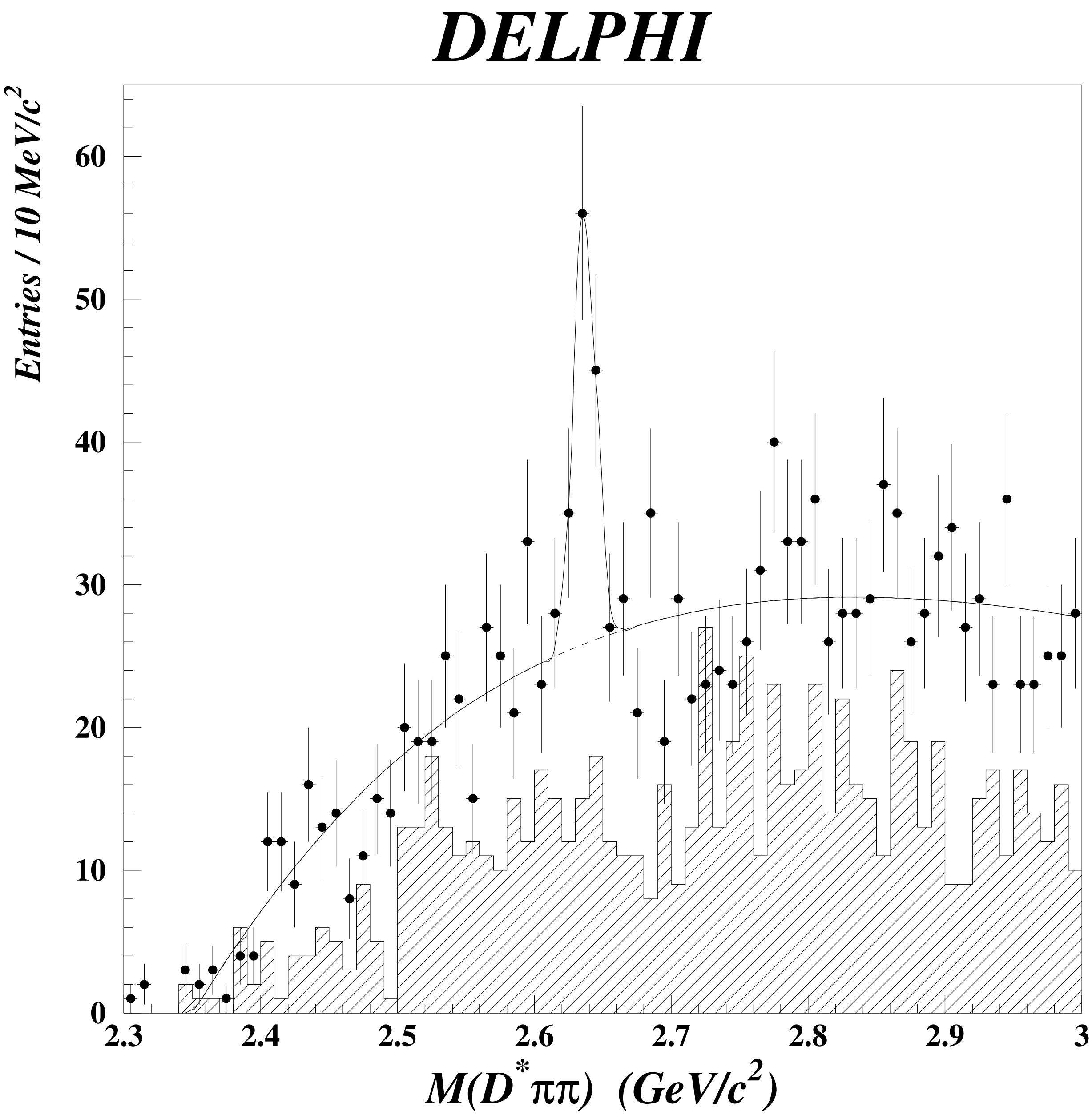


Figure 4: Invariant mass distributions ($D^{*+}\pi^+\pi^-$) (dots) and ($D^{*+}\pi^-\pi^-$) (hatched histogram). The mass computation and the fitted curves are explained in the text.