

**Observation in BaBar of a Narrow Resonance  
in the  $D_s\pi^0$  System at  $2317 \text{ MeV}/c^{2*}$**

Roger Barlow  
Department of Physics and Astronomy  
The University of Manchester  
Manchester M13 9PL, UK

and

Stanford Linear Accelerator Center  
Stanford University  
Stanford, CA 94309 USA

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# Observation in *BABAR* of a narrow resonance in the $D_s\pi^0$ system at 2317 MeV/c<sup>2</sup>

*Roger Barlow*

Department of Physics and Astronomy  
The University of Manchester  
Manchester M13 9PL, UK

The *BABAR* collaboration has observed a state of mass 2317 MeV/c<sup>2</sup> which decays to  $D_s\pi^0$ , using 91 fb<sup>-1</sup> of data from asymmetric  $e^+e^-$  collisions of energy around 10.6 GeV produced by the PEP-II storage ring. The observed width is compatible with the experimental resolution, indicating that the state is narrow, with  $\Gamma < 10$  MeV. Properties of the state are presented, and implications are discussed.

## 1 Introduction

Although the *BABAR* detector, like the asymmetric PEP-II B factory at which it runs, was built for the prime purpose of studying CP violation in  $B$  mesons produced by the  $\Upsilon(4S)$ , it also has many other possibilities for physics studies. We present here the observation of a new meson in the charm-strange system, provisionally named the  $D_{s,J}^*(2317)$ . The analysis was performed on 91 fb<sup>-1</sup> of data taken during the period 1999 to 2002, with centre of mass energy equal or close to the mass of the  $\Upsilon(4S)$ . An account is given in [1].

## 2 Candidate Selection

We look for mass combinations in the  $D_s\pi^0$  system. As preliminary selections for good events we require at least 3 charged tracks in the tracking chambers, at least 2 clusters in the electromagnetic calorimeter, and the ratio of Fox Wolfram moments  $H_2/H_1$  below 0.9. (This removes many of the isotropically decaying  $\Upsilon(4S) \rightarrow B\bar{B}$  events.)

The mass plot of photon pairs in Figure 1a shows a clear  $\pi^0$  signal.  $\pi^0$  candidates are formed from clusters above 100 MeV, with a probability for the kinematic and geometric fit to the  $\pi^0$  hypothesis above 0.1%, and neither photon associated with another possible  $\pi^0$  candidate.

The  $D_s$  is identified through its decay to  $K^+K^-\pi^\pm$ . Particle identification is done using information from the Čerenkov detector combined, using a neural network, with  $\frac{dE}{dx}$  measurements from the tracking chambers. The 3 tracks are required to have a vertex fit probability greater than 0.1%. The mass spectrum (shown in Figure 1b) shows the  $D_s$  peak at 1.97 GeV/c<sup>2</sup>, together with peaks from the Cabibbo-suppressed decay of the  $D^\pm$  at 1.87 and from the  $D^{*\pm}$  at 2.01 through its decay to  $D^0\pi^\pm$ . Although the signal peak is clear, the background is large. It is reduced by a further set of cuts.

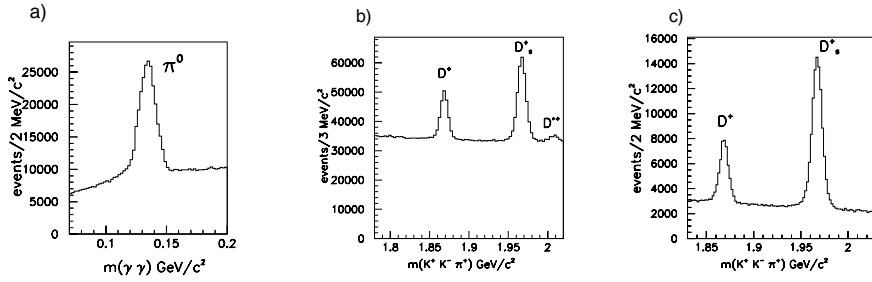


Figure 1: Mass distributions for (a) photon pairs, and for  $KK\pi^\pm$  combinations before (b) and after (c) the cuts described

- We require the  $K^+K^-$  mass to be less than 1.84 GeV/c<sup>2</sup>, to eliminate the  $D^{*+}$ .
- As this  $D_s$  decay is known to proceed mostly through the two body states  $\phi\pi$  and  $K^*K$ , we require that either the  $K^+K^-$  mass lie between 1.010 and 1.030 GeV/c<sup>2</sup> or that the  $K^\mp\pi^\pm$  mass lie between 0.842 and 0.942 GeV/c<sup>2</sup>.
- In both of these channels (for which the regions do not overlap) the decay of a scalar meson to scalar + vector requires the vector particle ( $\phi$  or  $K^*$ ) to decay with a distribution in the helicity angle  $\theta_h$  proportional to  $\cos^2\theta_h$ . We therefore require that  $|\cos\theta_h| \geq 0.5$ .
- We require a total cms momentum of the combined  $K^+K^-\pi^\pm\pi^0$  system above 2.5 GeV/c.

The mass distribution after these cuts is shown in Figure 1c, and candidates are accepted as  $D_s$  if the mass lies between 1955 and 1979 MeV/c<sup>2</sup>. In subsequent analysis the measured mass of accepted  $D_s$  candidates is replaced by the standard value [2].

Having found clean  $\pi^0$  and  $D_s$  particles - the cuts above have been given in detail to show their simplicity - we plot the invariant mass of the  $D_s\pi^0$  combination in Figure 2. This shows a large, narrow and completely unexpected peak around 2320 MeV/c<sup>2</sup>. (The spike on the left is produced by decays of the  $D_s^*(2112)$ , for which this decay is just above threshold.)

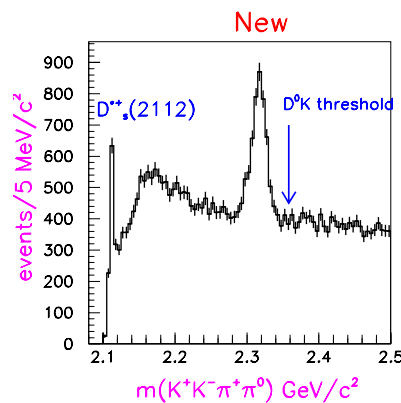


Figure 2: The  $D_s\pi^0$  mass combination

### 3 Checks and Properties

To check that this peak is not an artefact produced by known particle decays, we examine the Monte Carlo simulation of the process  $e^+e^- \rightarrow c\bar{c}$  including the effects of detector simulation. The mass plot (Figure 3) does not display any peak in this region, though it does provide a good description of the  $K^+K^-\pi^\pm$  mass combinations.

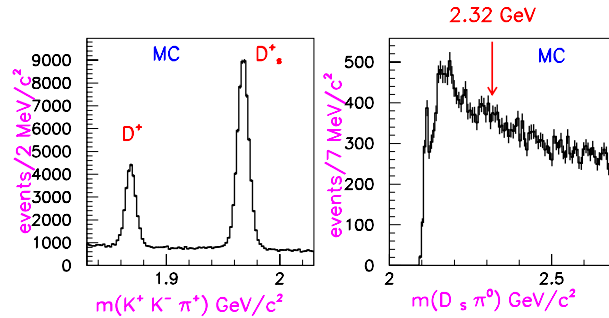


Figure 3: Monte Carlo simulation of the  $K^+K^-\pi^\pm$  and  $D_s\pi^0$  mass combination

We make many further checks. There is no sign of this peak if events are selected from sidebands in either the  $\pi^0$  or the  $D_s$  combinations. We see the same peak in both the  $\phi\pi^\pm$  and the  $K^\pm K^{*0}$  decay modes of the  $D_s$ . We also observe it in the decay  $D_s \rightarrow K^+K^-\pi^\pm\pi^0$ , i.e. in the  $K^+K^-\pi^\pm\pi^0\pi^0$  configuration, with a consistent value for the mass.

We check that this is not an artefact produced by known resonances with a pion misidentified as a kaon: if we take events in the signal peak and reassign one of the identified  $K^\pm$  particles as a  $\pi^\pm$  there is no sign of a peak at the mass of the  $D^+$ ,  $D^0$ ,  $D^*$  or elsewhere. Nor is it produced by the  $D_s^*(2112) \rightarrow D_s\gamma$  decay with an extra  $\gamma$ : if we remove events for which the mass of a  $D_s\gamma$  combination is in the region of 2112 MeV/c<sup>2</sup> the peak at 2317 MeV/c<sup>2</sup> is actually enhanced.

Having verified that the peak is genuinely a new particle, we now investigate its properties.

The production of the state is studied by examining the mass plot in different regions of  $p^*$ , the cms momentum of the  $K^+K^-\pi^\pm\pi^0$  system, shown in Figure 4. The significance of the peak rises with increasing  $p^*$ . This is what would be expected if the particle is produced in  $e^+e^- \rightarrow c\bar{c}$  interactions, as opposed to arising in  $b \rightarrow c$  decays of the  $\Upsilon(4S)$ .

We select the region  $p^* > 3.5$  GeV/c as providing high statistics and good signal to noise, and fit the mass as  $2316.8 \pm 0.4$  MeV/c<sup>2</sup>, using a single Gaussian and a polynomial background, shown in the large plot of Figure 4. We therefore give it the provisional name of  $D_{sJ}^*(2317)$ . (The fit gives  $1267 \pm 53$  events in the peak - so it is established with a statistical significance of 24 standard deviations.) From comparison of other mass measurements with their standard values we conservatively estimate the systematic uncertainty on this as better than 3 MeV/c<sup>2</sup>.

The single Gaussian provides a good fit to the data with an acceptable  $\chi^2$ . It fits the width as  $\sigma = 8.6 \pm 0.4$  MeV/c<sup>2</sup>. From Monte Carlo simulation, and from the width in the data of the  $D_s \rightarrow K^+K^-\pi^\pm\pi^0$  peak, we find this to be compatible with our experimental resolution. We are thus unable to measure it, and can only say that it must be narrow:  $\Gamma \leq 10$  MeV/c<sup>2</sup>.

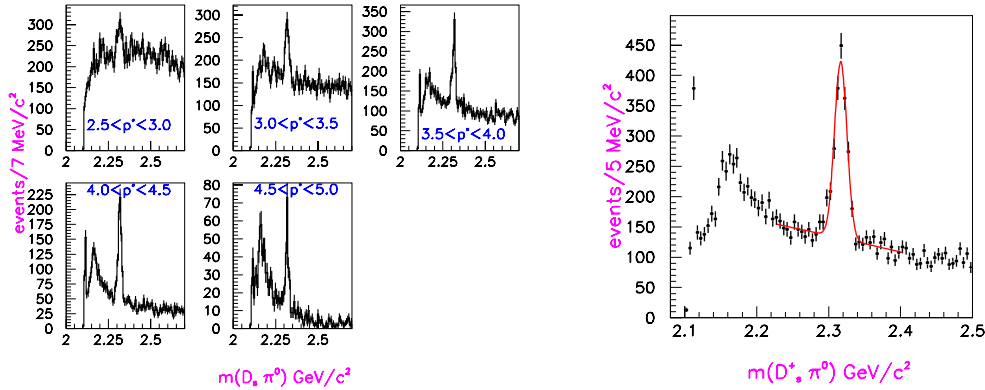


Figure 4: The  $D_s\pi^0$  mass in bins of  $p^*$  and for  $p^* > 3.5$  GeV/c showing the fit to the peak plus background

The helicity angle (of the  $\pi^0$  in the  $D_s^*(2317)$  frame) is, after correcting for efficiency, consistent with being flat. (The efficiency varies strongly with angle due to the loss of slow  $\pi^0$  particles.) This suggests that this is a  $J = 0$  zero-spin particle, although it is consistent with any spin assignment if the particle is produced in an unpolarised state.

We have searched for the  $D_{sJ}(2317)$  in other decay modes:  $D_s\gamma$ ,  $D_s^*(2112)\gamma$ ,  $D_s\gamma\gamma$ ,  $D_s\pi^0\gamma$  and  $D_s\pi^0\pi^0$ . In no case do we see a significant signal in the  $D_{sJ}(2317)$  region.

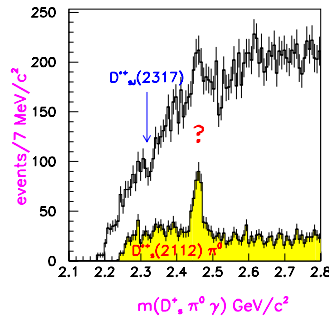


Figure 5: The  $D_s\gamma$  mass

The  $D_s\pi^0\gamma$  mode needs further comment. The mass distribution for the combination is shown in Figure 5. There is no sign of any peak at 2317 MeV/c<sup>2</sup> but a strong suggestion of one at 2460. This is enhanced if one requires the  $D_s\gamma$  mass combination to be in the range 2096 to 2128 MeV/c<sup>2</sup>, the  $D_s^*$  region, giving the shaded histogram, which shows a very clear peak.

This needs careful interpretation. In this three body system there are known to be peaks in the  $D_s\pi^0$  combination at 2317 and in the  $D_s\gamma$  combination at 2112. The coincidence of these peaks corresponds to a total mass of around 2460. So there is certainly a contribution to this

peak from a reflection of the 2317 and 2112. (Also, a state at 2460 will produce a peak in the  $D_s\pi^0$  mass around 2317. But we have verified that this cannot account for the entire signal.)

If the 2460 peak does indeed contain a contribution from another new state, then this cross-feeding means that a careful analysis is required to establish the production ratio and detailed properties of the two particles [3]

## 4 Conclusions and Implications

The *BABAR* discovery [1] has now been confirmed by CLEO and BELLE [4, 5]. The natural interpretation of this particle is as a  $c\bar{s}$   $L = 1$  orbital excitation, with  $J = 0$ .

The two lowest-lying ( $L = 0$ )  $c\bar{s}$  states are well known: the  $D_s(1969)$  is the  $S = J = 0$  spin-opposed state and the  $D_s^*(2112)$  is the  $S = J = 1$  spin-aligned state. It is believed that the most appropriate quantum number description is through the total angular momentum  $j$  of the  $s$  quark about the heavier  $c$  quark (i.e. using  $jj$  coupling rather than  $LS$  coupling). For the  $L = 1$  excitation, there should thus be one doublet with  $j = \frac{1}{2}$  and  $J = 0, J = 1$ , and a second with  $j = \frac{3}{2}$  and  $J = 1, J = 2$ . The second doublet has been provisionally identified with masses of 2536 and 2573 MeV/c<sup>2</sup> respectively [2]. There is thus good reason, supported by theoretical predictions [6], to suppose that the masses of the two  $j = \frac{1}{2}$  states would be similar. Such a state is thus expected to be broad, appearing only through a phase shift analysis. But if this is the  $L = 1, J = 0$  state at a mass of only 2317 MeV/c<sup>2</sup>, it cannot undergo a normal strong decay to  $DK$ , but can only access the isospin-violating mode  $D_s\pi$ . The unexpectedly narrow width is explained by the unexpectedly low mass.

That this state appears with such a low mass indicates either that it has some different (unconventional) quark content or that the mass splittings in the  $c\bar{s}$  system are very different from what was generally expected: in either case this provides an illustration of the importance for experimenters of looking at every channel they can for interesting new phenomena, not just at the ones favoured by theorists.

## References

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