Study of antiproton nucleon annihilations at rest into five pions

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The Crystal Barrel Experiment at LEAR allows the detection of charged particles and photons with almost 4π angular coverage, respectively. Here we present a study of $\bar{p}p$ annihilation and $\bar{p}d$ annihilation at rest into five-pion final states ($\bar{p}p\to 5\pi^0$, $\bar{p}p\to\pi^+\pi^-3\pi^0$, $\bar{p}d\to\pi^-4\pi^0$p and $\bar{p}d\to\pi^+2\pi^-2\pi^0$p). These reactions are well suited to look for four pion decays of scalar and vector mesons. Previous experiments on $\bar{p}n\to 2\pi^+3\pi^-$ [3], $\bar{n}p\to 3\pi^+2\pi^-$ [4], and $\bar{p}p\to\pi^+\pi^-3\pi^0$ [5] established the dominance of the production of a scalar isoscalar resonance with a mass of about 1370 MeV and a width of about 350 MeV. The $f_0(1370)$ was found to have a sizeable decay branching ratio into $\sigma\sigma$ and $\rho\rho$.
We show, in an analysis of the reaction $\bar{p}p\to 5\pi^0$, that there is indeed a scalar resonance decaying into $4\pi^0$, but this resonance can be identified with the $f_0(1500)$, a new resonance, observed by the Crystal Barrel Collaboration in the decay modes $\pi^0\pi^0$, $\eta\eta$ and $\eta\eta'$. In the $5\pi^0$ final state we found evidence for the $f_0(1500)$ decay to $\sigma\sigma$ and $\pi(1300)\pi$. A preliminary result of a combined analysis of the four five-pion data sets mentioned above confirms the existence of the $f_0(1500)$ in the data and shows that the $\sigma\sigma$ decay of the $f_0(1500)$ is more important than its decay to $\rho\rho$.

First data on $\bar{p}N$ annihilation at rest into five pions were reported in 1966 by Bettini et al. [1]. They analysed bubble chamber data on $\bar{p}n\to 2\pi^+3\pi^-$ and found a $J^{PC} = 0^{++}$ resonance with a mass of about 1410 MeV decaying to $\rho\rho$. Later analyses claimed that this reaction is dominanted by one tensor state with a mass of 1480 MeV [2]. This was challenged in a reanalyses by Gaspero [3] in 1993, who found scalar quantum numbers and M = (1386±38)MeV, Γ = (310±64)MeV. The OBELIX group presented similar evidence for a 0^+ resonance at M = (1345±12)MeV, Γ = (398±26)MeV, decaying 29% to $\rho\rho$ and 71% to $\sigma\sigma$ [4] (σ is the low mass $\pi\pi$-S-wave). We ourselves observed a resonance at (1374±38)MeV, with width (375±261)MeV, but decaying more strongly to $\rho\rho$ (61%) than to $\sigma\sigma$ (39%) [5]. The last three results are in quite good agreement concerning mass, width and spin-parity of the $f_0(1370)$. Therefore the common opinion until 1995 was that the $f_0(1370)$ plays the dominant role in describing the five-pion data.

In 1995 we started an analysis of the high statistic $\bar{p}p\to 5\pi^0$ data set which is very clean data to study the $\sigma\sigma$ decay of resonances. We found that only one f_0 was not enough to describe the data. An additional f_0 was needed with a mass and width which optimizes at the well known parameters of the $f_0(1500)$. In the reaction $\bar{p}p\to 5\pi^0$ we found decays into $\sigma\sigma$ and $\pi(1300)\pi$.

This $5\pi^0$ data set has the advantage that it is a very clean final state and that there are not so many possible intermediate states. On the other hand it has the disadvantage of a large number of combinatorical possibilities. If we want to learn something about the $\rho\rho$ decay of resonances for example of the $f_0(1500)$ we have to analyse five-pion data which involves charged particles. In particular we analyse data on

$$\begin{aligned}&\bar{p}p\to 5\pi^0\\&\bar{p}d\to\pi^-4\pi^0 p_{spectator}\\&\bar{p}p\to\pi^+\pi^-3\pi^0\\&\bar{p}d\to\pi^+2\pi^-2\pi^0 p_{spectator}\end{aligned}$$

All mesons of the final states are fully reconstructed. In case of annihilations in deuterium we asked for a proton spectator momentum lower than 100 MeV/c^2 in order to select reactions on quasi-free neutrons. In addition an anticut on the $\eta,\omega\to 3\pi$ was done.
The study of $\bar{p}n$ annihilation offers distinctive advantages compared to that of $\bar{p}p$ annihilation. Firstly the $\bar{p}n$ system has isospin I=1, hence an-

nihilation from S-wave into five pions is restricted to the $^1S_0$ state of the $\bar{p}n$ system (this is the same for same for $5\pi^0$) in $\bar{p}p$ annihilation. The advantage of analysing different data sets in parallel is that all the final states have a different sensitivity for different resonances and decay modes. So we can learn from one channel what is important for the next one.
The neutral 4π invariant mass distributions for the four different data sets are shown in Fig.1. In all data a clear enhancement compared to phase space is visible in the region of 1500 MeV/c^2. This could be a first hint for the existence of the $f_0(1500)$.

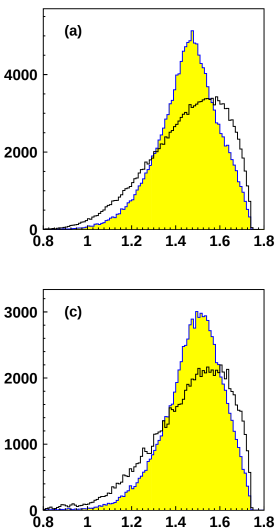

Figure 1. Neutral 4π invariant masses: $4\pi^0$ invariant mass of the $5\pi^0$ (a) and $\pi^-4\pi^0$ (b) data, $\pi^+\pi^-2\pi^0$ invariant mass of the $\pi^+\pi^-3\pi^0$ (c) and $\pi^+2\pi^-2\pi^0$ (d) data. The shaded distribution shows the data, the curve the phasespace plotted for the same number of events.

Fig.2 shows some additional invariant mass distributions but now only for the $\pi^+2\pi^-2\pi^0$ data. The plots suggest contributions from particles like $f_0(1500)$, $\rho(1450)$ and the charged and neutral $\rho(770)$ in the data. In addition, as we know from earlier analyses particles like the σ and the $\pi(1300)$ should contribute.

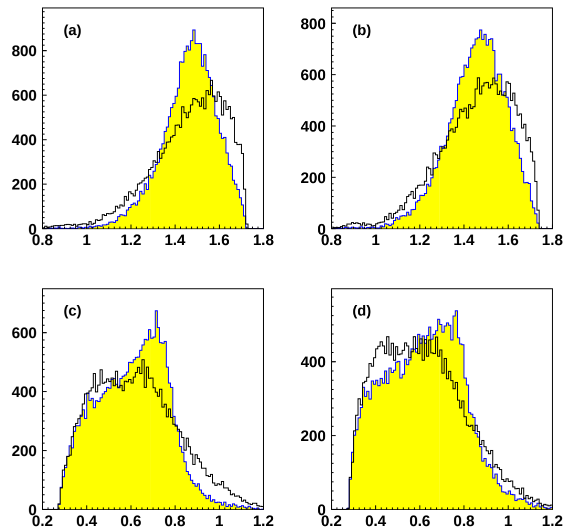

Figure 2. $\pi^+\pi^-2\pi^0$ (a), $\pi^+2\pi^-\pi^0$ (b), $\pi^+\pi^0$ (c) and $\pi^+\pi^-$ (d) invariant mass of the $\pi^+2\pi^-2\pi^0$ data set. The shaded distribution shows the data, the curve the phasespace plotted for the same number of events. The first plot shows an enhancement compared to phase space in the region around $1500 MeV/c^2$ which could be due to the $f_0(1500)$, the second one an enhancement in the mass region around $1450 MeV/c^2$ which could be related to the $\rho(1450)$. In the 2π invariant mass distributions clear peaks in the region of the $\rho(770)$ are visible.

Therefore we performed a likelihood fit using the isobar model starting with a $\rho(1450)$ fixed to parameter found in the analyses of $\bar{p}n \rightarrow \pi^-2\pi^0$: M = (1411±14)MeV, Γ = (343±20)MeV [7] and a f_0 which was scanned in mass and width.

Fig.3-6 show the result of these scans. A maximum of log(likelyhood), - i.e. the best description of the data -, is reached for all four data sets at a mass between 1350 MeV and 1450 MeV and a width between 250 and 350 MeV. These values are in a good agreement with the values of the $f_0(1370)$ found in earlier analyses. For this hypothesis, with only one f_0 allowed, Fig.7 shows the best fit one can reach for the $5\pi^0$ data. The fit is not satisfactory at all.

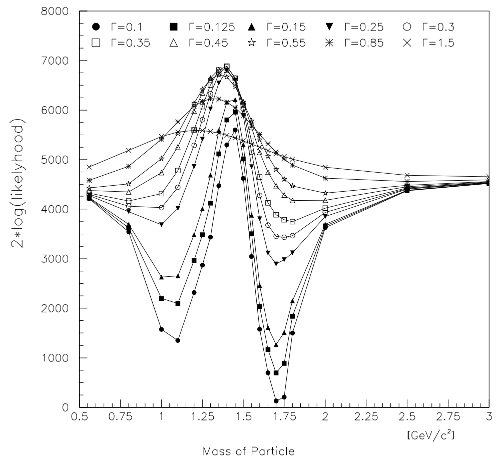

Figure 3. $5\pi^0$ data set, mass and width of one f_0 scanned. The different curves correspond to different widths of the particle.

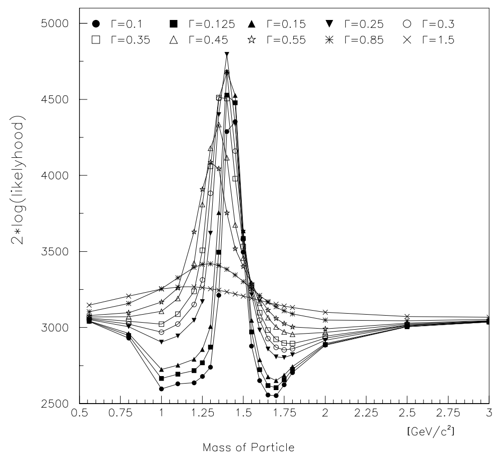

Figure 4. $\pi^-4\pi^0$ data set, the $\rho(1450)$ is fixed and the single f_0 is scanned in mass and width.

Therefore we introduced a second f_0 and scanned this one in mass and width. The results of these scans do not depend significantly on the mass and width of the first broad f_0, as long as it has a width bigger than 300 MeV. The second f_0 leads to a significant improvement in log(likelyhood) as one can see in Fig.8-11 .

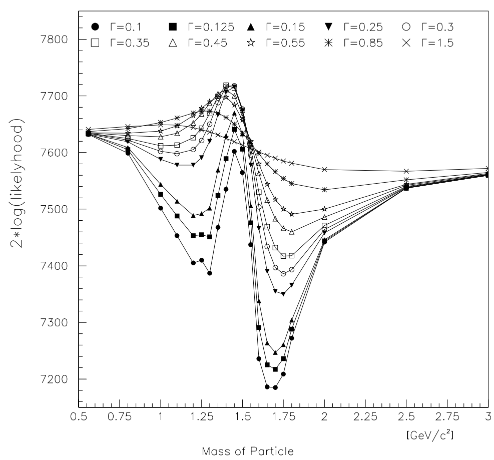

Figure 5. $\pi^+\pi^-3\pi^0$ data set, the $\rho(1450)$ is fixed in mass and width and a single f_0 is scanned. Here the f_0 can decay in addition to $\rho\rho$.

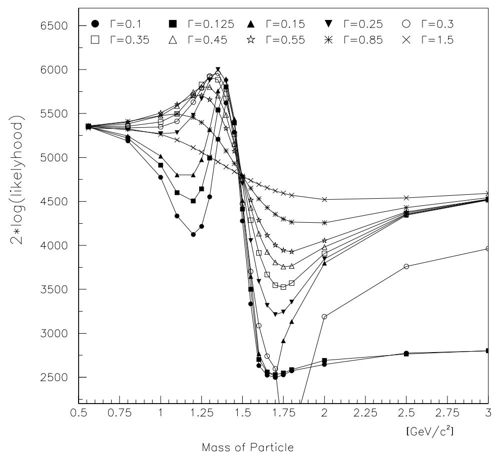

Figure 6. $\pi^+2\pi^-2\pi^0$ data set, the $\rho(1450)$ is fixed and a single f_0 is scanned in mass and width. The f_0 decay to $\rho\rho$ is also allowed in this data set.

The best value of log(likelyhood) is found at values which are close to the well known parameters of the $f_0(1500)$.

In the $\pi^-4\pi^0$ and $5\pi^0$ final state we expect a dominant contribution from the f_0, because there are not so many intermediate states possible. In-

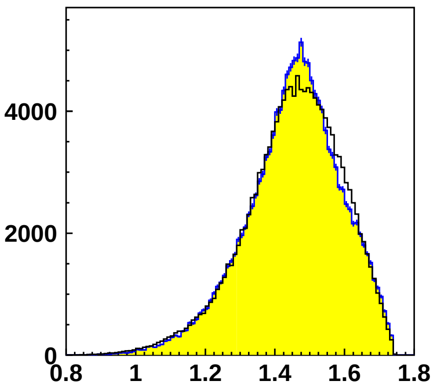

Figure 7. $4\pi^0$ invariant mass distribution ($5\pi^0$ data set): Data and fit if we allow only one f_0. The shaded distribution shows the data, the curve shows the best fit one can reach for this hypothesis. A clear deviation in the maximum is visible.

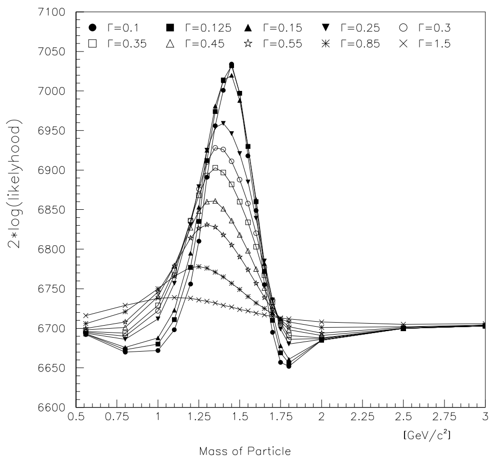

Figure 8. $5\pi^0$ data set: One broad f_0 is fixed in mass and width and the second one is scanned. In this data set only the f_0 decay to $\sigma\sigma$ is possible.

deed we get there a very nice clear maximum in log(likelyhood) in the region around 1500 MeV. This maximum is visible in the two other data sets too.

Using the $\pi^+\pi^-3\pi^0$ and $\pi^+2\pi^-2\pi^0$ data set we looked for the significance of the $f_0(1500)$

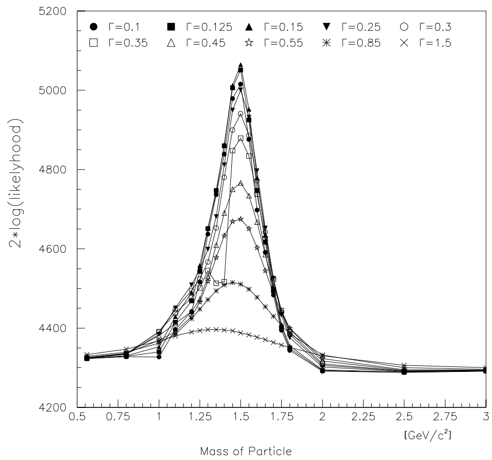

Figure 9. $\pi^-4\pi^0$ data set: The $\rho(1450)$ and one broad f_0 are fixed in mass and width and the second f_0 is scanned. In this data set only the f_0 decay to $\sigma\sigma$ is possible.

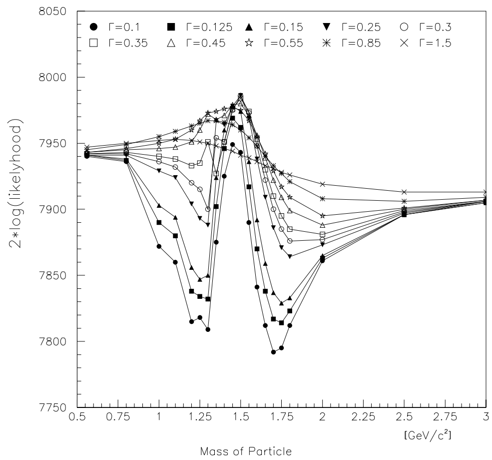

Figure 10. $\pi^+\pi^-3\pi^0$ data set: The $\rho(1450)$ and one broad f_0 are fixed in mass and width and the second f_0 is scanned, here the f_0 is allowed to decay to $\rho\rho$ too.

decay to $\rho\rho$ and $\sigma\sigma$ seperately. Fig.12,13 show scans where we allowed only the $\sigma\sigma$ decay of the $f_0(1500)$, Fig.14,15 plots where only the $\rho\rho$ was introduced.

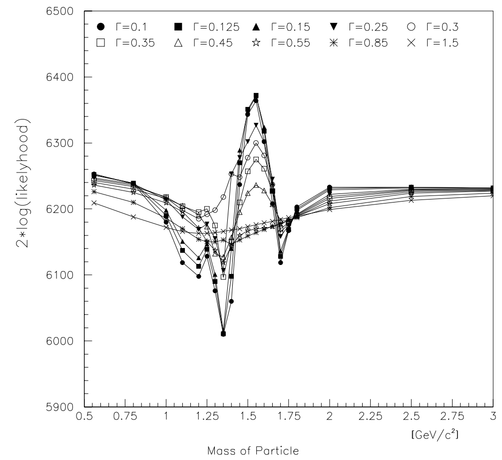

Figure 11. $\pi^+2\pi^-2\pi^0$ data set: The $\rho(1450)$ and one broad f_0 are fixed in mass and width and the second f_0 is scanned, here the f_0 is allowed to decay to $\rho\rho$ too.

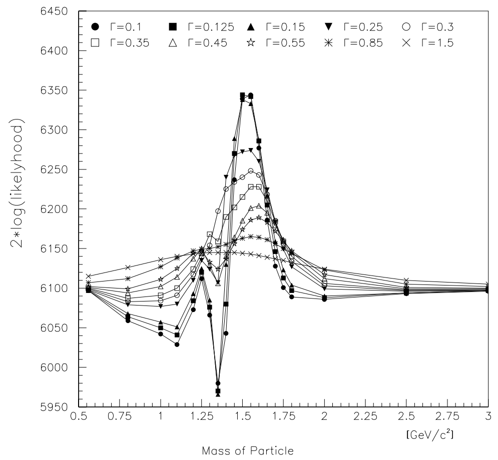

Figure 13. $\pi^+2\pi^-2\pi^0$ data set: The $\rho(1450)$ and one broad f_0 are fixed in mass and width and the second f_0 is scanned, but we allow only the decay to $\sigma\sigma$ for the second f_0.

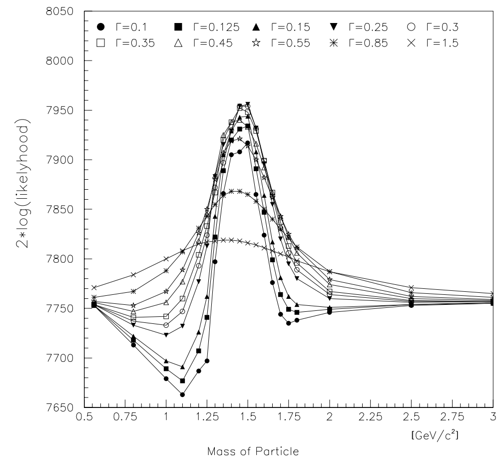

Figure 12. $\pi^+\pi^-3\pi^0$ data set: The $\rho(1450)$ and one broad f_0 are fixed in mass and width and the second f_0 is scanned, but we allow only the decay to $\sigma\sigma$ for the second f_0.

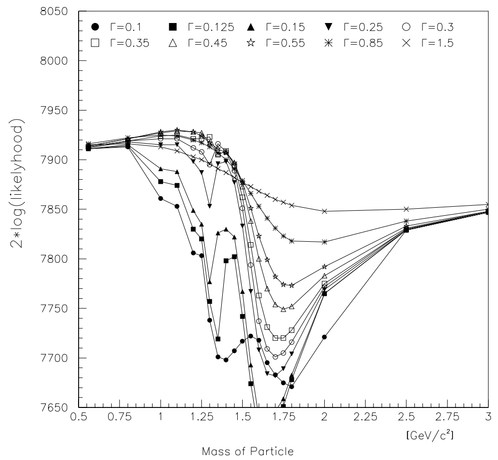

Figure 14. $\pi^+\pi^-3\pi^0$ data set: The $\rho(1450)$ and one broad f_0 are fixed in mass and width and the second f_0 is scanned, but we allow only the decay to $\rho\rho$ for the second f_0.

In the case where we allow only the $\sigma\sigma$ decay (Fig.12,13) we find a clear improvement in log(likelyhood) around 1500 MeV. If we look at the $\rho\rho$ plots, we do not. There might be some hints for a structure in this 1500 MeV region, but there appears no clear maximum in log(likelyhood). From this we conclude that the $\sigma\sigma$ decay mode of the $f_0(1500)$ is much more im-

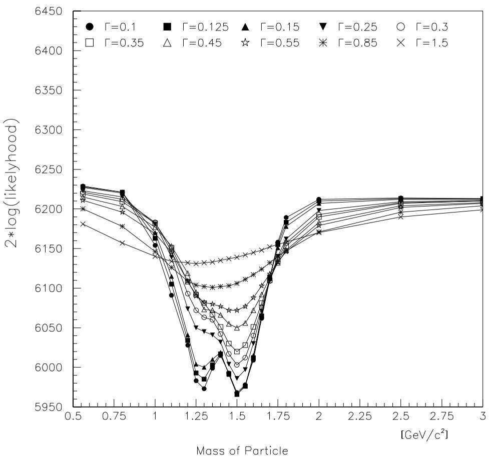

Figure 15. $\pi^+2\pi^-2\pi^0$ data set: The $\rho(1450)$ and one broad f_0 are fixed in mass and width and the second f_0 is scanned, but we allow only the decay to $\rho\rho$ for the second f_0.

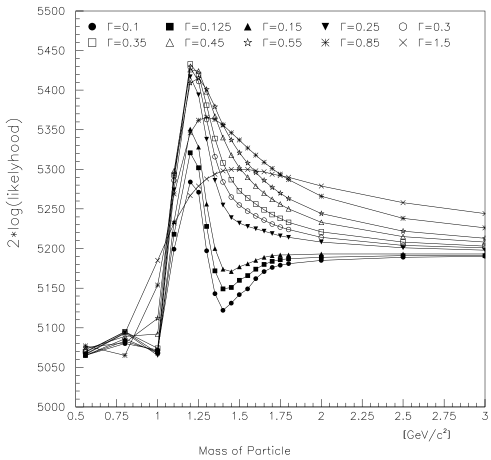

Figure 16. $\pi^+2\pi^-2\pi^0$ data set: Scan of the $\pi(1300)$ mass and width. The $\rho(1450)$ and one broad f_0 and the $f_0(1500)$ are fixed, the $f_0(1500)$ is allowed to decay to $\sigma\sigma$ and $\pi(1300)\pi$

portant than $\rho\rho$.

In the $5\pi^0$ analysis [6] we found evidence for the $\pi(1300)\pi$ decay mode of the $f_0(1500)$. Another interesting question in this context is if it is possible to observe this decay also in the other data sets.

Fig.16 shows a scan of the $\pi(1300)$ mass and width for the $\bar{p}n\to\pi^-4\pi^0$ channel. Here we fixed the $\rho(1450)$, the broad 'background' f_0 and the $f_0(1500)$. This resonance was now allowed to decay to $\sigma\sigma$, $\rho\rho$ and $\pi(1300)\pi$, and we scanned the $\pi(1300)$ mass and width. From this scan we find a mass of about 1200 MeV and a width of about 350 MeV for the $\pi(1300)$. Therefore this final state is also sensitive to the $\pi(1300)\pi$ decay of the $f_0(1500)$. Hence we come to the following conclusion: with only one scalar resonance we can reproduce the results of earlier analyses [3], [4], [5], namely the $f_0(1370)$. This hypothesis however does not lead to a satisfactory description of the data. All four data sets require the existence of a comparatively narrow $f_0(1500)$ and of a broad scalar 'background' resonance. It seems that $\sigma\sigma$ decay mode of the $f_0(1500)$ is more important than $\rho\rho$.

An additional question which maybe can be solved with these data is the question if the $\rho'(1450)$ decays to πa_1 and πh_1. This is important for the hybrid interpretation of this state. Close et al. [8] for example calculated that a hybrid ρ decays into πa_1 and not into πh_1.

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