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Measurement of the Radiative Width of the $A_2(1320)$ in Two-Photon Interactions

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Abstract. The reaction $e^+e^- \to e^+e^- A_2(1320)$ has been observed by detecting the decay $A_2 \to \pi^+\pi^-\pi^0$. The two-photon width of the A_2 has been measured to be $\Gamma(A_2 \to \gamma\gamma) = (0.90 \pm 0.27\,(\mathrm{stat}) \pm 0.16\,(\mathrm{syst}))$ keV. The cross section $\sigma(\gamma\gamma \to \pi^+\pi^-\pi^0)$ has been determined outside the A_2 resonance region.

Measurements of the two-photon partial widths of light mesons provide information to test their classification within $SU(3)$ multiplets. At e^+e^- storage rings a resonance R with positive charge conjugation can be produced via the exchange of two predominantly quasi-real photons in the reaction

$$e^+e^- \to e^+e^- + R. \tag{1}$$

In this paper the measurement of the two-photon width of the $A_2(1320)$ is reported. The A_2 is the isovector partner of the $f(1270)$ and the $f'(1525)$ in the $J^{PC} = 2^{++}$ multiplet. The A_2 was observed via its $\rho\pi$ decay in the following reaction chain:

$$\begin{aligned} &e^+e^- \to e^+e^- + A_2 \\ &\qquad\qquad\quad \hookrightarrow \rho^\pm \pi^\mp \\ &\qquad\qquad\qquad\ \ \hookrightarrow \pi^\pm \pi^0 \\ &\qquad\qquad\qquad\qquad\quad \hookrightarrow \gamma\gamma. \end{aligned} \tag{2}$$

The measurement was performed at an average beam energy of 17 GeV using the TASSO detector at PETRA. The scattered leptons in the final state were not detected since they are predominantly emitted at very small angles (no tag mode). Charged particles were measured with the central tracking detector which is described elsewhere [1]. Photons were detected in three different electromagnetic calorimeters, the liquid argon barrel calorimeters (LABC), the liquid argon endcap calorimeters (LAEC), and the hadron arm shower counters (HASH). In front of the calorimeters are between 1.0 to 1.5 radiation lengths (X_0) of various materials.

The LABC and the LAEC are liquid argon lead sampling calorimeters with a total thickness of $14.0\,X_0$ and $13.5\,X_0$, respectively. They cover solid angles of 40 % (LABC) and 10 % (LAEC) of 4π. The HASH are lead scintillator shower counters ($7.4\,X_0$) with wavelength shifter readout. Their angular coverage is 18 % of 4π. A detailed description of the shower counters and the shower cluster analysis can be found in [2–5].

Shower counter information was available for an integrated luminosity of $66\,\mathrm{pb}^{-1}$ for the LABC, $71\,\mathrm{pb}^{-1}$ for the LAEC and $76\,\mathrm{pb}^{-1}$ for the HASH. Events were required to fulfill at least one of the following trigger conditions based on the information from the central detector:

1. At least two charged tracks separated by more than 154° in azimuth.

2. Two or more tracks with at least one track originating from the interaction point within ± 15 cm along the beam direction.

For each track the momentum component perpendicular to the beam direction, $|\mathbf{p}_t|$, had to exceed a preselected nominal value of 0.22 GeV/c (0.32 GeV/c) for about 75 % (25 %) of the data. For the 0.22 GeV/c threshold the trigger efficiency per track was determined to be 50 % for $|\mathbf{p}_t| = 0.17$ GeV/c increasing to 95 % for $|\mathbf{p}_t| > 0.29$ GeV/c. The polar angle acceptance for the triggering tracks was $|\cos\Theta| < 0.82$.

In the offline analysis each reconstructed track was required to have a transverse momentum $|\mathbf{p}_t| > 0.1$ GeV/c, a polar angle $|\cos\Theta| < 0.87$ and to originate within ± 5 cm of the interaction point along the beam axis and within ± 1 cm in a plane perpendicular to the beam. An energy cluster in the electromagnetic calorimeter was considered a photon if the measured energy was larger than 0.10, 0.15, and 0.16 GeV and if no charged track pointed into the direction of the cluster within 10°, 6°, and

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17° for the LABC, LAEC, and HASH, respectively. For the LAEC this criterium was only applicable for polar angles above 20° (below 160°) because for smaller (larger) angles no charged particle tracking was available. The efficiencies to detect and reconstruct photons were determined with the EGS shower simulation program [6].

For the analysis of reaction (2) events were selected with two oppositely charged tracks and two photons. The charged tracks were assumed to be pions (From time of flight measurements it was found that about 3 % of the tracks were consistent with a kaon or a proton; the fraction of events with both charged tracks being consistent with a kaon was negligible). The following event selection criteria were used:

1. The total energy of charged particles and photons had to be less than 25 % of the available c.m. energy, in order to reject one photon annihilation events.

2. The charged tracks were required to be acollinear in a plane perpendicular to the beam by more than 10°, in order to exclude QED background.

3. The angle between the two photons was required to be less than 90°.

Figure 1 shows the distribution of the invariant mass of the two photons for the exclusively produced state $\pi^+\pi^-\gamma\gamma$, selected by requiring the transverse momentum squared of the $\pi^+\pi^-\gamma\gamma$ system with respect to the beam axis, $|\sum \mathbf{p}_t|^2$, to be smaller than 0.0225 (GeV/c)^2. A clear π^0 signal is seen, its width and mass value being in good agreement with a Monte Carlo simulation.

The photon pairs with $0.07 \leqq m(\gamma\gamma) \leqq 0.20$ GeV are kinematically fitted to the π^0 mass and events with a χ^2 probability of less than 1 % are removed. For the remaining events Fig. 2 shows the correlation between the mass of the $\pi^+\pi^-\pi^0$ state and its transverse momentum squared. A clear enhancement around the A_2 mass is observed for events having low $|\sum \mathbf{p}_t|^2$.

For the study of exclusive two-photon events a cut $|\sum \mathbf{p}_t|^2 \leqq 0.0225$ (GeV/c)^2 was applied for the distributions in Fig. 3. The $\pi^+\pi^-\pi^0$ mass spectrum of Fig. 3a exhibits a pronounced A_2 peak. The shaded area corresponds to events satisfying the additional requirement that at least one of the $\pi^+\pi^0$ or $\pi^-\pi^0$ mass combinations lies in the ρ region ($0.62 \leqq m(\pi^\pm\pi^0) \leqq 0.92$ GeV). There is almost no reduction of the A_2 signal. The distribution is consistent with the expectation that the A_2 decay into three pions proceeds entirely via the $\rho^\pm\pi^\mp$ intermediate state.

Two kinds of possible background below the A_2 signal were considered, namely the reactions

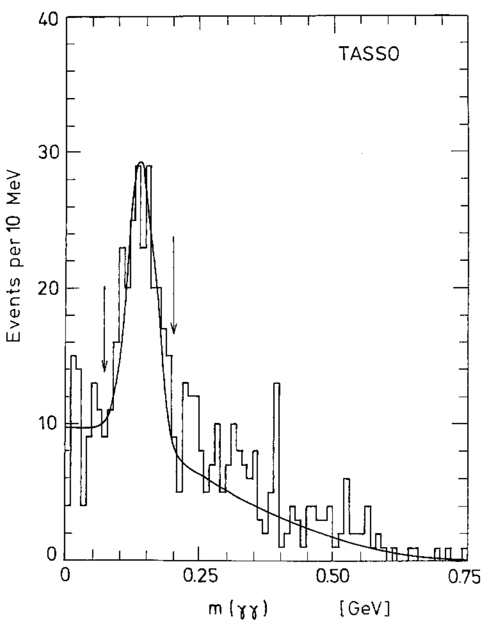


Fig. 1. Invariant mass of the two photons in exclusive $\pi^+\pi^-\gamma\gamma$ events requiring $|\sum \mathbf{p}_t|^2 \leqq 0.0225$ (GeV/c)^2. The solid curve shows the Monte Carlo prediction for the π^0 mass distribution plus a polynomial background. The arrows indicate the cuts used

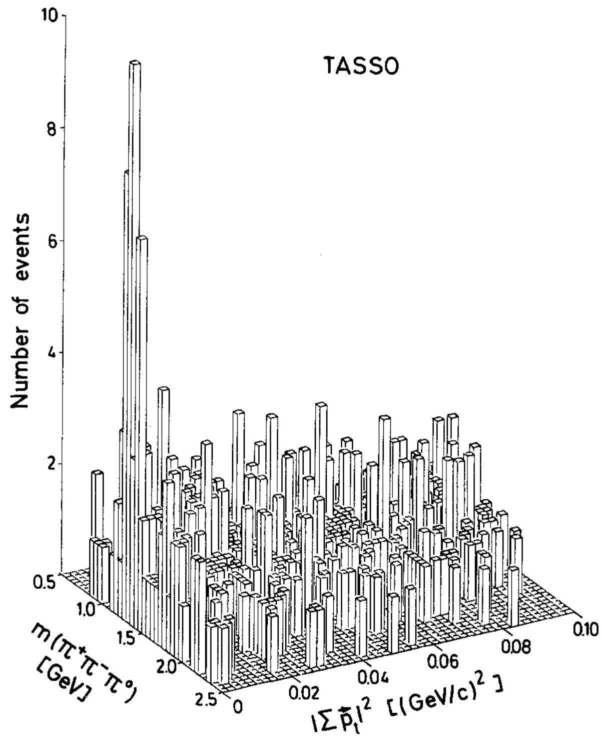
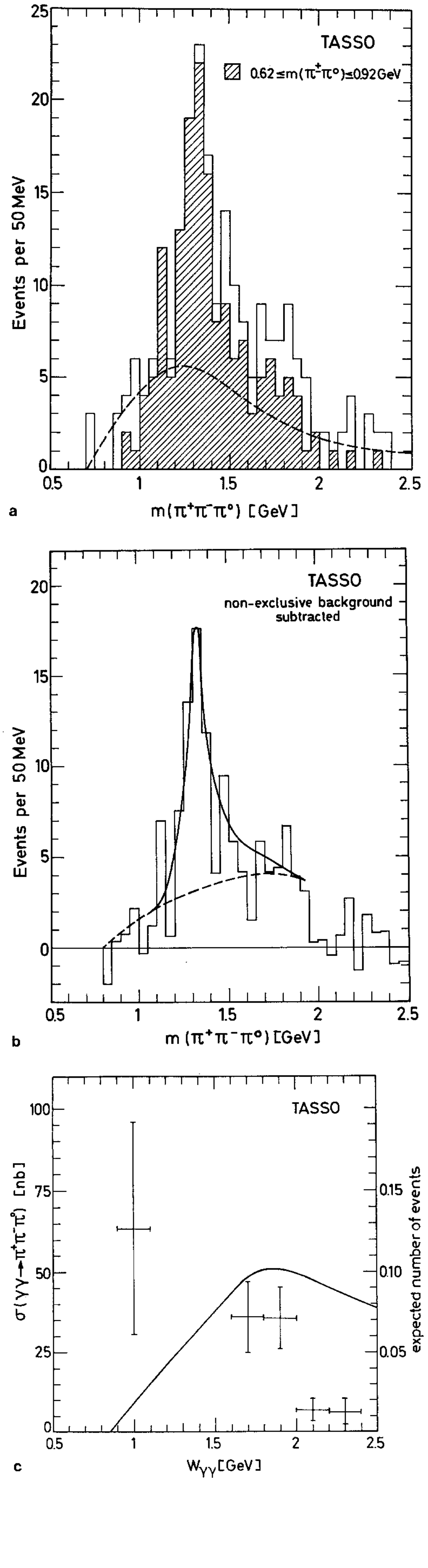


Fig. 2. Invariant mass of the $\pi^+\pi^-\pi^0$ final state versus $|\sum \mathbf{p}_t|^2$ after the kinematical fit to the π^0 mass



$\gamma\gamma \to \pi^+\pi^-\pi^0 + X$, referred to as non-exclusive background, and $\gamma\gamma \to \pi^+\pi^-\pi^0$, referred to as non-$A_2$ exclusive contribution.

The contribution from non-exclusive events was investigated by studying the $\pi^+\pi^-\pi^0$ mass distribution as a function of $|\sum \mathbf{p}_t|^2$. Figure 4 shows the transverse momentum distributions for different mass regions below, at, and above the A_2. Their common feature is a linear $|\sum \mathbf{p}_t|^2$ dependence with the same slope above $|\sum \mathbf{p}_t|^2 \gtrsim 0.03$ (GeV/c)^2 (solid lines in Fig. 4). The extrapolation to $|\sum \mathbf{p}_t|^2 \approx 0$, as indicated by the dashed lines, gives a good description of the data below the A_2 mass (Fig. 4a), whereas an excess of events is observed for the data above (Figs. 4c, d) which can be attributed to non-A_2 $\pi^+\pi^-\pi^0$ production. The distribution at the A_2 mass (Fig. 4b) shows a large enhancement at $|\sum \mathbf{p}_t|^2 \approx 0$. Besides A_2 resonance production this peak also contains a small non-A_2 exclusive contribution which can be inferred from the neighbouring mass intervals of Figs. 4a, c.

In order to determine the partial width $\Gamma(A_2 \to \gamma\gamma)$ Monte Carlo events were generated convoluting the cross section of the two photon resonance production $\sigma(\gamma\gamma \to A_2 \to \rho\pi)$ with the flux of transverse photons [7] and passed through a detector simulation program. The cross section is given by

$$\sigma(\gamma\gamma \to A_2 \to \rho\pi) = 8\pi(2J+1) \cdot \frac{m_A^2}{s} \frac{\Gamma(A_2 \to \gamma\gamma)\,\Gamma(A_2 \to \mathrm{all})\,\mathrm{BR}(A_2 \to \rho\pi)}{(m_A^2 - s)^2 + m_A^2\,\Gamma(A_2 \to \mathrm{all})^2}, \tag{3}$$

with s being the three pion invariant mass squared, and J the spin of the A_2. The mass m_A, the total width $\Gamma(A_2 \to \mathrm{all})$, and the branching ratio $\mathrm{BR}(A_2 \to \rho\pi)$ of the A_2 were taken from PDG [8]. The mass dependence of the A_2 width was taken into account by the expression [9]:

$$\Gamma(m_{\rho\pi}) = \Gamma(m_A) \left(\frac{p_\rho}{p_\rho^0}\right)^{2L+1} \frac{D_L(r p_\rho^0)}{D_L(r p_\rho)}. \tag{4}$$

Fig. 3. **a** Invariant mass distribution of the $\pi^+\pi^-\pi^0$ events satisfying $|\sum \mathbf{p}_t|^2 \leqq 0.0225$ (GeV/c)^2. The dashed line represents the background from non-exclusive reactions. The shaded area shows the invariant mass for events where at least one of the $\pi^\pm\pi^0$ combinations lies in the ρ mass region. **b** Invariant mass distribution of the $\pi^+\pi^-\pi^0$ events after subtraction of non-exclusive background. The solid line shows the result from a fit of the A_2 Monte Carlo prediction plus a background term for $\pi^+\pi^-\pi^0$ phase space production (dashed curve) as described in the text. **c** Measured cross section $\sigma(\gamma\gamma \to \pi^+\pi^-\pi^0)$ as function of $W_{\gamma\gamma}$ (left scale). The curve shows the number of events expected to be observed in this experiment for a constant cross section of 1 nb (right scale). Phase space production of the three pions was assumed

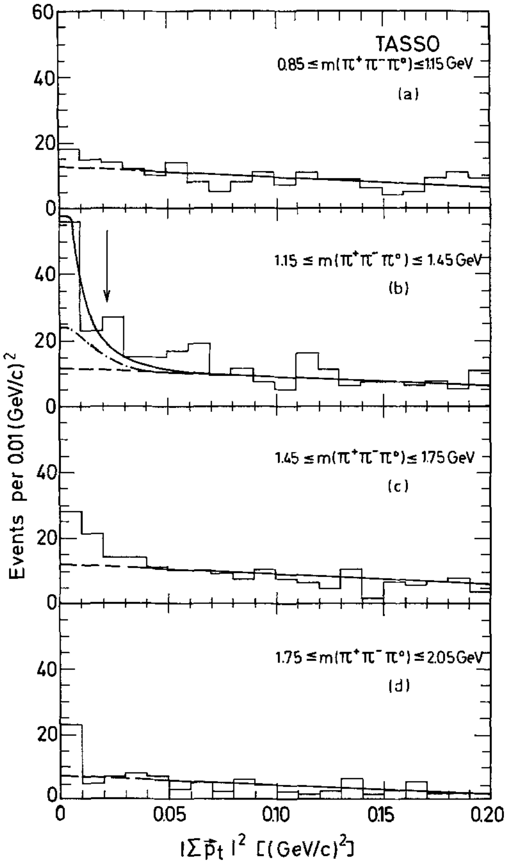


Fig. 4a–d. $|\sum \mathbf{p}_t|^2$ distribution for $\pi^+\pi^-\pi^0$ events in four mass regions: **a** $0.85 \leq m(\pi^+\pi^-\pi^0) \leq 1.15$ GeV; **b** $1.15 \leq m(\pi^+\pi^-\pi^0) \leq 1.45$ GeV; **c** $1.45 \leq m(\pi^+\pi^-\pi^0) \leq 1.75$ GeV; **d** $1.75 \leq m(\pi^+\pi^-\pi^0) \leq 2.05$ GeV. The solid line in **b** represents the result from a fit to the Monte Carlo prediction plus a background term as described in the text. The dashed and dashed-dotted curves show the non-exclusive and the $\pi^+\pi^-\pi^0$ non-A_2 background contributions. The solid lines in **a, c, d** are linear parametrizations of $|\sum \mathbf{p}_t|^2$ for the non-exclusive background

Here p_ρ^0 is the ρ momentum in the three pion rest frame at the A_2 mass and p_ρ is the corresponding value calculated for the invariant mass $m_{\rho\pi}$. The orbital angular momentum of the $\rho\pi$ system is $L=2$. The functions D_L are damping factors [10]. The parameter r has a value of 1 fm [11].

The decay $A_2 \to \pi^+\pi^-\pi^0$ was described by a three-body phase space multiplied with the following matrix element:

$$|M|^2 \sim |\mathrm{BW}(\rho^+)\mathrm{ANG}(\rho^+, \pi^-) + \mathrm{BW}(\rho^-)\mathrm{ANG}(\rho^-, \pi^+)|^2. \quad (5)$$

The matrix elements is a coherent sum of two relativistic Breit-Wigner (BW) distributions for the $A_2 \to \rho^+\pi^-$ and the $A_2 \to \rho^-\pi^+$ decays:

$$\mathrm{BW}(\rho) = \frac{\sqrt{m_\rho \Gamma_\rho m_{\pi\pi}/p_\pi}}{m_\rho^2 - m_{\pi\pi}^2 - i m_\rho \Gamma_\rho}.$$

Here m_ρ is the mass of the ρ, Γ_ρ its mass dependent width [9], $m_{\pi\pi}$ is the invariant mass of the decay pions, and p_π is the pion momentum in the rest frame of the $\pi\pi$ system. The combined angular distribution of the A_2 decay and the subsequent ρ decay is given by:

$$\mathrm{ANG}(\rho, \pi) = \sum_{j_3} C(J, J_3 | L, J_3 - j_3; j, j_3) \cdot Y_L^{J_3 - j_3}(\vartheta_\rho, \varphi_\rho)\, Y_j^{j_3}(\vartheta_\pi, \varphi_\pi).$$

Here $\vartheta_\rho, \varphi_\rho (\vartheta_\pi, \varphi_\pi)$ are the polar and azimuthal angles of the $\rho(\pi^0)$ evaluated in the $\gamma\gamma$ cm system (ρ rest frame). $J(J_3)$ is the spin of the A_2 (third component of the spin, identical to the $\gamma\gamma$ helicity), $j(j_3)$ the ρ spin (third component) and $L=2$ is the angular momentum of the $\rho\pi$ system. All angles are calculated with respect to the $\gamma\gamma$ direction as the angular quantization axis, which was assumed to coincide with the e^+ beam direction. The functions Y are spherical harmonics and the functions $C(J, J_3 | L, J_3 - j_3; j, j_3)$ are Clebsch-Gordon coefficients. The $\gamma\gamma$ helicity was assumed to be ± 2 [12, 16].

The partial width $\Gamma(A_2 \to \gamma\gamma)$ was extracted from the $\pi^+\pi^-\pi^0$ mass spectrum with $|\sum \mathbf{p}_t|^2 \leq 0.0225$ (GeV/c)^2 (Fig. 3a). The contribution from non-exclusive reactions was estimated from the two-dimensional distribution $m(\pi^+\pi^-\pi^0)$ versus $|\sum \mathbf{p}_t|^2$ of Fig. 2 in the following way. The smoothed mass spectrum of events with $0.03 \leq |\sum \mathbf{p}_t|^2 \leq 0.06$ (GeV/c)^2 was used to describe the shape of the background. The shape of this background was found to be independent of $|\sum \mathbf{p}_t|^2$ for $|\sum \mathbf{p}_t|^2 \gtrsim 0.03$ (GeV/c)^2, whereas its absolute magnitude could be adequately described by a linear $|\sum \mathbf{p}_t|^2$ dependence (see discussion above and Fig. 4). It was assumed that this procedure results in a reasonable description of the background at low $|\sum \mathbf{p}_t|^2$. The extrapolated non-exclusive background is shown as the dashed curve in the mass distribution of Fig. 3a; the mass spectrum after subtracting this contribution is displayed in Fig. 3b. Besides the A_2 signal additional $\pi^+\pi^-\pi^0$ production is observed. To estimate this non-A_2 contribution the behaviour of the $\pi^+\pi^-\pi^0$ phase space was studied by a Monte Carlo simulation. The acceptance folded with the two-photon luminosity is displayed as curve in Fig. 3c. From this the cross section $\sigma(\gamma\gamma \to \pi^+\pi^-\pi^0)$ was determined outside the A_2 resonance accounting properly for the tails of the resonance. The results are shown in Fig. 3c. The contribution underneeth the A_2 peak was estimated assuming a $1/W_{\gamma\gamma}$ dependence of the measured cross section $\sigma(\gamma\gamma \to \pi^+\pi^-\pi^0)$ for $W_{\gamma\gamma} < 2.0$ GeV. The sum of the A_2 shape from the Monte Carlo simulation and a background curve determined as described above was fitted to the $\pi^+\pi^-\pi^0$ invariant mass distribution of Fig. 3b. The fit yielded (55 ± 16) A_2 events corresponding to the A_2 partial width of $\Gamma(A_2\to\gamma\gamma)=(0.90\pm0.27)$ keV. The result of the fit is shown as well in Fig. 3b. The uncertainty of the background determination which is mainly due to the parametrization of the non-A_2 cross section was further investigated. The following assumptions were tried: A linear interpolation of $\sigma(\gamma\gamma\to\pi^+\pi^-\pi^0)$, a constant cross section, and a linearly rising background for $W_{\gamma\gamma}<2$ GeV, as well as a hypothetical resonance contribution around 1.8 GeV plus $\pi^+\pi^-\pi^0$ phase space production up to $W_{\gamma\gamma}<2.5$ GeV. All investigations gave A_2 partial widths in agreement with the previous value. The largest deviations between any two values were less than 0.1 keV. Thus the result is not very sensitive to changes in the background description, however, background contributions from other resonances cannot be excluded.

The result of this analysis was checked by investigating the transverse momentum distribution of Fig. 4b. The background in the A_2 region was determined by taking the average of the two neighbouring mass intervals. The contributions from non-exclusive and non-A_2 processes are displayed in Fig. 4b as the dashed and dashed-dotted curves, respectively. The sum of the background terms and the shape expected from the Monte Carlo simulation of the process $A_2\to\rho^\pm\pi^\mp$ was fitted to the $|\sum \mathbf{p}_t|^2$ distribution. The result is (52 ± 19) events corresponding to a width of (0.88 ± 0.32) keV.

Both analysis methods give consistent results within statistical errors. It should be noted that no constraint on the ρ mass was demanded, thus avoiding possible problems due to the large ρ width. Introducing this additional requirement does not change the results, but gives larger errors due to poorer background determination. Repeating the analysis without a kinematical π^0 fit did not change the results.

The systematic error comes mainly from the different models used for the background estimate (0.11 keV), the detector acceptance (0.11 keV), the luminosity measurement (0.05 keV) and the uncertainty in the q^2 dependence of the A_2 production (0.01 keV). Adding these contributions in quadrature a systematic error of 0.16 keV was obtained.

The final result is:

$$\Gamma(A_2\to\gamma\gamma)=(0.90\pm0.27\,(\text{stat})\pm0.16\,(\text{syst}))\ \text{keV}.$$

Our value of $\Gamma(A_2\to\gamma\gamma)$ is in good agreement with previous measurements of Crystal Ball (at SPEAR), $\Gamma(A_2\to\gamma\gamma)=(0.77\pm0.18\pm0.27)$ keV [13], CELLO, $\Gamma(A_2\to\gamma\gamma)=(0.81\pm0.19\pm0.27)$ keV [14], PLUTO, $\Gamma(A_2\to\gamma\gamma)=(1.06\pm0.18\pm0.15)$ keV [15], and Crystal Ball (at DORIS), $\Gamma(A_2\to\gamma\gamma)=(1.14\pm0.20\pm0.26)$ keV [16].

Using the quark model with the assumption of $SU(3)$ symmetry the following relations between the $\gamma\gamma$ widths of tensor mesons can be obtained [17]:

$$\frac{\Gamma(A_2\to\gamma\gamma)}{m_{A_2}^3}:\frac{\Gamma(f\to\gamma\gamma)}{m_f^3}:\frac{\Gamma(f'\to\gamma\gamma)}{m_{f'}^3}$$
$$=3:(\sin\vartheta+\sqrt{8}\cdot R\cos\vartheta)^2:(\cos\vartheta-\sqrt{8}\cdot R\sin\vartheta)^2, \quad (6)$$

where ϑ is the singlet-octet mixing angle and R is the ratio of the singlet to octet wave functions at the origin. In order to evaluate ϑ and R from (6) we take the present result of $\Gamma(A_2\to\gamma\gamma)$, our previous measurement [18] on $\text{BR}(f'\to K\bar{K})\ \Gamma(f'\to\gamma\gamma)=(0.11\pm0.02\pm0.04)$ keV, with $\text{BR}(f'\to K\bar{K})=1$, and the world average of $\Gamma(f\to\gamma\gamma)=(2.65\pm0.12)$ keV [19]. The result of a fit is $\vartheta=27.2°\pm7.7°$ and $R=1.06\pm0.38$. The mass dependence in (6) cannot be rigorously justified from the theoretical side. The values assuming no mass dependence are $\vartheta=30.8°\pm8.1°$ and $R=1.01\pm0.35$. This value of the mixing angle is consistent with results derived from mass relations [8]. It is close to the ideal mixing angle of $\vartheta=35.3°$, i.e. the f is built up from u and d quarks only, while the f' is an almost pure $s\bar{s}$ state. The result is also consistent with the assumption of nonet symmetry $(R\approx1)$ which implies that in the tensor meson multiplet besides u, d and s quarks no large admixtures of other states like gluonium or $qq\bar{q}\bar{q}$ are required.

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