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Two-Photon Excitation of the Tensor Meson $f^0(1270)$

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Abstract. We have measured charged particle pair production in two-photon scattering at the e^+e^- storage ring PETRA. While the main source of such events is the production of lepton pairs, the presence of an additional process is clearly indicated by the measured invariant mass distribution of the two particles and their angular distributions. We determine that the excess is mainly due to the decay $f^0(1270) \rightarrow \pi^+\pi^-$. We derive a width $\Gamma(f^0 \rightarrow \gamma\gamma) = 3.2 \pm 0.2 \pm 0.6$ keV (statistical and systematic).

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The two-photon (2γ) mechanism in e^+e^- collisions is represented by the process

$$e^+e^- \to e^+e^- + \gamma\gamma \to e^+e^- + X,$$

where X is any produced system of invariant mass M_x. Such reactions, providing a wide range of $\gamma\gamma$ center of mass energies at fixed e^+e^- beam energy, have long been recognized as well suited for the detection of C-even resonances which couple to two photons [1]. First results on two-photon production of η' [2] and f^0 [3–6] have been reported. Here we present a study of photon-photon mediated resonance production of pairs of charged particles obtained with the TASSO detector at the e^+e^- storage ring PETRA.

For most of the two-photon events the primary electrons and positrons are scattered at extremely small angles with respect to their original direction and thus are not detected. The 2γ events can be separated from one-photon annihilation events and other background by kinematic cuts without requiring the observation of a scattered electron. These data are referred to as "no tag" events. For a smaller number of events ("single tag") one of the scattered electrons is observed in a narrow angular region between 24 and 60 mrad relative to the beam direction.

In this analysis we considered events for which the produced system consisted of a pair of oppositely charged particles observed in the central detector. The TASSO detector and the reconstruction procedure have been described previously [7]. The *rms* momentum resolution including multiple scattering was $\sigma/p = 0.02 \cdot \sqrt{1+p^2}$ (p in GeV/c).

The tagged electrons were detected in two forward detector modules which surrounded the beam pipe at either end of the interaction point. Figure 1 is a view of one of the forward detectors along the beam axis. Each consisted of an array of 36 lead glass shower counters, about 12 radiation lengths thick, preceded by an azimuthally segmented scintillator hodoscope.

The data for this analysis correspond to a total integrated luminosity of 9240 nb^{-1} at beam energies ranging from 13.7 to 18.35 GeV.

The no tag events were obtained with the pair trigger designed for one-photon QED events which are coplanar with the beam axis [8]. This trigger covered in polar angle $|\cos\Theta| < 0.8$ and had a 2π acceptance in azimuth. It had a transverse momentum (p_T) dependent efficiency, with a threshold at about 0.3 GeV/c, and rising to 90% above 0.5 GeV/c. The combined efficiency of the trigger and the event selection and reconstruction program was 83%.

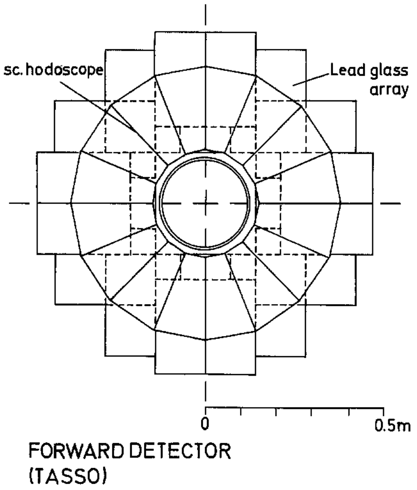

Fig. 1. View of one forward detector module along the beam axis

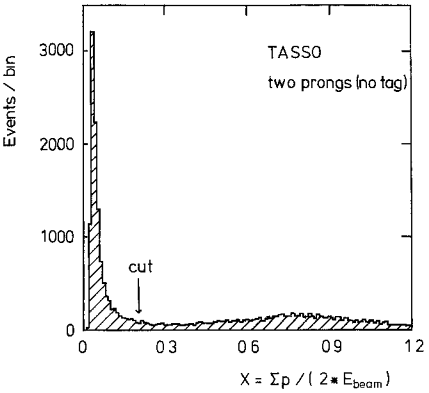

Fig. 2. $e^+e^- \to$ two charged particles + anything (no tag): Distribution of x before cuts, where x is the sum of the momenta of the two particles in each event divided by twice the beam energy

Two-photon induced two-prong events were selected requiring two oppositely charged tracks originating from the interaction region which were coplanar with the beam axis within 10°. These cuts reduced the background from beam gas scattering. Two-prong events originating from cosmic rays and one-photon processes (mainly lepton pairs) were rejected by requiring the two tracks to be non-collinear by more than 7.5° and the sum of the magnitudes of their momenta to be less than 20% of twice the beam energy. The effect of the latter cut is illustrated by Fig. 2 which shows the distribution of the sum of the track momenta divided by twice the sum of the beam energies. The indicated cut eliminates most of the one-photon events surviving the collinearity cut.

In Fig. 3 we plot the transverse momentum $|\vec{p}_{T1} + \vec{p}_{T2}|$ of the observed system for the events selected with these cuts. The distribution is strongly peaked near zero, as expected if the two photons go along the beam line and all particles in the produced system are detected. Requiring $|\Sigma\vec{p}_T| < 0.3$ GeV/c reduced the contamination from 2γ-multihadron production. From Figs. 2 and 3 we conclude that the events in our sample originate from two-photon production of a

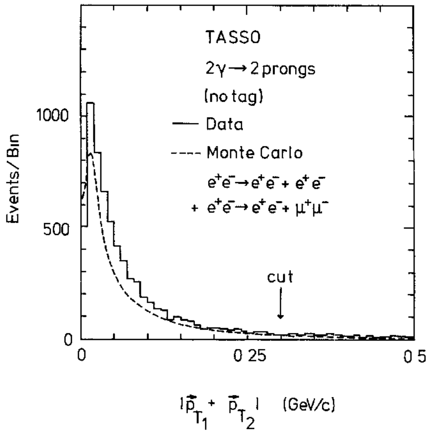

Fig. 3. $e^+e^-\to$two charged particles+anything (no tag): Modulus of the vector sum of the transverse momenta of the two charged particles The dashed curve shows the QED prediction for lepton pair production

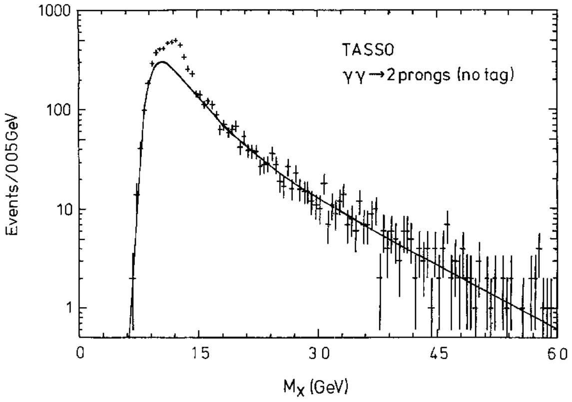

Fig. 4. $e^+e^-\to e^+e^-$ +two charged particles (no tag): Invariant mass distribution of the two charged particles assuming pion masses; the curve is the prediction for QED lepton pair production

pair of charged particles. After all cuts the background contamination in these data was about 2% beam gas events, less than 1% from one photon annihilation and cosmic rays and about 1.5% from 2γ-multihadron production. The dashed curve in Fig. 3 shows the QED prediction for the sum of $e^+e^-\to e^+e^-e^+e^-$ and $e^+e^-\mu^+\mu^-$. The excess of events observed is mainly due to the resonance contribution (see below).

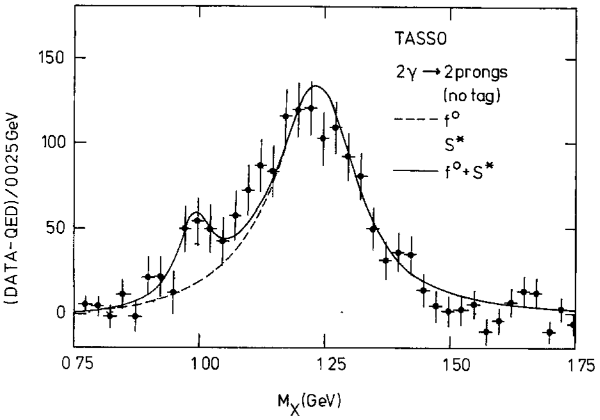

Fig. 5. Same as in Fig. 4 but with the QED contribution subtracted. The curves show fits for f^0 and S^* production with the f^0, S^* parameters taken from the PDG [16]

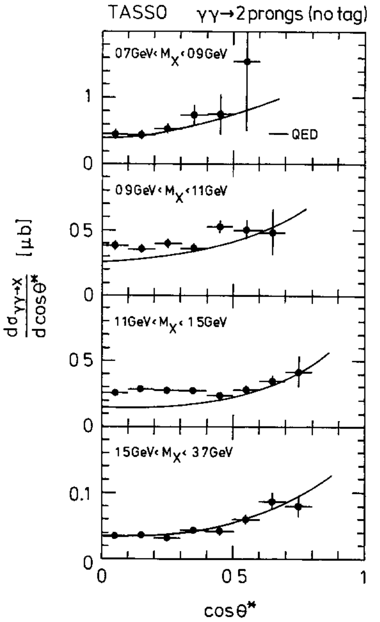

Fig. 6. $e^+e^-\to e^+e^-$+two charged particles (no tag): Angular distribution for different regions of the two particle mass. The distributions are corrected for acceptance; Θ^* is the angle between the beam axis and one of the charged particles in the two-particle center of mass system. The solid lines are the QED predictions for lepton pair production

In Fig. 4 we show the distribution of the invariant mass M_x of the two prongs assigning pion masses to the particles. In this plot we compare our data to the prediction for QED pair production. The curve gives the sum of the yields from the reactions

$$e^+e^-\to e^+e^-e^+e^- \quad \text{and} \quad e^+e^-\to e^+e^-\mu^+\mu^-$$

as simulated in our detector using the event generator written by Vermaseren [9]. The contribution from two-photon production of $\tau^+\tau^-$ to the two-prong sample was calculated and found to be negligible. Radiative corrections have not been included. This may be justified by the result of first calculations of radiative corrections for two-photon processes [10], which yielded contributions less than a few percent. For the M_x range above 1.5 GeV out to 6 GeV the shape of the observed invariant mass distribution agrees with the expectation from QED within 1%. The systematic uncertainty of our overall normalization in this mass region is ±8%. For M_x between 0.9 and 1.5 GeV we observe a pronounced excess over the QED prediction peaking at around 1.25 GeV. The invariant mass distribution after subtraction of QED is shown in Fig. 5. It suggests a considerable contribution

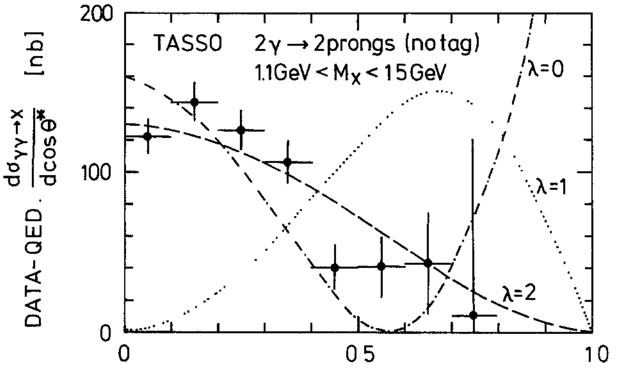

Fig. 7. Same as in Fig. 6 for the f^0 mass region but with the QED contribution subtracted. The cross section is corrected for acceptance. The curves show the expectations for helicities of the 2γ system $\lambda=0$, 1 and 2

from resonance production. Figure 6 shows angular distributions for different mass regions. The data are corrected for acceptance. Here Θ^* is the angle between the beam axis and one of the charged particles in the two-particle center of mass system. Again, for M_x below 0.9 GeV and above 1.5 GeV the data are well described by the 2γ-QED prediction. But for $0.9\,\text{GeV} < M_x < 1.5\,\text{GeV}$ a clear deviation from the QED expectation is observed.

We have made fits to the two-dimensional distribution M_x vs. $\cos\Theta^*$, in the range $0.7 < M_x < 2.0\,\text{GeV}$ and $|\cos\Theta^*| < 0.8$. The prediction for the QED background was normalized to the data for M_x between 2.0 GeV and 3.7 GeV. Contributions from various C-even resonances were then tried in the fit. The differential cross section for the production and the decay of resonances were calculated according to

$$\frac{d^2\sigma}{dM_x d\cos\Theta^*} = A(M_x, \cos\Theta^*)\cdot\Phi(M_x)\cdot|Y_J^\lambda(\cos\Theta^*)|^2 \cdot\Gamma_{\gamma\gamma}\cdot\Gamma_{\pi^+\pi^-}\cdot\mathrm{BW}(M_x, M_{\text{res}}, \Gamma_{\text{tot}}), \qquad (1)$$

where M_x = photon-photon center of mass energy and $A(M_x, \cos\Theta^*)$ is the acceptance. $\Phi(M_x)$ contains the integral of the photon-photon luminosity functions [11] multiplied by rho form factors $F(Q_1^2)^2\cdot F(Q_2^2)^2$, where $-Q_1^2$, $-Q_2^2$ are the squares of the photon masses and $F(Q^2) = \frac{1}{1+Q^2/m_\varrho^2}$.

For our no tag data inclusion of the rho form factor led to an increase of the radiative width of about 15%. $|Y_J^\lambda(\cos\Theta^*)|^2$ is the angular distribution for a resonance of spin J and helicity λ of the initial two-photon state. For the f^0 we have set the width $\Gamma_{\pi^+\pi^-} = 0.83\cdot 2/3\cdot\Gamma_{\text{tot}}$ where 0.83 is the branching ratio $B(f^0\to\pi\pi)$ taken from the Particle Data Group [16] and 2/3 is the fraction of charged pions. A relativistic Breit-Wigner formula was used with an energy dependent width

$$\Gamma_{\text{tot}}(M_x) = \Gamma_{\text{tot}}(M_{\text{res}})\cdot(q/q_0)^{2J+1}\cdot D(q_0 r)/D(qr), \qquad (2)$$

using a barrier penetration factor as suggested in [12]. The pion momentum q (q_0) is taken in the dipion rest system at M_x (M_{res}) and r is set to 2 fm as in [13].

The mass distribution shows a clear indication of a strong excitation of a resonance with approximately the mass and width of the $f^0(1270)$ and the angular distribution in this mass region clearly favors spin 2 over spin 0. This is demonstrated in Fig. 7, which shows the acceptance corrected angular distribution for M_x between 1.1 and 1.5 GeV after subtraction of the QED background. A spin 0 resonance would give a flat distribution. A spin 2 object such as the f^0 can be produced with helicity amplitudes $\lambda = 0, 1, 2$. They lead to different decay angular distributions which are also plotted in Fig. 7. The angular acceptance and the requirements on p_T in our measurement limited the center of mass angular acceptance to $|\cos\Theta^*| < 0.8$. However, due to low efficiency the uncertainty for $0.7 < |\cos\Theta^*| < 0.8$ is already so large that a complete helicity analysis is not possible (Fig. 7). The $\lambda=1$ contribution is small as shown by the data; it has to vanish according to Yang's theorem [14]. The angular distribution for $\lambda=2$ agrees well with the data although the presence of a sizeable $\lambda=0$ contribution cannot be excluded. The $\lambda=2$ helicity amplitude is expected to be dominant for the production of spin 2 resonances by two quasi-real photons [15]. As may be seen in Fig. 7 we find consistency with these expectations in our fits. Consequently, in the following we assume helicity 2 production of a spin 2 resonance.

First we tried to attribute all the observed excess to the f^0. Describing the f^0 with the standard parameters from the Particle Data Group (PDG) [16], $M(f^0) = 1273$ MeV and $\Gamma_{\text{tot}}(f^0) = 178$ MeV, resulted in a rather bad fit and an excess of events below the f^0 peak. Leaving the resonance parameters free to vary led to values of $M(f^0) = 1240 \pm 7$ MeV and $\Gamma_{\text{tot}}(f^0) = 245 \pm 21$ MeV, inconsistent with the established values of the f^0 parameters. We conclude that additional contributions are necessary to explain the data. In the following we discuss possible additions.

The data show a small enhancement near 1 GeV. One possible explanation for this could be a $\pi^+\pi^-$ continuum contribution which falls off towards higher masses and is cut off by the acceptance at low invariant masses. Nonresonant $\pi^+\pi^-$ background could also interfere with f^0-production and distort the resonance shape. As a check the Born term contribution to pion pair production, which is likely to be an overestimate, was calculated using a computer program written by Krasemann and Vermaseren [17]. It amounts to 18% of the QED lepton pair production in the invariant mass range from 2 GeV to 3.7 GeV. Such a large contribution is unlikely to be consistent with our data. We conclude that the $\pi^+\pi^-$ continuum cross section must drop faster with increasing mass than the simple

Born term ansatz. This suggests a modification of the Born term e.g. by taking into account absorption corrections as described in [18]. In the absence of a canonical procedure we have tried empirical form factors with the result that the Born continuum in our mass region is suppressed entirely. With no reliable calculation of the $\pi^+\pi^-$ background available, we are unable to decide whether the observed shape of the subtracted spectrum is affected by a contribution from the pion pair continuum.

Another possibility to explain the enhancement near 1 GeV is the excitation of the scalar meson $S^*(980)$, which has the proper quantum numbers to be excited in photon-photon interactions. We have tried a fit to the data describing the S^* with a Breit-Wigner. When leaving the parameters of both the f^0 and the S^* free the f^0 still comes out rather wide, 210 ± 22 MeV, but not inconsistent with other measurements [16].

Fixing the parameters for both resonances at the standard values yields an acceptable fit, which is shown in Fig. 5. With this fit we obtain

$$\Gamma(f^0 \to \gamma\gamma) = 3.2 \pm 0.2\,\mathrm{keV} \pm 0.6\,\mathrm{keV}$$

(statistical and systematic). The systematic error includes the uncertainty due to the assumptions chosen.*

If we assign the small enhancement near 1 GeV to S^* production this fit gives a product of $\Gamma(S^* \to \gamma\gamma) \cdot B(S^* \to \pi^+\pi^-) = 1.3 \pm 0.4$ keV, with a large systematic error of 40% (± 0.6 keV) caused by the uncertainty in our efficiency, which is rapidly falling in the relevant mass region.

No significant deviation from the combined resonance shape is observed but some data points lie systematically above the fit at masses around 1150 MeV. We have checked if this could be caused by the $f'(1515)$ decaying into two charged kaons, which would contribute in this mass region since we have assigned pion masses to all tracks. The width $\Gamma(f' \to \gamma\gamma) \cdot B(f' \to K^+K^-)$ would have to be around 0.4 keV (with $\lambda = 2$ production) to explain the observed excess. This is consistent with an upper limit of $\Gamma(f' \to \gamma\gamma) \cdot B(f' \to K^+K^-) < 1.3$ keV (95% c.l.) which we have derived from a small sample of kaon pairs. Kaons were identified by time of flight measurement [19]. A width of about 0.4 keV is also compatible with the upper limit reported in [20]. We conclude that our mass distribution could be affected by mislabeled kaons from f^0 decay.

Adding another scalar resonance of the ε-type with the parameters taken from the PDG does not improve the fit. In fact we find no indication for the excitation of a broad (~ 300 MeV) resonance. We obtain an upper limit for the product of radiative width times branching ratio $\Gamma(\varepsilon \to \gamma\gamma) \cdot B(\varepsilon \to \pi^+\pi^-) < 1.5$ keV (95% c.l.). This upper limit is valid for a range of ε-masses between 1300 and 1500 MeV and total widths of 200 to 400 MeV. It is also valid for a fit with the ε-parameters from a recent analysis [21] which found the resonance at a mass of 1425 MeV and a width of 165 MeV.

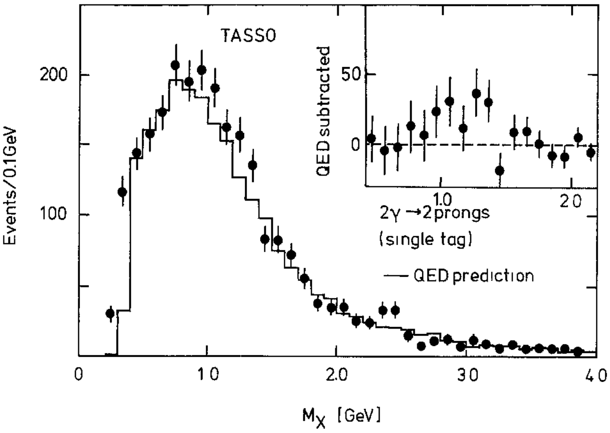

Fig. 8. $e^+e^- \to e^+e^- +$ two charged particles (single tag): Invariant mass distribution of the two-prongs assuming pion masses. The histogram shows the QED prediction for lepton pair production. The insert shows the mass distribution with the QED contribution subtracted

For comparison, another measurement [3] yielded a width $\Gamma_{\gamma\gamma}(f^0) = 2.3 \pm 0.5$ keV also assuming helicity 2 excitation, while an upper limit was reported by [5] of $\Gamma_{\gamma\gamma}(f^0) < 4.7$ keV (95% c.l.). A result from a double tagging experiment [4] which did not separate the f^0 from other resonances is $\Gamma_{\gamma\gamma}(f^0) = 9.5 \pm 3.9$ keV.

We now turn to the analysis of our "single tag" data, which could provide information e.g. on the Q^2 dependence of the $f\gamma\gamma$-vertex. For these events the mean Q^2 of the tagged photons was 0.35 (GeV/c)^2. The trigger required at least 4 GeV deposited by a charged particle in the forward detector and at least one track in the central drift chamber. From this sample we selected events having two tracks of opposite sign from the interaction region. Each track was required to have $p_T > 0.2$ GeV/c and $|\cos\Theta| < 0.84$. The direction of the tagged electron was predicted from the momenta of the two tracks, with the assumption that the untagged electron was at zero degrees. Incomplete events were removed by requiring that the predicted and detected positions agree within the measurement error. Monte Carlo studies showed that a 4% multiprong background remained after this cut. The beam gas background was determined from the observed vertex distribution to be less than 4%.

The two-prong invariant mass distribution for the single tag data was calculated assuming pion masses and is plotted in Fig. 8. The contribution of the QED

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* The preliminary result reported in [6], which gave a larger width for the f^0 was obtained attributing all the observed excess over the QED-prediction to one resonance with spin 2 with a slightly lower mass parameter and a larger width than those given by the Particle Data Group [16]. In addition the data available now correspond to more than twice the integrated luminosity, and our efficiencies for low momentum tracks are better understood

reactions $e^+e^- \to e^+e^-e^+e^-$ and $e^+e^- \to e^+e^-\mu^+\mu^-$ to this distribution was calculated using the Vermaseren program [9] and is compared to the data. The QED Monte Carlo gives a good description of the data, both in shape and in magnitude except in the mass region from 0.9 to 1.4 GeV. In contrast to the no tag data there is only a slight excess over QED in this mass region.

The Krasemann-Vermaseren model [17] was used to calculate the contribution of the f^0. This model includes a Q^2 dependence of the helicity contributions for $\lambda = 0$, 1, and 2. It also includes an effective form factor in the cross section for f^0 production by one real and one virtual photon which leads to a suppression factor of about 0.5 at the average Q^2 of 0.35 $(\mathrm{GeV/c})^2$. When we calculated the f^0 production for the no tag data with this model (which also includes helicity 2 dominance for the no tag condition) we obtained almost the same result that we get using formulae (1) and (2), namely $\Gamma_{\gamma\gamma}(f^0) = 3.1 \pm 0.2$ keV.

Fitting this f^0 model and QED to the single tag data we extract a width $\Gamma(f^0 \to \gamma\gamma; Q^2 = 0) = 1.6 \pm 0.6 \pm 0.3$ keV (statistical and systematic). This is lower than the value obtained from the no tag data. The confidence level for the width to be same as in the no tag case is 8%. Therefore our data is not inconsistent with the Q^2 dependence of the Krasemann-Vermaseren model [17], but a somewhat stronger Q^2 dependence is preferred. This may indicate that the helicity structure of the model, which strongly influences the detection efficiency, does not have the correct Q^2 behavior. On the other hand the discrepancy could be caused by the effective form factor. Using a rho pole form factor instead of the effective form factor of the Krasemann-Vermaseren model would yield a width $\Gamma_{\gamma\gamma}(f^0)$ about 20% larger.

In summary, we have identified events in e^+e^- collisions coming from two-photon production of charged particle pairs for invariant masses of the pairs ranging from 0.8 to 6.0 GeV. Above a continuum consistent with the expectation from 2γ QED reactions we observe resonant production of the tensor meson f^0. When we fit our data with a small additional contribution from S^* production we derive a $\gamma\gamma$-width for the f^0 of $\Gamma(f^0 \to \gamma\gamma) = 3.2 \pm 0.2 \pm 0.6$ keV, (statistical and systematic) with predominant helicity 2 production of the f^0, which is supported by the data and predicted by [15]. From the single tag data with photons having a mean Q^2 of 0.35 $(\mathrm{GeV/c})^2$ and using a particular model to describe the Q^2 dependence of the $f\gamma\gamma$ vertex, we obtain a width $\Gamma_{\gamma\gamma}(f^0)$ which is smaller but not inconsistent with the one from the no tag case. We derive an upper limit for the excitation of a broad ε-type scalar resonance of $\Gamma(\varepsilon \to \gamma\gamma) \cdot B(\varepsilon \to \pi^+\pi^-) < 1.5$ keV (95% c.l.).

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