Search for New Particles in e^+e^- Annihilation from 39.79 to 45.52 GeV

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We have searched for resonances in the reaction $e^+e^- \rightarrow \text{hadrons}, \gamma\gamma, \mu\mu$, and ee , in the energy range $39.79 < \sqrt{s} < 45.52$ GeV, using the Mark J detector at PETRA. We obtain stringent upper limits on the production of toponium and particles postulated to explain $Z^0 \rightarrow \text{lepton pair} + \gamma$ events observed at the CERN $\bar{p}p$ collider. We also set limits on the mass and coupling constant of excited electrons.

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High-energy e^+e^- collisions are well suited for searching for new particles, and at $\sqrt{s} = 45$ GeV PETRA provides a unique opportunity for particle searches. The reaction

$$e^+e^- \rightarrow \text{hadrons} \quad (1)$$

has been used to search for new quark-antiquark states.¹ Excited electrons, e^* , modify the angular distribution of the reaction

$$e^+e^- \rightarrow \gamma\gamma. \quad (2)$$

Muons at large transverse momentum can be used in searches for sequential heavy leptons. New particles may be seen in lepton-pair final states

$$e^+e^- \rightarrow \mu^+\mu^-, \quad (3)$$

$$e^+e^- \rightarrow e^+e^-, \quad (4)$$

as well as in reactions (1) and (2). We have measured cross sections for reactions (1) through (4) in a continuous energy scan from 39.79 to 45.52 GeV with the Mark J detector and with an integrated luminosity of 13.0 pb^{-1} to search for toponium¹ and other resonances. In particular, we look for resonances postulated to explain the abnormally large rate² of Z^0 decays which contain lepton pairs

accompanied by a hard photon. The recent observation³ of the neutral intermediate boson Z^0 in the dilepton channel with an invariant mass around 93 GeV was predicted by the standard electroweak unification model. However, in three out of seventeen events, the Z^0 decays into a lepton pair and an energetic gamma. The standard model fails to explain the rate and the energy spectrum of the particles from this decay mode. It has been suggested that a new particle X is produced^{4,5} in the reaction

$$Z \rightarrow X + \gamma, \quad X \rightarrow l^+l^-. \quad (5)$$

The mass of the X particle, as computed from the two $ee\gamma$ events observed at the CERN collider, lies between 40 and 50 GeV. This X particle can have either spin 1 or spin 0. The decay channels for a spin-1 particle⁴ are expected to be lepton or quark pairs, and for a spin-0 particle,⁵ lepton pairs, quark pairs, or two photons.

If the reaction (5) were to explain the apparent abundance of hard photon plus dilepton events, the partial widths of $Z \rightarrow X + \gamma$ and $X \rightarrow e^+e^-$ would both have to be unusually large. The X particle could then be observed in e^+e^- annihilation into

hadrons, lepton pairs, or two-photon final states. Observation of this X particle would have a profound implication on our understanding of the substructure of the intermediate vector boson as well as of leptons and quarks.

The integrated cross sections due to the direct

production of a resonance of spin J for reactions (1)–(3) are

$$S_i = \int \sigma_i \sqrt{s} = n(2J+1)(2\pi^2/M_X^2)\Gamma_{ee}B_i, \quad (6)$$

where B_i denotes the branching ratio Γ_i/Γ into final

FIG. 1. The measured cross sections, normalized to the pointlike QED total cross section σ_0 , in the energy region from $\sqrt{s} = 39.79$ to 45.52 GeV. The solid curves are the best fit for a hypothetical resonance, and the dashed curves are the 95% confidence level limits for such a resonance for the reactions (a) $e^+e^- \rightarrow \text{hadrons}$, total cross section (corrected for acceptance); (b) $e^+e^- \rightarrow \gamma\gamma$, integrated over $|\cos\theta| < 0.8$; (c) $e^+e^- \rightarrow \mu\mu$, total cross section (corrected for acceptance); (d) $e^+e^- \rightarrow e^+e^-$, integrated over $|\cos\theta| < 0.5$. The dashed curve includes the contribution of a hypothetical scalar particle with mass equal to 46 GeV and the solid curve with mass equal to 47.8 GeV as suggested by Ref. 5.

state i , Γ is the total width of the resonance, and n is the number of degenerate states of angular momentum J .

Assuming that the resonance couples to all leptons with the same strength, we can determine Γ_{ee} for any particle decaying predominantly into lepton pairs, hadrons, or two photons by summing the S_i :

$$6S_{\mu\mu} + S_{\gamma\gamma} + S_h = n(2J+1)(2\pi^2/M_X^2)\Gamma_{ee}, \quad (7)$$

where 6 is the number of leptons. Γ_{ee} as determined from (7) can be compared with the lower-limit values deduced from the collider data.⁵

The Mark J detector is a 4π calorimetric detector which measures the energy vectors of electrons, photons, charged and neutral hadrons, and especially jets. A detailed description of the detector can be found elsewhere.⁶

The selection of hadron, dimuon, and Bhabha events follows the exact same procedure as for the lower-energy data described before.^{6,7} For the detection of photons, the acceptance is uniform in θ for $10^\circ < \theta < 170^\circ$. The measured energy of each photon is required to be $> E_{\text{beam}}/3$ and the acollinearity angle between the two photons is required to be $< 50^\circ$. We have reported the angular distribution of the two-photon final states⁸ at lower energy. In order to enhance the resonance contribution we select events with $|\cos\theta| < 0.8$.

R , the measured hadronic cross section normalized to the lowest-order pointlike pair production cross section (σ_0), is shown in Fig. 1(a) for the energy region from 39.79 to 45.52 GeV. The corresponding cross sections $R_{\gamma\gamma}$ and $R_{\mu\mu}$, for $e^+e^- \rightarrow \gamma\gamma$ with $|\cos\theta| < 0.8$ and $e^+e^- \rightarrow \mu^+\mu^-$, are shown in Figs. 1(b) and 1(c), respectively. There are no obvious resonances in these distributions. The following fits were made to the data in order to set limits on a hypothetical resonance.

(1) We fitted the hadron data [Fig. 1(a)] to a constant $\langle R \rangle$ plus a narrow toponium-type resonance including the beam-energy resolution and radiative corrections.⁹ The maximum hypothetical signal is at 44.00 GeV and the 95% confidence level limit on the integrated cross section is $S_h < 34$ MeV nb or $\Gamma_{ee}B_h < 2.9$ keV for a spin-1 particle. From the fact the Γ_{ee}/Q_q^2 is constant for s , c , and b quarks and $B_h \sim 70\%$,¹⁰ we expect $\Gamma_{ee}B_h = 3.5$ keV for the ground state of toponium. Thus our data are inconsistent with the existence of a toponium state with a constant Γ_{ee}/Q_q^2 below 45.52 GeV. More generally, the limit for any narrow¹¹ resonance, of spin J , is

$$n(2J+1)\Gamma_{ee}B_h < 8.7 \text{ keV}.$$

(2) We make a similar fit to the $e^+e^- \rightarrow \gamma\gamma$ data

[Fig. 1(b)] as a function of energy and find that the maximum hypothetical signal at the 95% confidence level limit is at $M_X = 44.00$ GeV and $S_{\gamma\gamma} < 15$ MeV nb or $n(2J+1)\Gamma_{ee}B_{\gamma\gamma} < 3.7$ keV.

(3) We use the $e^+e^- \rightarrow \mu^+\mu^-$ data [Fig. 1(c)] and find that the maximum hypothetical signal is at 41.13 GeV and the mean value $\langle R_{\mu\mu} \rangle = 0.98$. The 95% confidence level limit is $S_{\mu\mu} < 21$ MeV nb or $n(2J+1)B_{\mu\mu}\Gamma_{ee} < 4.5$ keV.

(4) Finally, on making a fit to the hadron, the dimuon, and the $\gamma\gamma$ data simultaneously, we find that $\langle R \rangle = 4.13$, $\langle R_{\mu\mu} \rangle = 1.0$, $\langle R_{\gamma\gamma} \rangle = 2.02$ and $M_X = 44.0$ GeV. The values¹² corresponding to the 95% confidence level limit of this fit are $S_h + S_{\gamma\gamma} + 6S_{\mu\mu} < 77$ MeV nb or $n(2J+1)\Gamma_{ee} < 20$ keV. For a degenerate doublet⁵ of scalar particles, we have $\Gamma_{ee} < 10$ keV compared with 1 MeV expected from the collider data. Our data therefore exclude the existence of this X particle in the mass range from 39.79 to 45.52 GeV.

For the case $M_X > \sqrt{s}$, it has been suggested that⁵ there is a sizable contribution to reaction (4), due to γ - X interference, which slowly decreases as $1/(M_X^2 - s)$ for increasing values of M_X . The measured Bhabha cross section, integrated over $|\cos\theta| < 0.5$ and normalized to σ_0 , is shown as a function of $\sqrt{s}$ in Fig. 1(d). We find the mean value $\langle R_{ee} \rangle = 4.8$. Also plotted are the expected cross sections if there were a scalar doublet⁵ with $M_X = 46$ GeV (dashed curve) and $M_X = 47.8$ GeV (solid curve), where $\Gamma = 70$ MeV and $\Gamma_{ee} = 2$ MeV have been assumed. We find that the data rule out the existence of such scalar particles with $M_X < 47.8$ GeV at the 95% confidence level limit.

The measured angular distributions for $e^+e^- \rightarrow \gamma\gamma$ are shown in Fig. 2(a). They agree with the QED prediction. We use these data to put limits⁸ on the mass of an excited electron, e^* , as a function of the $ee^*\gamma$ coupling constant, λ . The allowed region in e^* mass and coupling is shown in Fig. 2(b). Because a virtual e^* will contribute to reaction (4), the mass limits extend well above the beam energy. The results are significantly improved over previous limits.⁸

In conclusion, we obtain model-independent limits on the production of new resonances between 37.79 and 45.52 GeV mass of $n(2J+1)\Gamma_{ee} < 20$ keV. Particles postulated to explain $l^+l^-\gamma$ events in the $\bar{p}p$ collider are ruled out for masses up to 47.8 GeV. New limits are placed on the mass and coupling constant of excited electrons.

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FIG. 2. (a) The angular distributions of $e^+e^- \rightarrow \gamma\gamma$ where the data are in good agreement with the QED prediction (curve) at both 35 and 41.5 GeV. (b) The allowed region in M_{e^*} and the $ee^*\gamma$ coupling constant λ are shown.

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¹²If we assume the resonance couples to each of the quark pairs with the same strength as to the lepton pairs (Ref. 5) we find $n(2J+1)\Gamma_{ee} < 16 \text{ keV}$ using the hadron and the $\gamma\gamma$ data alone.