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Search for High-Mass Narrow Resonances in Virtual Photon-Photon Interactions

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We report on the first search with virtual photon-photon collisions for narrow, neutral resonances with even C parity in the mass range $4.5 < W < 19$ GeV. The data were obtained via the process $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-R$ with both the scattered e^+ and e^- detected. We find upper limits (95% confidence level) for the partial decay width of a resonance into two photons, ranging from 50 keV at $W = 4.5$ GeV to 10 MeV at $W = 19$ GeV. These limits constrain theoretical models involving neutral composite bosons.

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Certain composite models of quarks, leptons, Higgs bosons, and gauge bosons require the existence of neutral particles with two tightly bound, charged components that an annihilate into two photons. Since the quarks, leptons, W, and Z seem to be pointlike, these components can be expected to be so close to one another that the two-photon annihilation rate is large. For example, Baur, Fritzsch, and Faissner[1] suggested a width of $(840/M_U)$ MeV, with M_U the mass in gigaelectronvolts of the composite particle. Renard[2] postulated an "H" particle (not necessarily a Higgs boson), which might have a two-photon decay width of $1.4 M_H$ MeV. Such resonances would be produced in photon-photon interactions and might be observable at existing e^+e^- colliders. More generally, the formation of even-C-parity resonances has been one of the primary motivations for the study of photon-photon collisions. The search for new resonances in such collisions is complementary to searches in e^+e^- annihilation to a single photon, where C is odd. We report here the results of the first such resonance search using the missing-mass technique in the reaction $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-R$. If both leptons in the final state are detected, then the photon-photon center-of-mass energy W can be calculated from the lepton kinematics. This missing-mass technique, in contrast to resonance detection through reconstruction of the decay products, has the advantage that the sensitivity is not affected by the branching fraction into a particular final state or by details of the decay kinematics. We have already reported[3] on the measurement of the total hadronic cross section using the same method.

The experiment was performed at the Stanford Linear Accelerator Center (SLAC) with the TPC/Two-Gamma apparatus and the e^+e^- collider PEP, with 29-GeV center-of-mass energy. The apparatus consisted of a central detector[4] and two small-angle spectrometers.[5] Outgoing $e^{\pm}$ were detected at angles of 22 to 90 mrad from the beam by two NaI electromagnetic shower detectors, each consisting of sixty hexagonal crystals. Absolute energy calibrations to 0.3% were achieved by use of elastic e^+e^- (Bhabha) events. These calibrations were corrected for short-term variations by means of a light-flasher system. The excellent resolution which results ($\sigma_E/E \simeq 2.9\%/E^{1/4}$, where E is in gigaelectronvolts) is essential for a good determination of W. The position (angular) resolution was 5 mm (1 mrad) rms. The small-angle spectrometers each also included a lead-scintillator shower counter covering 100–180 mrad, a threshold Čerenkov counter, a time-of-flight scintillator hodoscope, fifteen planes of drift chambers, a set of muon chambers, and a septum magnet with $\int B\,dl = 0.26$ T m. The central detector included the Time Projection Chamber (TPC), inner and outer drift chambers, central and pole-tip electromagnetic calorimeters, muon chambers, and a solenoidal magnet with a field of 0.4 T. The trigger for this measurement required localized energy deposition greater than 0.8 GeV in each of the two NaI calorimeters. Requirement of the depositions and the interaction point to be acollinear reduced the number of triggers due to Bhabha scattering by a factor of 25. The analyzed integrated e^+e^- luminosity is 50 pb^{-1}.

In the analysis, events with both a scattered e^+ and e^- were selected by our requiring an energy deposition of at least 3 GeV in each NaI calorimeter, with evidence of charge from the drift chambers. The laboratory acoplanarity angle of the outgoing e^+ and e^- was required to be greater than 0.55 rad to reduce backgrounds from the reaction $e^+e^- \to e^+e^-\gamma$. Hadronic events were selected by our requiring a minimum total detected multiplicity of three particles (excluding the scattered $e^{\pm}$), at least two of which were charged. The charged multiplicity included tracks only if they originated at the event vertex and had a momentum greater than 200 MeV/c in the forward spectrometers or 50 MeV/c in the TPC. Additionally, at least one charged track had to be identified as a hadron (or hadron/muon ambiguity), primarily by use of dE/dx and momentum as measured by the TPC. The neutral multiplicity counted calorimeter energy depositions greater than 300 MeV which were isolated from any charged track. The final sample of 457 events in the mass range $3.5 < W < 20.5$ GeV has a missing-mass spectrum as shown in Fig. 1. No significant resonance signals are seen.

We place limits only on the production of "narrow" resonances, whose total width is less than the detector resolution. The mass resolution is dominated by the error in the energy measurement of the higher-energy one of the $e^{\pm}$ which is usually near the beam energy. Both the energy and position resolution of the NaI arrays are obtained at the beam energy from Bhabha scattering. Figure 2 shows the resolution in W. This resolution has been checked at low W by use of the reaction $e^+e^- \to e^+e^-\mu^+\mu^-$, for which the dimuon effective mass can be compared with the missing mass.

To calculate the acceptance, a Monte Carlo simulation was performed with use of the following cross section[6] for $e^+e^- \to e^+e^-R$:

$$E_1' E_2'\, d^6\sigma/d^3p_1'\, d^3p_2' = L_{TT}\sigma_{\text{eff}}, \tag{1}$$

where

$$\sigma_{\text{eff}} \equiv \sigma_{TT} + \varepsilon_2\sigma_{TL} + \varepsilon_1\sigma_{LT} + \varepsilon_1\varepsilon_2\sigma_{LL}. \tag{2}$$

Here $(E_i', \mathbf{p}_i')$ is the four-momentum of outgoing lepton i. The subscripts T and L refer to transverse and longitudinal photons, respectively. L_{TT} (the virtual-photon flux factor) and ε_1 and ε_2 (photon polarization parameters)

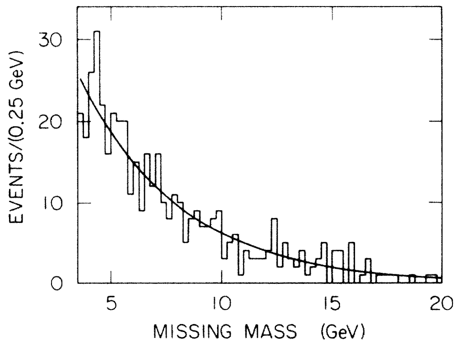

FIG. 1. Missing-mass spectrum for hadronic events. The smooth curve is described in the text.

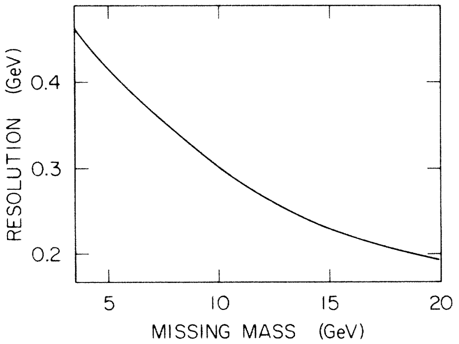

FIG. 2. The 1-standard-deviation mass resolution as a function of W.

are given exactly by QED and are calculable from the kinematics of the detected leptons. We have neglected interference terms in $\sigma_{\rm eff}$ because their integral over accepted azimuth contributes no more than 5% to the total hadronic cross section.[3] The four $\gamma^*\gamma^*$ cross sections (σ_{ab}) are functions of W and the photon four-momenta squared, q_1^2 and q_2^2. The Monte Carlo program which simulated detector response and event selection took $\sigma_{\rm eff}$ constant and accounted for radiation by the incident leptons.[7]

The detection efficiency in this mass region depends very little on the characteristics of the decay of a resonance. The simulation assumes that a resonance has an isotropic decay into two quarks in its own center-of-mass frame. These quarks are then fragmented into observable hadrons by means of a Lund Monte Carlo model.[8] Given that the outgoing leptons are detected, the efficiency for detection of the final state is shown in Fig. 3. Also shown is the detection efficiency for background events taken from Ref. 3. There it was assumed that the final-state hadrons are produced with limited p_T (relative to the $\gamma\gamma$ collision axis), as in hadron-hadron collisions. Thus the hadrons emerge at small angles with respect to the e^+e^- collision axis, leading to lower detection efficiency. This result may be considered a lower limit for the detection efficiency of a resonance. In order to reduce our sensitivity to the model dependence in the efficiency, and to have sufficient resolution for the detection of a resonance, we have limited ourselves in the event selection to the region $W > 3.5$ GeV.

Figure 1 shows no evidence for a narrow resonance—a peak whose width is consistent with the estimated resolution shown in Fig. 2. To quantify this statement, we fitted the data with the smooth, resonance-free curve shown in Fig. 1:

$$b(W,a) = A(e^{-Wa} - e^{-29a}),$$

where W is the mass, a and A are parameters in the fit, and the e^{-29a} term forces the curve to go to zero at the kinematic limit. A Kolmogorov statistic[9] was used to verify that statistical fluctuations in the data can account for any discrepancy between the data and the curve.

To extract upper limits on the two-photon width of a resonance $\Gamma_{\gamma\gamma}$, we employ a Monte Carlo procedure which uses the quantity

$$Y(W) = \sum_{i=1}^{N} \frac{\exp[-(W_i - W)^2/2\sigma_i^2]}{\sigma_i b(W,a)},$$

where N is the number of events, W_i is the mass of event i, and σ_i is the corresponding resolution. When a maximum likelihood method is used to estimate the number of events in a narrow resonance at mass W, that number is zero for $Y(W) = (2\pi)^{1/2}$. A larger $Y(W)$ corresponds to an especially large number of events clustered near W. We calculated the probability, as a function of W, that a statistical fluctuation produces a value of $Y(W)$ bigger than was observed. This was done with a large number of Monte Carlo simulations of the data. Each Monte Carlo experiment had its N events distributed according to $b(W,a')$, where a' is the value of a determined from the real data but smeared by the uncertainty in that determination. This Monte Carlo experiment was treated the same way as the real data—a new $b(W,a'')$ was found that fitted the Monte Carlo data, and $Y_{\rm MC}(W)$ was produced. We then determined the probability for $Y_{MC}(W) > Y(W)$. This probability is plotted in Fig. 4, which shows no low probabilities at any value of W. To avoid edge effects inherent in our method, we limit our results to $4.5 < W < 19$ GeV.

How many events can be in a resonance without making $Y_{MC}(W)$ almost always larger than $Y(W)$? To answer this question, we used the same Monte Carlo procedure except that now, for a given W and a given number of events in the resonance at that W, we added resonance events while removing an equal number of background events from the entire W range. The resonance events were redistributed near W according to the resolution in W. Figure 5 shows the 95% confidence level for

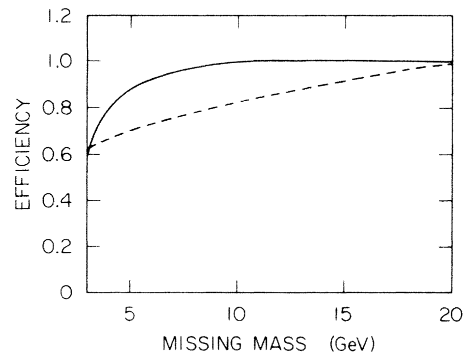

FIG. 3. Efficiency for detection of the hadronic final state including effects of event selection (solid curve). Also shown is an estimate of background efficiency (dashed curve) based upon production with limited p_T; see text.

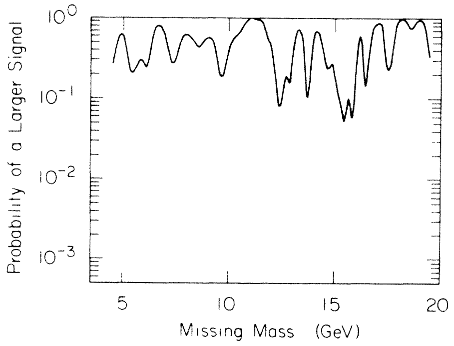

FIG. 4. Probability that the background fluctuates to give peaks at least as high as those in the spectrum of Fig. 1.

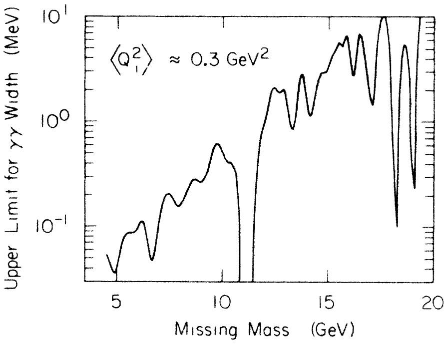

FIG. 5. 95%-confidence-level upper limit for the two-photon width of a narrow resonance, with spin 0, as a function of mass.

the two-photon width $\Gamma_{\gamma\gamma}$ which corresponds to that number of events for which $Y_{MC}(W)$ is greater than $Y(W)$ 95% of the time. The conversion from number of events to two-photon width was done by use of Eq. (1) with

$$\sigma_{\text{eff}} = [16\pi^2\sqrt{X}(2J+1)\Gamma_{\gamma\gamma}\delta(W^2 - m_R^3)]/m_R^3, \qquad (3)$$

where $\sqrt{X} = [(q_1 \cdot q_2)^2 - q_1^2 q_2^2]^{1/2}$ is the Møller flux factor. In Fig. 5, J, the spin of the resonance, was set equal to zero.

Some q^2 dependence may be present in σ_{eff}, although the q^2 of each virtual photon in the data covers only the small range from -0.1 to -1.6 GeV^2, with an average of approximately -0.3 GeV^2. For $J=0$, σ_{LT} and σ_{TL} must vanish, so that σ_{eff} is essentially the value of $\sigma_{\gamma\gamma}$ for $q_i^2 \rightarrow 0$, multiplied by a form factor squared. It is likely that heavy resonances would be produced with a rather gentle q^2 dependence. However, in the extreme case of a ρ form factor for each photon, the upper limits for $\Gamma_{\gamma\gamma}$ would increase by a factor ranging from 7 at low W to 2 at high W. For $J=1$, resonance production is suppressed because the otherwise dominant σ_{TT} term vanishes in the limit $q_1^2, q_2^2 \rightarrow 0$ (Yang's theorem); it is not relevant to extrapolate this case to $q_i^2 = 0$. For $J \geq 2$, the inclusion of the last three terms of Eq. (2) would require model-dependent assumptions regarding their magnitude and q^2 dependence. However, they would only tend to reduce the upper limits on $\Gamma_{\gamma\gamma}$ and so can be conservatively ignored. For $J > 0$, the upper limits in Fig. 5 would also be reduced by a factor of $2J+1$.

This first search for neutral, $C=+$ particles which couple to two photons in the mass region $4.5 < W < 19$ GeV shows no evidence for narrow resonances. Upper limits on the two-photon widths for such resonances are derived which constrain some of the theoretical models for compositeness.

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