LIMITS ON SPIN 0 BOSONS IN e^+e^- ANNIHILATION UP TO 45.2 GeV CM ENERGY

CELLO Collaboration

H.-J. BEHREND, J. BÜRGER, L. CRIEGEE, H. FENNER, G. FRANKE, J. MEYER, V. SCHRÖDER, H. SINDT, U. TIMM, G.G. WINTER, W. ZIMMERMANN
Deutsches Elektronen-Synchrotron, DESY, Hamburg, Germany

P.J. BUSSEY, A.J. CAMPBELL, J.B. DAINTON, D. HENDRY, J.M. SCARR, I.O. SKILLICORN, K.M. SMITH
University of Glasgow, UK

M. POPPE, H. SPITZER
II. Institut für Experimentalphysik, Universität Hamburg, Germany

O. ACHTERBERG, G. D'AGOSTINI [1], W.-D. APEL, J. ENGLER, G. FLÜGGE, B. FORSTBAUER, D.C. FRIES, W. FUES, K. GAMERDINGER, Th. HENKES, G. HOPP, J. KNAPP, M. KRÜGER, H. KÜSTER, H. MÜLLER, H. RANDOLL [2], K.H. RANITZSCH, G. SCHMIDT [3], H. SCHNEIDER
Kernforschungszentrum Karlsruhe und Universität Karlsruhe, Germany

W. de BOER, G. BUSCHHORN, G. GRINDHAMMER, P. GROSSE-WIESMANN [4], B. GUNDERSON, C. KIESLING, R. KOTTHAUS, H. LIERL [5], D. LÜERS, H. OBERLACK, P. SCHACHT
Max-Planck-Institut für Physik und Astrophysik, Munich, Germany

G. BONNEAUD [6], P. COLAS, A. CORDIER, M. DAVIER, D. FOURNIER, J.F. GRIVAZ, J. HAISSINSKI, V. JOURNÉ, F. LeDIBERDER, U. MALLIK [7], E. ROS, J.-J. VEILLET
Laboratoire de l'Accélérateur Linéaire, Orsay, France

J.H. FIELD [8], R. GEORGE, M. GOLDBERG, O. HAMON, F. KAPUSTA, F. KOVACS, R. PAIN, L. POGGIOLI, M. RIVOAL
Laboratoire de Physique Nucléaire et Hautes Energies, Université de Paris, France

M. GASPERO, B. STELLA
University of Rome, Italy

R. ALEKSAN, J. BOUCHEZ, G. CARNESECCHI [9], G. COZZIKA, Y. DUCROS, A. GAIDOT, P. JARRY, Y. LAVAGNE, F. OULD SAADA, J. PAMELA, J.P. PANSART, F. PIERRE
Centre d'Etudes Nucléaires, Saclay, France

and

G. ALEXANDER, G. BELLA, Y. GNAT and J. GRUNHAUS
Tel Aviv University, Israel

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We have studied the reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$, $e^+e^- \to \mu^+\mu^-$, and $e^+e^- \to \tau^+\tau^-$ in the centre-of-mass (CM) energy range from 39.8 to 45.2 GeV using the CELLO detector at PETRA. Upper limits on the partial widths for new spin 0 bosons with masses both within and above the energy range covered are determined. No evidence for contributions of such new particles has been observed up to the highest PETRA energies in a model independent way. Under the assumptions of recently suggested models relating the existence of spin 0 bosons to the radiative width Γ_γ of the Z^0 we exclude such bosons at the 95% confidence level for masses below the Z^0-mass if $\Gamma_\gamma > 20$ MeV.

Introduction. The occurrence of spin 0 bosons (scalar or pseudoscalar) is naturally expected in models, in which the weak gauge bosons, as well as quarks and leptons, are composite objects [1–5].

In this paper we report on a search for such spin 0 bosons X in the reactions

$$e^+e^- \to e^+e^- , \quad (1)$$

$$e^+e^- \to \gamma\gamma , \quad (2)$$

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

$$e^+e^- \to \tau^+\tau^- , \quad (4)$$

up to the highest PETRA energy (45.2 GeV).

Spinless bosons can contribute to s-channel exchange in all four reactions. In addition reaction (1) can be mediated by X-exchange in the t-channel. Since X has spin 0 and the photon spin 1, there is no interference in the s-channel between the photon exchange and boson exchange (e.g. for $q\bar{q}$, $\mu^+\mu^-$, or $\tau^+\tau^-$ production). Interference between s- and t-channel exchange is expected in the reactions (1) and (2). For the $\gamma\gamma$ final states this term is proportional to the electron mass and hence negligible. However, for Bhabha scattering this term turns out to be large and thus observable if present.

If the boson mass M_X lies within the CM energy range covered, a sizeable resonance effect should be seen in the cross sections for the four reactions. On the other hand, if M_X is above the energy accessible to experiment, we still expect an effect due to the tail of the resonance.

An experimental hint for the existence of heavy spin 0 bosons might be the observation at the $\bar{p}p$ collider at CERN of an apparent excess of radiative decays [6] $Z^0 \to ee\gamma$ and $\mu\mu\gamma$. Among the different mechanisms proposed to interpret these events we consider the transition [1–5]

$$Z^0 \to X\gamma , \qquad X \to e^+e^- . \quad (5)$$

Corresponding radiative decays of the charged intermediate vector bosons $W^\pm$ were not observed [6].

Detector and trigger. The data were taken in 1983 with the CELLO-detector [7] at PETRA at CM energies W between 38.66 and 45.22 GeV with a time integrated luminosity of 8.1 pb^{-1}. The beam energy was varied in steps of 15 MeV ensuring a continuous coverage of the CM energy ranges of $38.66 < W < 38.78$ and $39.79 < W < 45.22$ GeV. The average energy is 42.48 GeV.

CELLO is a general purpose magnetic detector equipped with a thin superconducting solenoid. Charged particles are measured in cylindrical drift and proportional chambers in a 1.3 T magnetic field yielding for high energy particles a momentum resolution of $\sigma(p)/p = 1.3\% \cdot p \sin\theta$ (p in GeV) over 86% of the solid angle. This leads to a charge misidentification probability of 5% at 20 GeV. For neutral particle reconstruction we use the barrel part of a fine grain lead liquid argon calorimeter which has a solid angle coverage of 86% of 4π. Each of 16 calorimeter modules samples the energy deposited by particles in the liquid argon 19 times in depth. The energy is collected on lead strips of three different orientations up to a maximum depth of 21 radiation lengths. For each particle this information is combined into seven clusters in depth. We obtain an energy resolution of $\sigma(E)/E = (2.5 + 10/\sqrt{E})\%$ (E in GeV), an angular resolution in azimuth of 6 mrad and a polar angular resolution of 10 mrad for photons. The latter is determined by the length of the interaction region along the beam axis. The muon detector consists of an 80 cm thick iron ha-

[1] Present address: Université de Paris, France.
[2] Present address: Blaupunkt, Hildesheim, Germany.
[3] Present address: Siemens, Munich, Germany.
[4] Present address: Universität Karlsruhe, Germany.
[5] Present address: DESY, Hamburg, Germany.
[6] CRN Strasbourg, France.
[7] Present address: University of Purdue, USA.
[8] On leave of absence from DESY, Hamburg, Germany.
[9] Present address: Cray Research, Paris, France.

dron absorber and one layer of large planar drift chambers covering 92% of 4π. The spatial resolution of these chambers is 0.6 cm for both coordinates.

Events used in this analysis were recorded on tape if they fulfilled one of the following criteria:
- An energy deposition of more than 3 GeV in each of two modules separated by at least 45° in azimuth.
- More than 6 GeV of energy in the calorimeter.
- At least two tracks in the central detector separated by more than 135°.
- At least one track in the central detector and 3 GeV in the calorimeter.

The trigger and preselection efficiencies for reactions (1) and (2) are 99.8% as determined by comparing the completely independent track and calorimeter triggers from Bhabha events. The trigger efficiencies are 74% for reaction (3) and 88% for reaction (4).

Data selection. For reactions (1) and (2) all events with at least two energy deposits of more than 3 GeV collinear within 90° in the calorimeter were processed through the reconstruction programs for charged particles in the inner detector and showers in the liquid argon calorimeter. They were further reduced by requiring:
- At least two reconstructed showers in the liquid argon calorimeter having a minimum energy of $0.1 \times W$.
- An acollinearity angle between the most energetic showers of less than 175 mrad.
- For reaction (1) at least one reconstructed track linked to an EM shower in the liquid argon calorimeter.
- For reaction (2) no charged particle.

All events surviving these cuts were scanned visually and the residual background (2%) due to Bhabha events in the $\gamma\gamma$ final state has been removed. The final sample contains 9099 events of reaction (1) and 657 events of reaction (2) for an integrated luminosity of 8.1 pb^{-1}. Small losses due to the cuts mentioned above as well as the geometrical acceptance have been corrected for using Monte Carlo (MC) generators [8,9] which include radiative corrections up to α^3 and contributions from the weak interactions. The MC generated events were propagated through the CELLO-detector according to a detailed detector simulation and were subsequently processed through the data reduction and analysis chain with the same cuts and constants as used for the real data. Finally radiative corrections were applied to the data using the MC generator [8,9].

For reaction (3) events were selected on the basis of the following criteria:
- Two charged particles with an acollinearity angle of $<30°$ and an acoplanarity angle of $<6°$.
- Each particle with a momentum $\geqslant 10$ GeV/c within $|\cos\theta| \leqslant 0.78$.
- The distance to the interaction point less than 2.5 cm along the beam axis.
- The energy deposited in the liquid argon less than 3 GeV.

Tracks were then propagated through the detector out to the muon chambers. The event was kept if there was at least one associated hit. The final sample contains 107 events of reaction (3) from an integrated luminosity of 6.6 pb^{-1}. The selection efficiency was estimated to be 45% by MC simulation.

In order to get a good signature for events of reaction (4) and suppress contamination due to Bhabha scattering and two-photon interactions, only such events were used where one τ decays into one charged prong and the other into three. This selection accepts 25% of the produced $\tau^+\tau^-$ pairs as inferred from known branching ratios [10]. The selection criteria were:
- Between three and five charged particles.
- One charged particle with a momentum $\geqslant 3$ GeV/c within $|\cos\theta| \leqslant 0.87$ and no other charged particle within a cone of 37°.
- The invariant mass M_{3p} of the three particles opposite to the isolated one is compatible with the decay of the τ ($0.2\ \mathrm{GeV}/c^2 < M_{3p} < 1.8\ \mathrm{GeV}/c^2$, assuming all particles to be pions).
- The total calorimetric energy associated with the track is $\leqslant 0.6\ W$.
- The total invariant mass of the event is $\geqslant 0.8$ GeV/c^2, assuming all particles to be pions.

The final sample contains 36 events of reaction (4) for an integrated luminosity of 6.2 pb^{-1}. Using a MC simulation the selection efficiency was estimated to be 50%.

Results. For the following discussion we assume the existence of a scalar and/or pseudoscalar particle with direct couplings to lepton and quark pairs and to photon pairs. By choosing such a doublet one conserves the chirality structure of the standard electro-weak (e.w.) theory. Both particles are assumed to have the same coupling constants. In our data we cannot distinguish whether one or two states contribute. We therefore introduce a factor ϵ into the formulae for the product of the coupling constants. ϵ can be 1 or 2 depending on the number of contributing bosons.

Contributions to the processes (1)–(4) due to a spin 0 boson add additional terms to the differential cross section. Using the notation $\Gamma_{aa} = \Gamma(X \to aa)$ it is written for reaction (1) as [5,11]:

$$\left(\frac{d\sigma}{d\Omega}\right)_{ee} = -\frac{\alpha\epsilon\Gamma_{ee}}{2MS}\left(\frac{4S(S-M^2)}{(1-c)[(S-M^2)^2+M^2\Gamma^2]} + \frac{S(1-c)^2[S(1-c)+2M^2]}{[S(1-c)+2M^2]^2+4M^2\Gamma^2}\right) \qquad (6)$$

$$+\frac{\epsilon\Gamma_{ee}^2}{M^2S}\left(\frac{S^2}{(S-M^2)^2+M^2\Gamma^2}+\frac{S^2(1-c)^2}{[S(1-c)+2M^2]^2+4M^2\Gamma^2} + \frac{(2-\epsilon)S^2(1-c)\{(S-M^2)[S(1-c)+2M^2]-2M^2\Gamma^2\}}{[(S-M^2)^2+M^2\Gamma^2]\{[S(1-c)+2M^2]^2+4M^2\Gamma^2\}}\right),$$

where $S = W^2$, $c = \cos\theta$, $M = M_X$ the mass and $\Gamma = \Gamma_X$ the total width of the X boson, and interference effects between X- and Z-exchange are omitted since they are negligible.

For the process (2) an isotropic term is added to the differential cross section [4,5]:

$$(d\sigma/d\Omega)_{\gamma\gamma} = 2(S/M_X^2)^2\,\epsilon\Gamma_{ee}\Gamma_{\gamma\gamma}/[(S-M_X^2)^2+M_X^2\Gamma_X^2]\,. \qquad (7)$$

Similarly an isotropic contribution is added for reactions (3) and (4) [4,5]:

$$(d\sigma/d\Omega)_{\mu\mu,\tau\tau} = (S/M_X^2)\,\epsilon\Gamma_{ee}\Gamma_{\mu\mu,\tau\tau}/[(S-M_X^2)^2+M_X^2\Gamma_X^2]\,. \qquad (8)$$

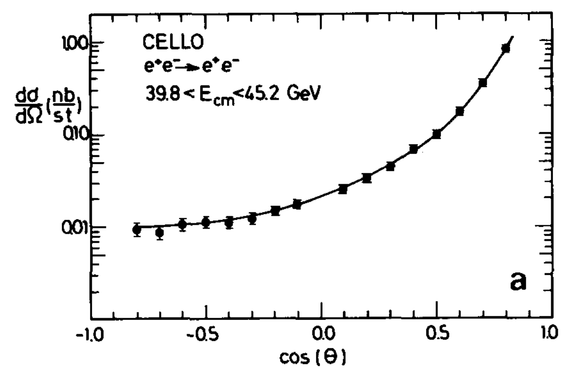
In these formulae we neglected the velocity dependent threshold factors since we only consider decays of X into light particles for which $\beta = 1$.

In order to derive upper limits on the exchange of spin 0 intermediate bosons we have to distinguish separate cases. We assume first that the mass M_X is below the maximal CM energy, i.e. $M_X < 45.2$ GeV. If the total width of the boson is smaller than the energy spread of the PETRA beams [$\sigma_W(\text{GeV}) = 2.2 \times 10^{-5} \times W^2(\text{GeV})$] one has to fold the experimental cross sections with the energy resolution function. In this case one obtains the following limits at the 95% confidence level (CL) neglecting radiative corrections:

$$\epsilon\Gamma_{ee}^2/\Gamma_X \leqslant 9.9\ \text{keV}\,, \quad \epsilon\Gamma_{ee}\Gamma_{\gamma\gamma}/\Gamma_X \leqslant 2.6\ \text{keV}\,,$$

$$\epsilon\Gamma_{ee}\Gamma_{\mu\mu}/\Gamma_X \leqslant 5.6\ \text{keV}\,, \quad \epsilon\Gamma_{ee}\Gamma_{\tau\tau}/\Gamma_X \leqslant 7.0\ \text{keV}\,.$$

If Γ_X is larger than the energy resolution of the scan at PETRA, the quantity $d = [(S-M_X^2)^2+\Gamma_X^2M_X^2]$ is well approximated by $d \approx \Gamma_X^2M_X^2$. We derive 95% CL upper limits on the cross sections from our measurements integrated over the total energy range. In order to increase the sensitivity to a contribution of a spin 0 boson, we restrict the Bhabha sample to $\cos\theta < 0.0$ and the $\gamma\gamma$ sample to $|\cos\theta| < 0.65$. For Bhabha scattering the normalization was taken from the angular range $0.65 < \cos\theta < 0.85$. The other reactions were normalized to the entire Bhabha sample. The reactions (1) and (2) agree very well with the predictions



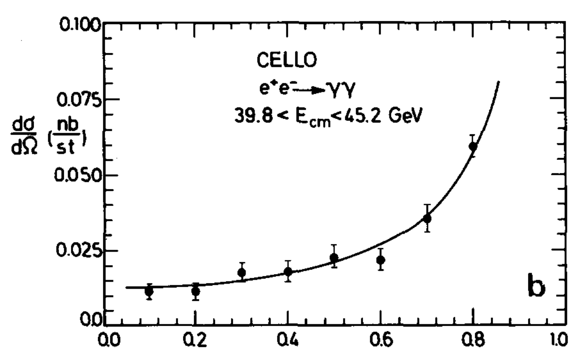


Fig. 1. Differential cross sections for (a) $e^+e^- \to e^+e^-$ and (b) $e^+e^- \to \gamma\gamma$. The solid lines correspond to the predictions of the e.w. theory at $\langle W \rangle = 42.5$ GeV.

of the e.w. theory over the measured angular range as shown by the differential cross sections in fig. 1. Taking $M_X = 42.5$ GeV we derive from the cross section limits the following upper limits:

$$\epsilon\Gamma^2_{ee}/\Gamma^2_X < 3.9 \times 10^{-6}, \quad \epsilon\Gamma_{ee}\Gamma_{\gamma\gamma}/\Gamma^2_X < 2.2 \times 10^{-6},$$

$$\epsilon\Gamma_{ee}\Gamma_{\mu\mu}/\Gamma^2_X < 3.0 \times 10^{-6},$$

$$\epsilon\Gamma_{ee}\Gamma_{\tau\tau}/\Gamma^2_X < 6.5 \times 10^{-6}.$$

If the mass of the spin 0 boson is greater than the available CM energy, one can produce e^+e^--, $\gamma\gamma$-, $\mu^+\mu^-$- and $\tau^+\tau^-$-pairs via a virtual boson. Approximating d by $d \approx (S - M^2_X)^2$ one can derive 95% CL upper limits on $\epsilon\Gamma_{ee}$ from reaction (1) and on $\epsilon\Gamma_{ee}\Gamma_{\gamma\gamma,\mu\mu,\tau\tau}$ from the other reactions independently of Γ_X. Such limits were obtained in two ways: For all reactions from the upper limits on the number of events observed

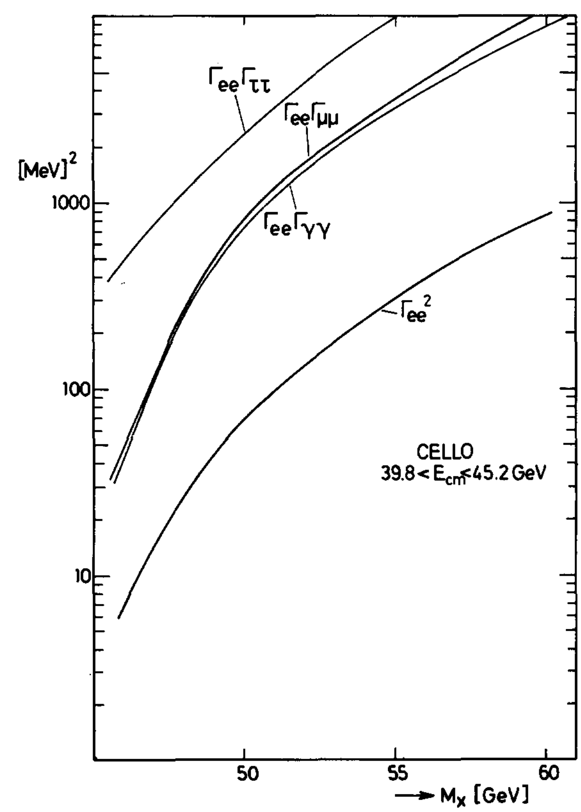


Fig. 2. Upper limits at the 95% CL for the product of the coupling constants $\epsilon^2\Gamma^2_{ee}$, $\epsilon\Gamma_{ee}\Gamma_{\gamma\gamma}$, $\epsilon\Gamma_{ee}\Gamma_{\mu\mu}$, and $\epsilon\Gamma_{ee}\Gamma_{\tau\tau}$ as a function of the mass M_X of the intermediate spin 0 boson.

in the angular ranges given above after subtraction of the expectations from the e.w. theory. These total cross sections limits are shown in fig. 2 for all reactions. The results include a 3% normalization uncertainty except for reaction (1) where we compare the backward with the forward region, and therefore the normalization uncertainties cancel. For the reactions (1) and (2) the 95% CL upper limits correspond to 7% and 10% of the total cross sections in the angular regions given above.

For reactions (1) and (2) limits on the partial widths were alternatively determined from a fit of the expressions for the differential cross sections to the data. One difficulty in such a fitting procedure is the strong correlation between the e.w. term and the contribution of a spin 0 boson. Therefore we added for the $\gamma\gamma$ reaction the precise normalization from the Bhabha scattering reaction into the fit, and for the Bhabha scattering reaction we kept the normalization fixed after determining it from a fit to the e.w. expressions alone. For Bhabha scattering the fit results can be transformed directly into a limit on the coupling constant α_h as a function of M_X. The result from the fit to the differential cross section yields 50% lowe- limits than the corresponding result from the total cross section. It is shown as a dashed line in fig. 3. The solid lines in fig. 3 show the limits from the fit to the differential cross sections for reaction (2) as will be discussed below.

Discussion. Our result on the partial widths of spin 0 bosons can be related to the radiative decay of the Z^0 if this occurs through the reaction (5) as recently discussed by various authors [1–5]. By allowing for (γ–W^0)-mixing in the lagrangian one obtains the relations [1,5]:

$$\Gamma_\tau = \Gamma(Z \to ee\gamma) = \Gamma(Z \to X\gamma)\,\mathrm{Br}(X \to ee)$$

$$= \epsilon\Gamma_{ee}\Gamma_{\gamma\gamma}/\rho\Gamma_X, \tag{9}$$

$$\rho = \Gamma(X \to \gamma\gamma)/\Gamma(Z \to X\gamma)$$

$$= \tfrac{3}{2}\sin^2\theta_W \cdot (M_Z/M_X - M_X/M_Z)^{-3}. \tag{10}$$

Here we took the most pessimistic value of ρ discussed in the literature, e.g. in ref. [4] it is a factor of 4 higher. Where applicable in this paper we use $\sin^2\theta_W = 0.23$, $M_Z = 94$ GeV and $\Gamma_\tau = 15$ MeV. The latter

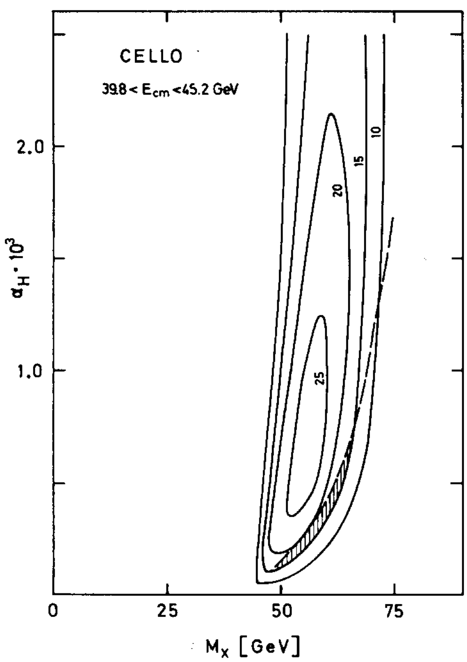


Fig. 3. Limits at the 95% CL for the universal coupling constant α_h as a function of the mass M_X of the spinless boson from fits to the differential cross sections of $e^+e^- \to e^+e^-$ (dashed line) and $e^+e^- \to \gamma\gamma$ (solid contours for different values of the radiative width Γ_τ of the Z Γ_τ, the numbers on the contours denote Γ_τ in MeV). $\epsilon = 1$ is assumed. The hatched area indicates the region allowed by the data for $\Gamma_\tau > 15$ MeV.

value is compatible with an estimate from $\bar{p}p$-data [6] if all of the 15–25% of the leptonic Z^0-decays having an additional hard photon are interpreted as radiative Z^0-decays. A lower limit

$$\epsilon\Gamma_{ee} \geqslant \rho\Gamma_\tau \qquad (11)$$

can be derived from relation (9) since the branching ratio $Br(X \to \gamma\gamma) < 1$. We first discuss whether the results on the search for a resonance within the energy range covered are compatible with a radiative width Γ_τ in the MeV range. For a narrow resonance one derives from $\epsilon\Gamma_{ee}\Gamma_{\gamma\gamma}/\Gamma_X$ and eq. (9) an upper limit of $\Gamma_\tau < 0.04$ MeV at $M_X = 42.5$ GeV. Similarly for a broad resonance we obtain a limit of $\Gamma_\tau < 35 \times 10^{-6} \times \Gamma_X$. For Γ_X smaller than several GeV both limits are incompatible with a Γ_τ of a few MeV.

In the following we consider the limits for a resonance above our energy range. Our limits on $\epsilon\Gamma_{ee}$ constrain the radiative width of the Z^0 if one assumes relation (9) to hold. From the upper limit of Γ_{ee} from eq. (11) with $\Gamma_\tau = 15$ MeV together with the limits given in fig. 2, we obtain limits on the partial widths. They are e.g. for $M_X = 50$ GeV:

$$\Gamma_{\gamma\gamma} < 355 \text{ MeV}, \quad \Gamma_{\mu\mu} < 362 \text{ MeV}, \quad \Gamma_{\tau\tau} < 1136 \text{ MeV}$$

If we assume that the total width Γ_X is determined by a universal coupling $\alpha_h = 2\Gamma_{ee}/M_X$ of X to 5 quarks and 3 leptons, i.e.

$$\Gamma_X = 18\Gamma_{ee} + \Gamma_{\gamma\gamma}, \qquad (12)$$

we derive an upper limit of $\Gamma_X < 505$ MeV from the $\gamma\gamma$-limit and the measured upper limit of Γ_{ee}.

Next we discuss the results from reaction (2). From the fit to the differential cross sections we obtain a 95% CL upper limit of 10% for the isotropic term relative to the QED term evaluated at $\theta = 90°$. This limit is equivalent to a limit on $\epsilon\Gamma_{ee}\Gamma_{\gamma\gamma}$. For a given value of Γ_τ one can relate $\Gamma_{\gamma\gamma}$ to Γ_{ee} – and thereby to α_h – if one substitutes relations (10)–(12) into (9). Thus one can draw a 95% CL contour of α_h versus M_X for a given value of Γ_τ (4). Such contours are shown in fig. 3 for $\epsilon = 1$ which yields the least stringent limits. The region inside the contours is allowed by our data. For $\Gamma_\tau > 30$ MeV this region vanishes, thus $\Gamma_\tau > 30$ MeV is excluded by our $\gamma\gamma$ data alone for all values of α_h and for all M_X below the Z^0-mass.

Bhabha scattering gives independently a stronger limit on α_h since the interference term is proportional to α_h and not to α_h^2. As can be seen from the dashed line in fig. 3, reaction (1) limits the coupling constant α_h for masses below 50 GeV independently of Γ_τ to $\epsilon\alpha_h < 1.5 \times 10^{-4}$. The allowed region from Bhabha scattering is below the dashed line. However, this region is outside of the contours from reaction (2) for all $\Gamma_\tau > 20$ MeV. Thus under the assumptions stated above spin 0 bosons with masses below the Z^0-mass are excluded for $\Gamma_\tau > 20$ MeV. For $\Gamma_\tau > 15$ MeV the only boson masses still allowed by our data are between 47 GeV and 68 GeV for α_h-values varying from 1.1×10^{-4} to 7.5×10^{-4} as indicated by the hatched area in fig. 3.

Conclusions. From an investigation of the reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \gamma\gamma$, $e^+e^- \to \mu^+\mu^-$, and $e^+e^- \to \tau^+\tau^-$ we find good agreement with the standard electroweak theory up to CM energies of 45.2 GeV. In these reactions we find neither a narrow nor a broad resonance in the energy range covered. We therefore can exclude the existence of a spin 0 boson up to 45.2 GeV in a model independent way. We put upper limits on the partial widths versus the mass for energies above the PETRA energy range. Because of the interference between s- and t-channel exchange Bhabha scattering puts the strongest limits on the coupling constant α_h yielding e.g. $\epsilon\alpha_h < 1.5 \times 10^{-4}$ at the 95% CL for a mass of 50 GeV of the spin 0 boson. Provided that the coupling constants of the spin 0 boson are related to the radiative width of the Z^0 by the relations of the adopted model, the existence of spin 0 bosons with masses below the Z^0-mass can be excluded at the 95% CL for values of the radiative width of the Z^0 above 20 MeV. Stronger limits are obtained for boson masses close to the energy covered by our experiment. For a boson mass equal to the average of the invariant masses of $M_X = 46$ GeV of the e^+e^--pairs in the radiative Z^0-decays of the $\bar{p}p$-data we find $\epsilon\alpha_h < 0.5 \times 10^{-4}$ at 95% CL yielding $\Gamma_\gamma < 12.5$ MeV assuming the most pessimistic case that the branching ratio $Br(X \to \gamma\gamma) \approx 1$.

After completion of this work we learned of a similar study by Adeva et al. [12].

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