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Search for Spinless Bosons in e^+e^- Annihilation

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ABSTRACT

We have measured the cross sections for $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \gamma\gamma$ and $e^+e^- \to$ hadrons in an energy scan at center of mass energies between 39.79 and 46.72 GeV in 30 MeV steps. New spinless bosons, whose existence has been postulated as a possible means to explain the anomalously large radiative width of the Z^0 found at the CERN SPS $p\bar{p}$ collider, are ruled out in the scan region. The data are used to set limits on the couplings to lepton, photon and quark pairs of bosons with masses above 46.72 GeV.

The observation of electroweak interference effects in e^+e^- reactions at PETRA and PEP energies |1| and the discovery at the CERN $p\bar{p}$ collider of the W and Z^0 bosons |2| constitute major triumphs of the Glashow-Weinberg-Salam theory of electroweak interactions |3|. However the indications of a large radiative width for $Z^0 \to e^+e^-\gamma$, $\mu^+\mu^-\gamma$ |4|, were not expected within this framework.

Several attempts have been made within the "standard" theory |5| as well as in some "conventional" extensions of it |6| to explain the dynamical origin of these events. In models of composite quarks and leptons the Z^0 is not elementary and the existence of a lighter spin zero partner X is expected, so that radiative transitions $Z^0 \to X\gamma$ could conceivably take place, followed by subsequent decays of X into lepton, quark or photon pairs (l^+l^-, $q\bar{q}$, $\gamma\gamma$).

The implications for e^+e^- reactions that would follow from such a scenario have been worked out in detail in Refs. |7| and |8|. They can be summarized as follows:

1. If the mass of the X boson is within the energy range attainable with PETRA, one should observe resonance excitations in the cross sections for $e^+e^- \to l^+l^-$, $q\bar{q}$, $\gamma\gamma$ as a function of the c.m. energy.

2. If the mass of the X-boson lies beyond the highest energies that PETRA can reach, the cross sections for the processes mentioned above and in particular for $e^+e^- \to e^+e^-$ should exhibit deviations from the QED expectations in a pattern which can be well distinguished from the γ-Z^0 interference effects.

We describe here an experimental search for spin zero bosons with the properties described above. The data were obtained with the TASSO detector working at the DESY e^+e^- storage ring PETRA. An energy scan was performed in steps of 30 MeV between c.m. energies W of 39.79 and 46.72 GeV, collecting at each step a luminosity of $\sim 60\ nb^{-1}$. Similar searches have been reported recently |9,10|.

Hadronic events were selected using the information on charged particle momenta measured in the central detector. For the selection of lepton and photon pair events , additional information provided by the barrel liquid argon calorimeter and the muon chambers was used.

The luminosity was measured via small angle Bhabha scattering |11|. The total integrated luminosity was 13.4 pb^{-1}, the systematic error being estimated to be 3.4%.

We analysed the following reactions:

1. $e^+e^- \to$ hadrons

   The data taking, analysis procedure and event selection have been described in detail in Ref. |11|. A total of 2377 events passed the acceptance criteria from which the total hadronic cross section was obtained as described in Ref. |11|. The ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{pt}$, of the total hadronic cross-section to the pointlike cross-section, $\sigma_{pt} = 4\pi\alpha^2/3s$, ($s = W^2$),is shown in Fig. 1a. These values for R, as well as all other cross-sections shown below, were corrected for QED radiative effects |12|. The result is consistent with a constant $R = 4.15 \pm 0.09$ over the scanned energy range.

2. $e^+e^- \to \mu^+\mu^-$

   The analysis for μ pair production has been described in Ref. |1g|. At least one track was required to be identified as a muon by the muon chambers or as a minimum ionizing particle by the liquid argon calorimeter. A total of 225 events passed the acceptance criteria. We determined the ratio of the corrected cross-section to the GWS prediction, for polar angles Θ satisfying $|\cos\Theta| < 0.8$. The results are shown in Fig. 1b. The systematic uncertainty in the cross section determination is 4.5%, of which 3.0% stems from the overall detection efficiency and 3.4% from the luminosity measurement.

3. $e^+e^- \to \gamma\gamma$

   The analysis for $e^+e^- \to \gamma\gamma$ has been described in Ref.|13|. A total of 282 events satisfied the selection criteria for polar angles $|\cos\Theta| < 0.7$. We determined for this angular range the ratio of the corrected cross-section to the cross-section for $e^+e^- \to \gamma\gamma$ expected in lowest order QED. The results are shown in Fig. 1c. The systematic error was determined to be 5%. The differential cross section multiplied by s and averaged over the scanned energy range is shown in Fig. 2a.

4. $e^+e^- \to e^+e^-$

   Bhabha events were selected as described in Ref. |1g|. Basically two collinear tracks were demanded. A total of 8965 events satisfied the acceptance criteria. We estimated the contamination from μ and τ pairs to be 4.2% and 0.6% respectively. These contributions were subtracted on a statistical basis. We determined for polar angles satisfying $|\cos\Theta| < 0.8$ the ratio of the corrected cross-section to the Bhabha cross-section calculated in the GWS theory. The results are shown in

Fig. 1d. The systematic error was estimated to be 4.9%. The differential cross-section multiplied by s and averaged over the scanned energy region is presented in Fig. 2b.

None of the cross-section ratios presented in Fig. 1 shows evidence for a significant narrow enhancement.

We briefly discuss the cross section expressions for production of a spin zero boson. The contribution of a spinless boson to the reaction $e^+e^-\to$hadrons can be written as [7,8]

$$\frac{d\sigma(X\to had)}{d\Omega} = \frac{s}{m_X^2} \frac{\Gamma_{Xee}\,\Gamma_{Xhad}}{(s-m_X^2)^2+(m_X\Gamma_X)^2} \qquad (5)$$

where Γ_{Xee} and Γ_{Xhad} are the partial widths for the decay of X into e^+e^- and hadrons respectively and Γ_X is the total width of the X-boson with mass m_X. For a narrow resonance the integration over the c.m. energy yields

$$\int \sigma(X\to had)\, dW = \frac{2\pi^2}{m_X^2} \frac{\Gamma_{Xee}\,\Gamma_{Xhad}}{\Gamma_X} \qquad (6)$$

The contribution to the reaction $e^+e^-\to\mu^+\mu^-$ mediated by X-exchange is given by Eqs. (5-6) after replacing Γ_{Xhad} by $\Gamma_{X\mu\mu}$, while that to the reaction $e^+e^-\to\gamma\gamma$ is given by

$$\frac{d\sigma(X\to\gamma\gamma)}{d\Omega} = 2\,\frac{s}{m_X^2} \frac{\Gamma_{Xee}\,\Gamma_{Xhad}}{(s-m_X^2)^2+(m_X\Gamma_X)^2} \qquad (7)$$

which in the limit of small Γ_X can be integrated to yield a result identical to Eq. (6) with Γ_{Xhad} replaced by $\Gamma_{X\gamma\gamma}$.

The implications for Bhabha scattering are more complicated. Neglecting the electron mass and Z^0 exchange contributions we can write

$$\frac{d\sigma(X\to ee)}{d\Omega} = \frac{s}{m_X^2}\frac{\Gamma_{Xee}^2}{(s-m_X^2)^2+(m_X\Gamma_X)^2} + \frac{\alpha\Gamma_{Xee}}{m_X}\frac{s}{t}\frac{s-m_X^2}{(s-m_X^2)^2+(m_X\Gamma_X)^2}$$
$$+ \frac{t^2}{sm_X^2}\frac{\Gamma_{Xee}^2}{(t-m_X^2)^2} + \frac{\alpha\Gamma_{Xee}}{s^2m_X^2}\frac{t^2}{t-m_X^2} + \frac{s-m_X^2}{m_X^2}\,\frac{t}{t-m_X^2}\,\frac{\Gamma_{Xee}^2}{(s-m_X^2)^2+(m_X\Gamma_X)^2} \qquad (8)$$

where $\sigma(X\to e^+e^-)$ is the contribution of X to the cross section, including interference terms.

The two dominant contributions are those due to the s-channel exchange of the X-boson and that coming from its interference with the t-channel photon exchange. In the limit of a small width Γ_X these can be integrated to give

$$\int \sigma(X\to ee)\, dW = \frac{\pi^2}{m_X^2}\frac{\Gamma_{Xee}^2}{\Gamma_X}(\cos\Theta_f - \cos\Theta_b) \qquad (9)$$

where Θ_f and Θ_b are the forward and backward limits of the $\cos\Theta$ integration, introduced to avoid the divergence originating from the second term in the r.h.s of Eq.(8).

We made maximum likelihood fits to the data shown in Fig. 1 using a constant term plus a Gaussian centered at a given c.m. energy which was increased in steps of 2 MeV. Its r.m.s. width was given by the c.m. energy spread which is proportional to s and is estimated to be 40 MeV at 42.5 GeV. Radiative effects were taken into account following Ref. [14]. Using a similar procedure as for the search for narrow toponium states [11] the following upper limits at the 95% confidence level were obtained

$$\Gamma_{Xee}\Gamma_{Xhad}/\Gamma_X < 7.5 \text{ keV }^{*)} \qquad (10)$$

$$\Gamma_{Xee}\Gamma_{X\mu\mu}/\Gamma_X < 6.0 \text{ keV} \qquad (11)$$

$$\Gamma_{Xee}\Gamma_{X\gamma\gamma}/\Gamma_X < 10.5 \text{ keV} \qquad (12)$$

$$\Gamma_{Xee}^2/\Gamma_X < 23.7 \text{ keV} \qquad (13)$$

We find that the limit (12) is incompatible with the relation given in Ref.[7],Eq. (17):

$$\frac{\Gamma_{Xee}\Gamma_{X\gamma\gamma}}{\Gamma_X} = 6\sin^2\Theta_W \left\{\frac{m_Z}{m_X} - \frac{m_X}{m_Z}\right\}^{-3}\Gamma(Z^0\to e^+e^-\gamma)/\rho = 0.213\ \Gamma(Z^0\to e^+e^-\gamma)/\rho \qquad (14)$$

---

*) The data presented here yields for the leptonic width times branching ratio of a narrow toponium resonance an upper limit of $\Gamma_{ee}B_h<2.5$ keV with 95% confidence level.

where Θ_W is the weak mixing angle, m_Z the Z^0 mass, $\Gamma(Z^0 \to e^+e^-\gamma)$ the radiative width of the Z^0 which is estimated to be around 20 MeV [4] and ρ a model dependent factor characterizing the relative strength of the couplings $XZ\gamma$ and $X\gamma\gamma$. It is uncertain within the range 1 to 4, Refs. [7,8].

For the numerical estimates on the r.h.s. of Eq. (14) we have taken $\sin^2\Theta_W=0.23$, $m_Z=93.5$ GeV as an average of the UA1 [2a] and UA2 [2b] values, and $m_X=40.67$ GeV from our fits to the data in Fig. 1c. Taking the UA1 and UA2 results at face value i.e. $\Gamma(Z^0 \to e^+e^-\gamma)=20$ MeV and using $\rho=4$ one obtains from Eq. (14) $\Gamma_{Xee}\Gamma_{X\gamma\gamma}/\Gamma_X= 1.06$ MeV, in disagreement with the upper limit given in (12).

Under the assumption that $q\bar{q}$ pairs, $l\bar{l}$ pairs and $\gamma\gamma$ pairs are the only open decay channels of the X-boson, and taking $\Gamma_{X\tau\tau}=\Gamma_{X\mu\mu}=\Gamma_{X\nu\nu}$, i.e. $\Gamma_X = \Gamma_{Xhad}+\Gamma_{Xee}+5\Gamma_{X\mu\mu}+\Gamma_{X\gamma\gamma}$, we find $\Gamma_{Xee}<71.7$ keV. This value is incompatible with the relation given in Ref. [7], Eq. (18b):

$$\Gamma_{Xee} > 6 \sin^2\Theta_W \left\{\frac{m_Z}{m_X} - \frac{m_X}{m_Z}\right\}^{-3} \Gamma(Z^0 \to e^+e^-\gamma)/\rho = 0.376\ \Gamma(Z^0 \to e^+e^-\gamma)/\rho \quad (15)$$

For the numerical estimates on the r.h.s. of Eq. (15) we have taken m_Z and $\sin^2\Theta_W$ as above and $m_X=45.97$ GeV which is where the maximum hypothetical signal for Γ_{Xee} is found. Taking again $\Gamma(Z^0 \to e^+e^-\gamma)\sim 20$ MeV [4] and $\rho=4$, one obtains from Eq. (15) the lower limit $\Gamma_{Xee}> 1.88$ MeV which is more than an order of magnitude larger than our upper limit. In conclusion we can exclude the existence of a narrow spinless boson with the expected properties and a mass between 39.79 and 46.72 GeV.

We now describe the search for a broad spinless boson. We made fits to the data shown in Figs. 1a-c using a constant term plus a Breit-Wigner contribution given by Eqs. (5) or (7). Its mass was centered at a given c.m. energy and increased in 2 MeV steps. The width was varied between 100 MeV and 3.5 GeV. For $\Gamma_X=100$ MeV we obtain upper limits comparable to those given in (10-12) for narrow resonances. With increasing Γ_X the corresponding upper limits increase steadily until reaching a plateau for Γ_X values larger than ~1GeV. At the 95% CL they amount to

$$\Gamma_{Xee}\Gamma_{Xhad}/\Gamma_X < 21.1 \text{ keV} \quad (16)$$

$$\Gamma_{Xee}\Gamma_{X\mu\mu}/\Gamma_X < 12.3 \text{ keV} \quad (17)$$

$$\Gamma_{Xee}\Gamma_{X\gamma\gamma}/\Gamma_X < 25.5 \text{ keV} \quad (18)$$

The upper limit given in (18) is more than an order of magnitude smaller than the expectation derived from Eq. (14), thus excluding the existence of broad spinless resonances with the properties discussed before and a mass within the limits of the energy scan.

We now describe the search for a spinless boson with mass outside of the range covered by the scan. For definitness we consider X to be a pseudoscalar. Such an object would lead to deviations from the electroweak predictions for the angular distributions and for the integrated cross sections for Bhabha scattering and photon pair production.

In order to extract upper limits on Γ_{Xee} and $\Gamma_{Xee}\Gamma_{X\gamma\gamma}$ the differential and the integrated cross-sections for the e^+e^- and $\gamma\gamma$ final states were fitted to the corresponding electroweak predictions plus additional X-boson contributions discussed above.

From these fits we derived 95% C.L. upper limits for $\Gamma_{Xee}\Gamma_{X\gamma\gamma}$ and Γ_{Xee} which correspond to deviations from the electroweak predictions of $\delta=(\sigma_{measured}/\sigma_{GWS})-1$, namely

$$\delta_{\gamma\gamma}\ (\ |\cos\Theta| < 0.7\ ) < 0.07 \text{ at } \bar{W}=43.1 \text{ GeV.} \quad (19)$$

$$\delta_{ee}\ (-0.8< \cos\Theta < 0.0\ ) < 0.07 \text{ at } \bar{W}=43.1 \text{ GeV.} \quad (20)$$

These limits are within a wide range independent of the values for the mass and width of the X-boson used in the fits. Following the spirit of Refs. [7] and [8] we now assume a universal coupling constant of the X-boson to fermions given by

$$\alpha_h= 2\Gamma_{Xff}/m_X\ , \quad f=q,l \quad (21)$$

so that in Eq. (14) Γ_X can be replaced by $21\Gamma_{Xff}+\Gamma_{X\gamma\gamma}$. For a given radiative Z^0 width $\Gamma(Z^0 \to e^+e^-\gamma)$, Eq. (14) yields a relation between Γ_{Xff} and $\Gamma_{X\gamma\gamma}$ so that the latter width can be eliminated. As proposed in Ref. [7] contour plots can be constructed in the (α_h, m_X) plane for a given ratio $\Gamma(Z^0 \to e^+e^-\gamma)/\rho$ if a limit δ_i, ($i=e^+e^-,\gamma\gamma$), is known at a given c.m. energy W. A combined contour plot for the $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ channels is shown in Fig. 3.

In summary, we exclude the existence of spinless bosons with masses in the region 39.79 - 46.72 GeV both for narrow and broad resonances. Our limit for $\delta_{\gamma\gamma}$ rules out $\Gamma(Z^0 \to e^+e^-\gamma)/\rho>10$ MeV for all m_X values below the Z^0

mass. The limit on δ_{ee} excludes the existence of a pseudoscalar boson to the left of the dashed line in fig. 3 provided $\Gamma(Z^0 \rightarrow e^+e^-\gamma)/\rho > 5$ MeV.

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2.0 FIGURE CAPTIONS

Fig. 1a: The values of R as a function of c.m. energy.

Fig. 1b: The cross-section for $e^+e^- \to \mu^+\mu^-$ integrated in the polar region $|\cos\Theta|<0.8$ and normalized to the GWS prediction as a function of c.m. energy

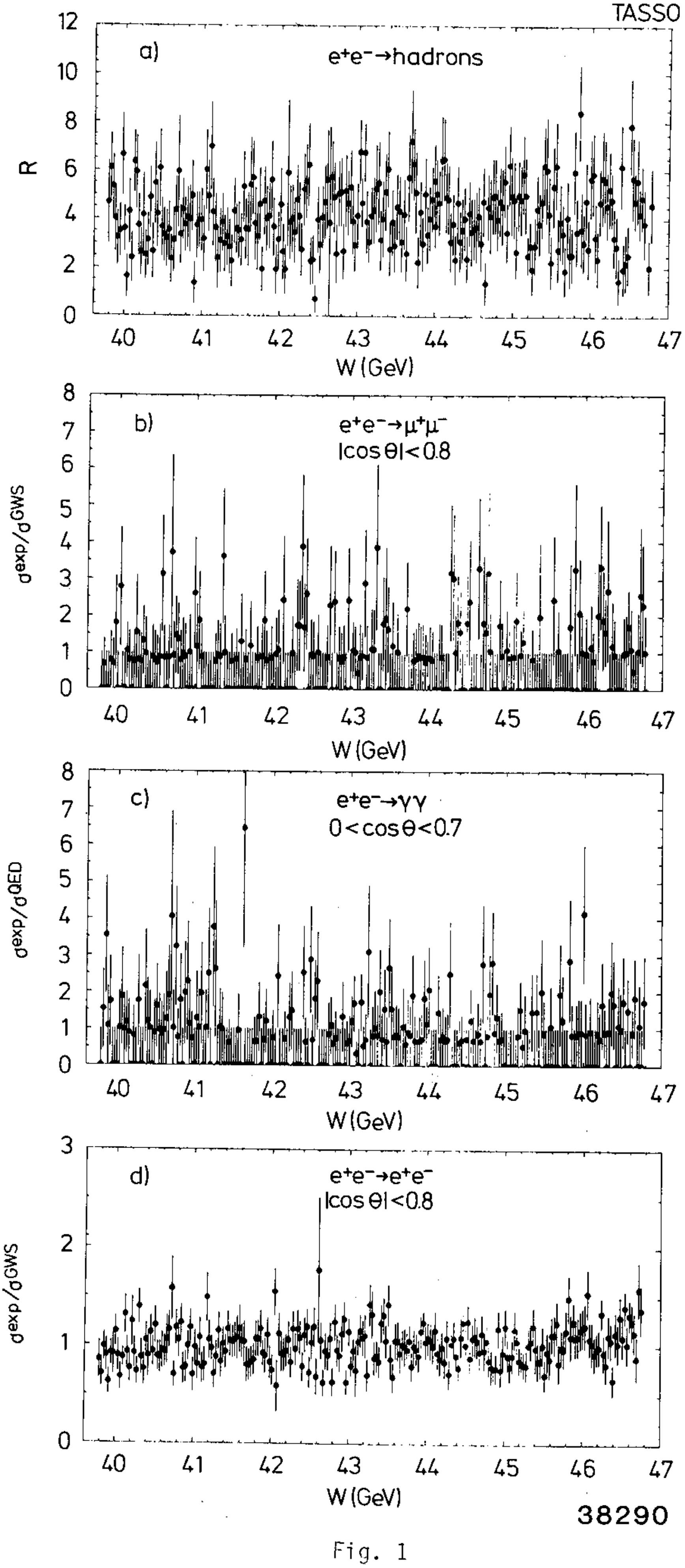
Fig. 1c: The cross-section for $e^+e^- \to \gamma\gamma$ integrated in the polar region $0.0<\cos\Theta<0.7$ and normalized to the QED prediction as a function of c.m. energy

Fig. 1d: The cross-section for $e^+e^- \to e^+e^-$ integrated in the polar region $|\cos\Theta|<0.8$ and normalized to the GWS prediction as a function of c.m. energy

Fig. 2a: The differential cross section for $e^+e^- \to \gamma\gamma$ at a mean c.m. energy of 43.1 GeV. The solid curve represents the QED prediction.

Fig. 2b: The differential cross section for Bhabha scattering at a mean c.m. energy of 43.1 GeV. The solid curve represents the GWS prediction.

Fig. 3 : Allowed regions in the (α_h, m_X) plane for various values of $\Gamma(Z^0 \to e^+e^-\gamma)/\rho$.



TASSO
a)
e+e-→hadrons
R
W (GeV)
b)
e+e-→μ+μ-
|cos θ| < 0.8
σexp/σGWS
W (GeV)
c)
e+e-→γγ
0 < cos θ < 0.7
σexp/σQED
W (GeV)
d)
e+e-→e+e-
|cos θ| < 0.8
σexp/σGWS
W (GeV)
38290

Fig. 1

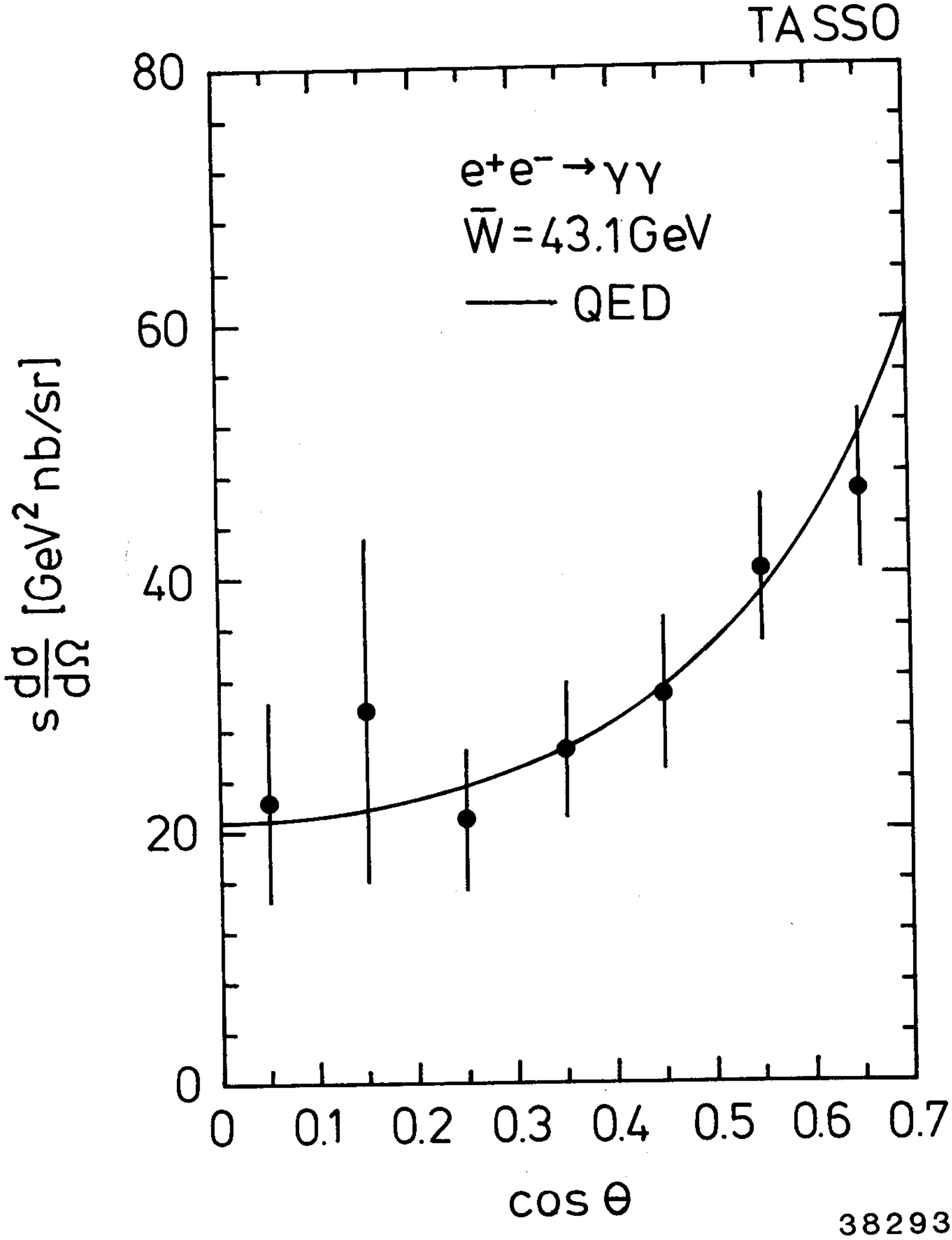

TASSO
$e^+e^- \to \gamma\gamma$
$\bar{W} = 43.1$ GeV
QED
$s\frac{d\sigma}{d\Omega}$ [GeV^2 nb/sr]
0
20
40
60
80
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$\cos\Theta$
38293

Fig. 2a

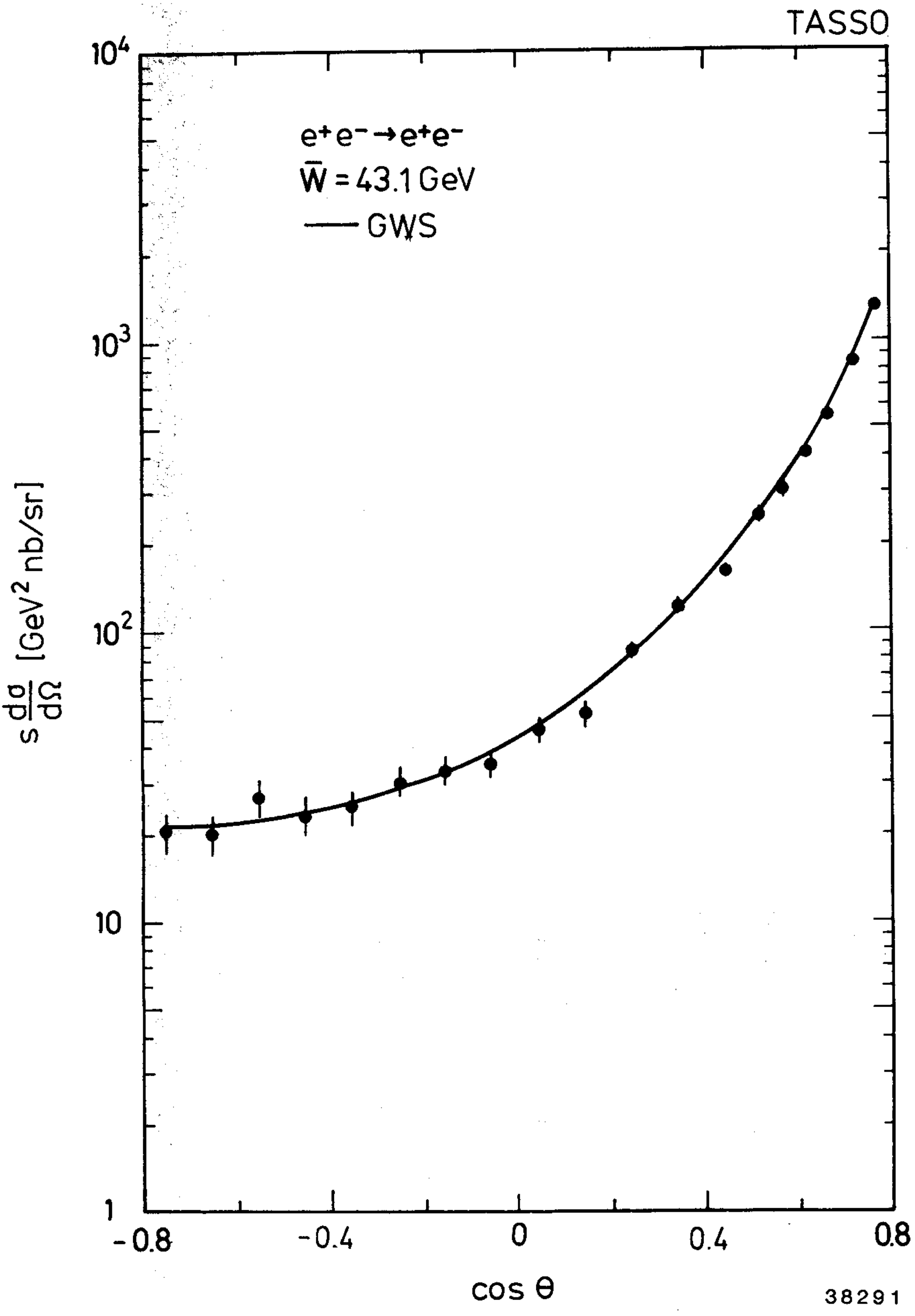

TASSO
$e^+e^- \to e^+e^-$
$\bar{W}$ = 43.1 GeV
—— GWS
$s\frac{d\sigma}{d\Omega}$ [GeV^2 nb/sr]
10^4
10^3
10^2
10
1
-0.8
-0.4
0
0.4
0.8
cos Θ
38291

Fig. 2b

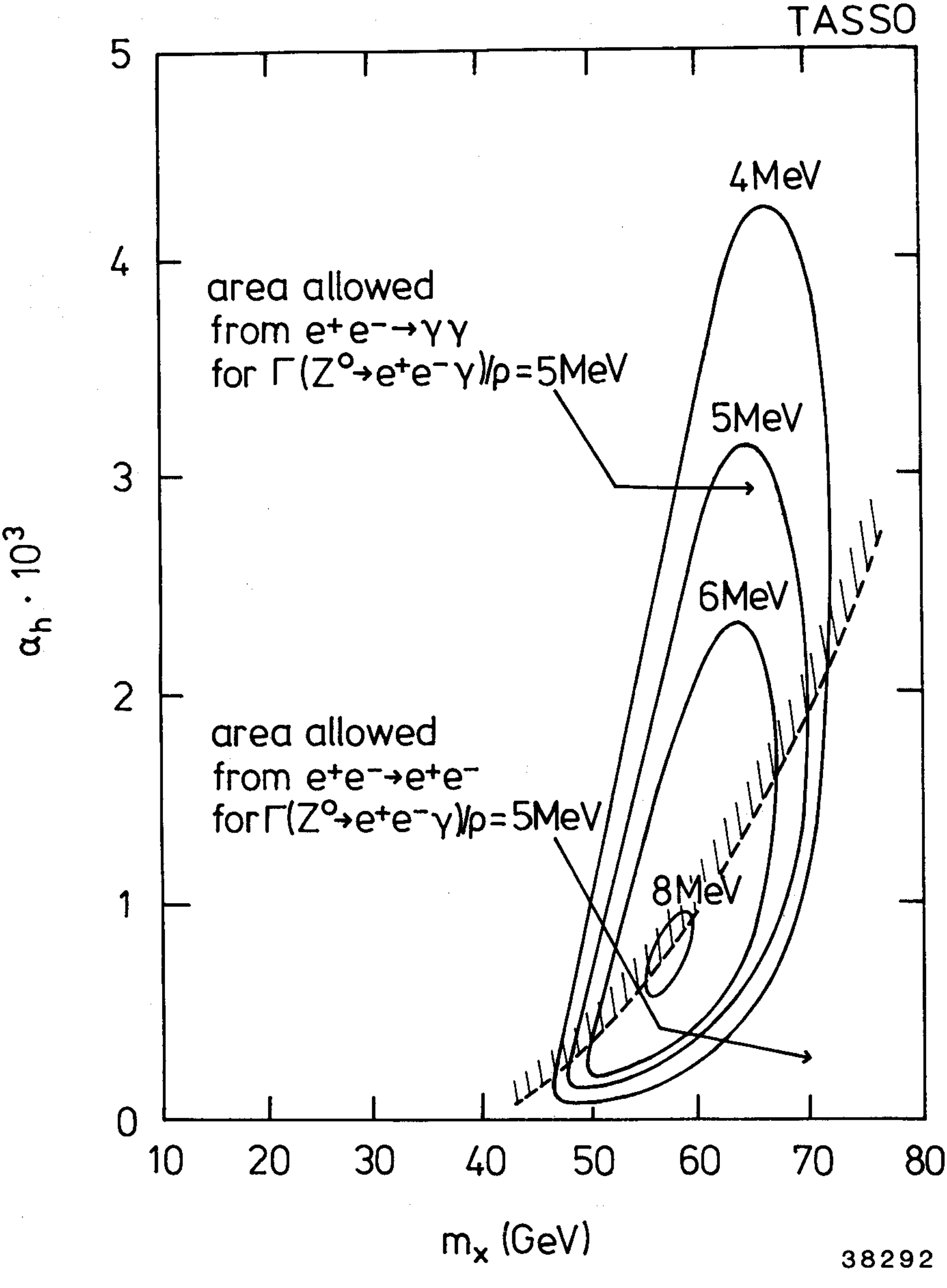

TASSO
4MeV
5MeV
6MeV
8MeV
area allowed
from e+e- → γγ
for Γ(Z° → e+e-γ)/ρ = 5MeV
area allowed
from e+e- → e+e-
for Γ(Z° → e+e-γ)/ρ = 5MeV
a_h · 10^3
m_x (GeV)
0
1
2
3
4
5
10
20
30
40
50
60
70
80
38292

Fig. 3