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Search for Anomalous Z$\rightarrow \gamma\gamma\gamma$ Events at LEP

The L3 Collaboration

Abstract

We have searched for anomalous $Z \rightarrow \gamma\gamma\gamma$ events with the L3 detector at LEP. No significant deviations from the expected QED $e^+e^- \rightarrow \gamma\gamma\gamma$ events are observed. The branching ratio upper limit for a composite Z decaying directly into three photons is found to be 1.0×10^{-5} at 95% C.L. The branching ratio upper limits for the process $Z \rightarrow \gamma X, X \rightarrow \gamma\gamma$ are in the range of 0.4 to 1.3×10^{-5}, depending on the mass and width of the scalar particle X. In the context of a model with magnetic monopoles coupling to the Z, we find $BR(Z \rightarrow \gamma\gamma\gamma) < 0.8 \times 10^{-5}$ at 95% C.L; this results in a lower mass limit of 510 GeV for a magnetic monopole.

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Introduction

In the Standard Model the decay $Z \rightarrow \gamma\gamma\gamma$ proceeds via fermion- and W-loops and is strongly suppressed; the branching ratio is expected to be about 5.4×10^{-10} [1]. An enhanced branching ratio would be a clear indication of new physics. Such enhancements are expected in the context of composite Z models [2,3] and models assuming a light magnetic monopole coupling to the Z [4]. In composite models the Z decay into $\gamma\gamma\gamma$ can either proceed directly via constituents of the Z, or indirectly, via a radiatively produced scalar partner, X, of the Z – *i.e.*, $Z \rightarrow \gamma X, X \rightarrow \gamma\gamma$. In the monopole model the decay proceeds via a monopole loop. Other recent theoretical studies of the process $Z \rightarrow \gamma\gamma\gamma$ are presented in refs. [5–7].

The above channel has been studied earlier at LEP [8]. The current analysis results in a significant improvement. For the analysis we used 65.8 pb^{-1} of data taken on and around the Z peak, at center of mass energies between 88.5 and 93.7 GeV, during the LEP 1991-1993 runs; this data sample contains 1,641,410 hadronic Z decays.

The L3 Detector

The L3 detector [9] measures e, γ, μ and hadronic jets with high precision. The central tracking chamber is a time expansion chamber (TEC) consisting of two coaxial cylindrical drift chambers; the electromagnetic calorimeter is composed of bismuth germanate (BGO) crystals; hadronic energy depositions are measured by an uranium-proportional wire chamber sampling calorimeter surrounding the BGO; scintillator timing counters are located between the electromagnetic and hadronic calorimeters. The muon spectrometer, located outside the hadron calorimeter, consists of three layers of drift chambers measuring the muon trajectory in both the bending and the non-bending planes. The energy resolution and angular resolution for electrons and photons for energies above 1 GeV is less than 2% and better than 0.5°, respectively. All subdetectors are installed inside a 12 m diameter solenoid which provides a uniform field of 0.5 T along the beam direction.

Event Selection

We select events having two or more highly energetic photons. Events with at least two photons in the final state are retained in the first stage of the analysis to be used as a check on the TEC efficiency. We require:

- the total energy, E_{BGO}, in the electromagnetic calorimeter to satisfy: $0.8 < E_{BGO}/\sqrt{s} < 1.1$;
- the number of electromagnetic clusters to be less than 9 (to reject hadronic events);
- the angle between the two most energetic electromagnetic clusters to be larger than 20° (to reject showering cosmic events);
- the polar angle of the two most energetic BGO clusters to satisfy: $16.1° < \theta_\gamma < 163.9°$ (This cut selects photon candidates which have traversed the inner TEC).

The main background is from the process $e^+e^- \rightarrow e^+e^-(\gamma)$. Such events are rejected by requiring that there be no tracks in the TEC. We use our hadron data sample to monitor the TEC performance.

With the above cuts we selected 2197 $e^+e^- \rightarrow \gamma\gamma(\gamma)$ candidates. Using a fully simulated Monte Carlo sample for the QED process $e^+e^- \rightarrow \gamma\gamma(\gamma)$, based on the generator described in ref. [10], we expect our data sample to consist of 2037 $\gamma\gamma(\gamma)$ events. In this estimate special care is given to photon conversions in the detector, which were studied using photons in radiative Bhabha events. Moreover, the detector simulation includes a small effect from time dependent BGO inefficiencies. We expect an additional 13 events due to contamination from $e^+e^- \rightarrow e^+e^-(\gamma)$. This number is derived from experimental $e^+e^- \rightarrow e^+e^-$ data by determining the probability of observing an electron as a photon using the above selection criteria and the TEC efficiency. Thus we expect to observe (2050$\pm$72) events from QED processes. The error in the expected number of QED events is dominantly due to uncertainties in the efficiency determination and Monte Carlo statistics.

The small difference between the number of observed and expected events might indicate some additional $e^+e^- \rightarrow e^+e^-(\gamma)$ contamination due to undetected TEC inefficiencies. This background typically has low energy photons and does not affect our search for anomalous three-photon events.

To obtain the three photon final state events we require, in addition to the above criteria:

- a third BGO cluster with an energy more than 2 GeV and with a polar angle in the above range, separated in angle from the other two clusters by at least 20°.

We obtained a 3-γ sample of 87 events. From QED processes we expect (76.3$\pm$2.8) events. Fig. 1 shows an example of such a $\gamma\gamma\gamma$ event.

Results

$Z \rightarrow \gamma\gamma\gamma$ via Compositeness

The most distinctive difference between QED and $Z \rightarrow \gamma\gamma\gamma$ events is the energy of the least energetic photon. In Fig. 2 we show the distribution of this variable, together with the QED expectation; also shown is the distribution resulting from a Monte Carlo simulation of $Z \rightarrow \gamma\gamma\gamma$ events (arbitrarily normalized). We require: $E\gamma_3/\sqrt{s} > 0.125$ [1]. The efficiency for selecting $Z \rightarrow \gamma\gamma\gamma$ is (52$\pm$2)%. In the upper limit calculation we take the error on the efficiency into account by reducing the efficiency by this error. We observe 25 events while our QED-expectation is (26.7$\pm$1.3).

An upper limit on the number of events is determined as described in ref. [11], *i.e.*, we use Poisson statistics and allow for background. Note that if we find the number of observed events (n_0) to be consistent with, but less than the number of expected events, we calculate the upper limit as if n_0 equals the number of expected events.

In the context of this composite Z model we find for the branching ratio:

$$BR(Z \rightarrow \gamma\gamma\gamma) < 1.0 \times 10^{-5} \tag{1}$$

at 95% C.L.

A composite Z might have scalar partners, X, as mentioned above. Such a scalar might be detected in the $\gamma\gamma$ invariant mass distribution $M\gamma\gamma$. Moreover, on kinematical grounds one expects to observe, for constant $\sqrt{s}$, monochromatic photons with energy $E_\gamma = (s - M_X^2)/(2\sqrt{s})$.

[1] Photons $\gamma_1, \gamma_2, \ldots$ are numbered in order of decreasing energy.

In Fig. 3a we show the $\gamma\gamma$ invariant mass distributions for the observed events with $E_\gamma >$ 2 GeV. In Fig. 3b we present the photon energy spectrum. Neither of these distributions displays a significant unexpected structure. However, in the mass plot a small signal might disappear due to the combinatorial background. Using Monte Carlo simulations it can be shown that the highest signal-to-background ratio for a high mass X ($\mathrm{M_X} \gtrsim 65$ GeV) is obtained by considering the mass distribution of the two most energetic photons only. Similarly, the best result is obtained for a low mass X ($\mathrm{M_X} \lesssim 35$ GeV) by using the two least energetic photons; for intermediate masses the best results are obtained by using both the $\mathrm{M}\gamma_1\gamma_2$ and $\mathrm{M}\gamma_1\gamma_3$ distributions.

Not observing any significant signal, we can derive an upper limit on $\mathrm{BR(Z}\rightarrow \gamma\mathrm{X}, \mathrm{X} \rightarrow \gamma\gamma)$, as a function of $\mathrm{M_X}$. We make a Monte Carlo model to determine conservative selection efficiencies. The main features of this model are: (i) X is produced according to a $(1+\cos^2\theta)$ distribution; (ii) The mass distribution of X is either a delta-function, or a Breit-Wigner with a width of either 1 or 2 GeV.

We divide the data in energy bins and determine for each bin, using the number of observed and expected QED events, the 95% C.L. upper limit on the number of signal events. If the mass distribution of X is a delta-function, the bin size varies from 1 to 2.5 GeV as $\mathrm{M_X}$ varies from 0 to $\mathrm{M_Z}$; if X has a 1 GeV width, it varies from 3 to 4 GeV; and for the 2 GeV width case the bin size is taken as a fixed 6 GeV. From fully simulated Monte Carlo samples we determine the following signal efficiencies for the different mass regions: $(49 \pm 2)\%$ for $\mathrm{M}\gamma\gamma < 35$ GeV; $(53 \pm 2)\%$ for $\mathrm{M}\gamma\gamma > 65$ GeV; and $(35 \pm 1)\%$ for masses in between. The upper limit curves are shown in Fig. 4. We find $\mathrm{BR(Z}\rightarrow \gamma\mathrm{X}, \mathrm{X} \rightarrow \gamma\gamma) < 0.4$ to 1.3×10^{-5} for $3 \lesssim \mathrm{M_X} \lesssim 89$ GeV at 95% C.L. The mass restrictions are essentially due to our cuts. Again, in the upper limit calculation the error on the efficiency is accounted for by reducing the efficiency by its error.

$\mathrm{Z} \rightarrow \gamma\gamma\gamma$ via Magnetic Monopoles

To search for magnetic monopoles by $\mathrm{Z} \rightarrow \gamma\gamma\gamma$ we note that the cross section for this process is enhanced in the central detector region, whereas the QED background is strongly peaked in the forward direction. We therefore require: $|\cos\theta_\gamma| < 0.75$.

To determine the selection efficiency for monopole events, we made a simple generator based on ref. [4] (using ref. [12] for the phase space generation), which produces the expected photon energy spectrum and the photon polar angle distribution. As above, we require: $E\gamma_3/\sqrt{s} >$ 0.125. The efficiency is $(40.0 \pm 1.6)\%$. The distribution for $E\gamma_3/\sqrt{s}$ in the central detector region is shown in Fig. 5. We observe 7 events, whereas we expect (7.1 ± 0.7) from QED. For the branching ratio we find:

$$BR(\mathrm{Z} \rightarrow \gamma\gamma\gamma) < 0.8 \times 10^{-5} \tag{2}$$

at 95% C.L. This limit results in a lower mass limit on a monopole [4] of 510 GeV.

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† Deceased.

Figure Captions

- Figure 1 : A display of a $\gamma\gamma\gamma$ event in the inner L3 detector, shown along the beam axis. The photon energies are indicated.
- Figure 2 : The energy distribution for least energetic photon, the prediction from QED and the prediction [2,3] for a composite Z decaying directly into $\gamma\gamma\gamma$ (arbitrarily normalized).
- Figure 3a : The $\gamma\gamma$ invariant mass spectra for the observed $\gamma\gamma\gamma$ events (three entries/event) with $E_\gamma > 2$ GeV and the prediction from QED.
- Figure 3b : The photon energy spectrum (three entries/event) for the observed $\gamma\gamma\gamma$ events and the prediction from QED.
- Figure 4 : The upper limit on BR(Z$\rightarrow \gamma$X, X $\rightarrow \gamma\gamma$) as a function of M_X. The scalar particle X is assumed to have a mass distribution which is either a delta-function or a Breit-Wigner with a width of 1 or 2 GeV, produced with a $(1 + \cos^2\theta)$ polar angle distribution.
- Figure 5 : The energy distribution for the least energetic photon in $\gamma\gamma\gamma$ events for γ's in the central detector region ($|\cos\theta_\gamma| < 0.75$), the prediction from QED and the prediction (arbitrarily normalized) from the monopole model [4].

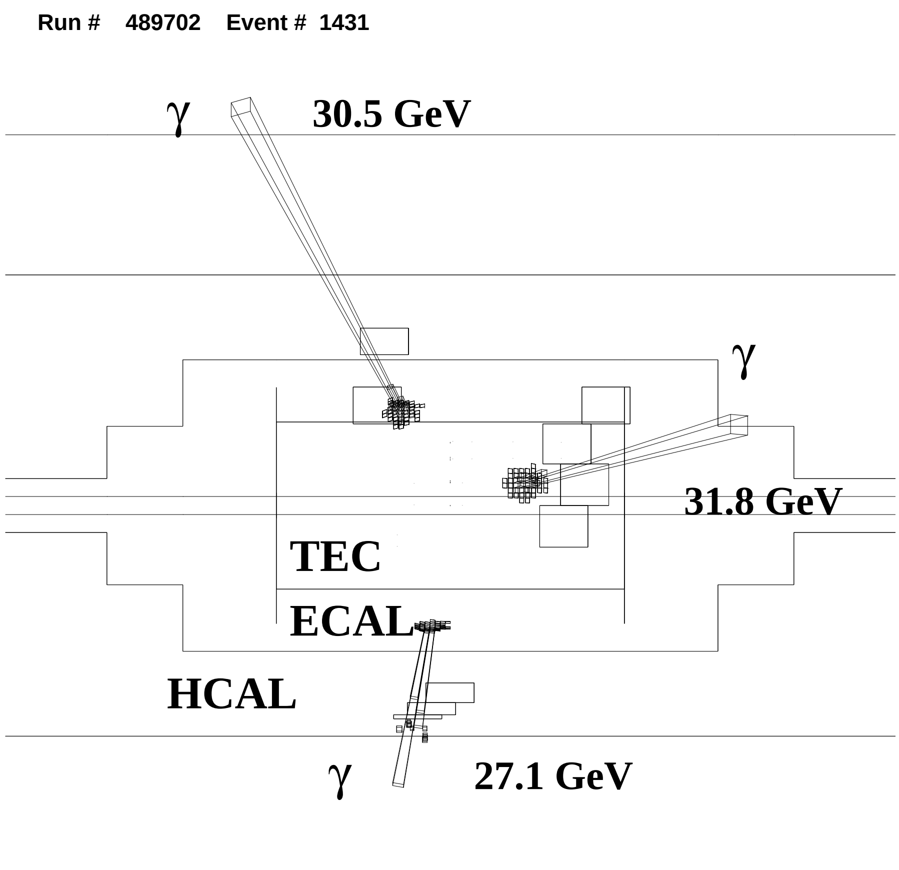
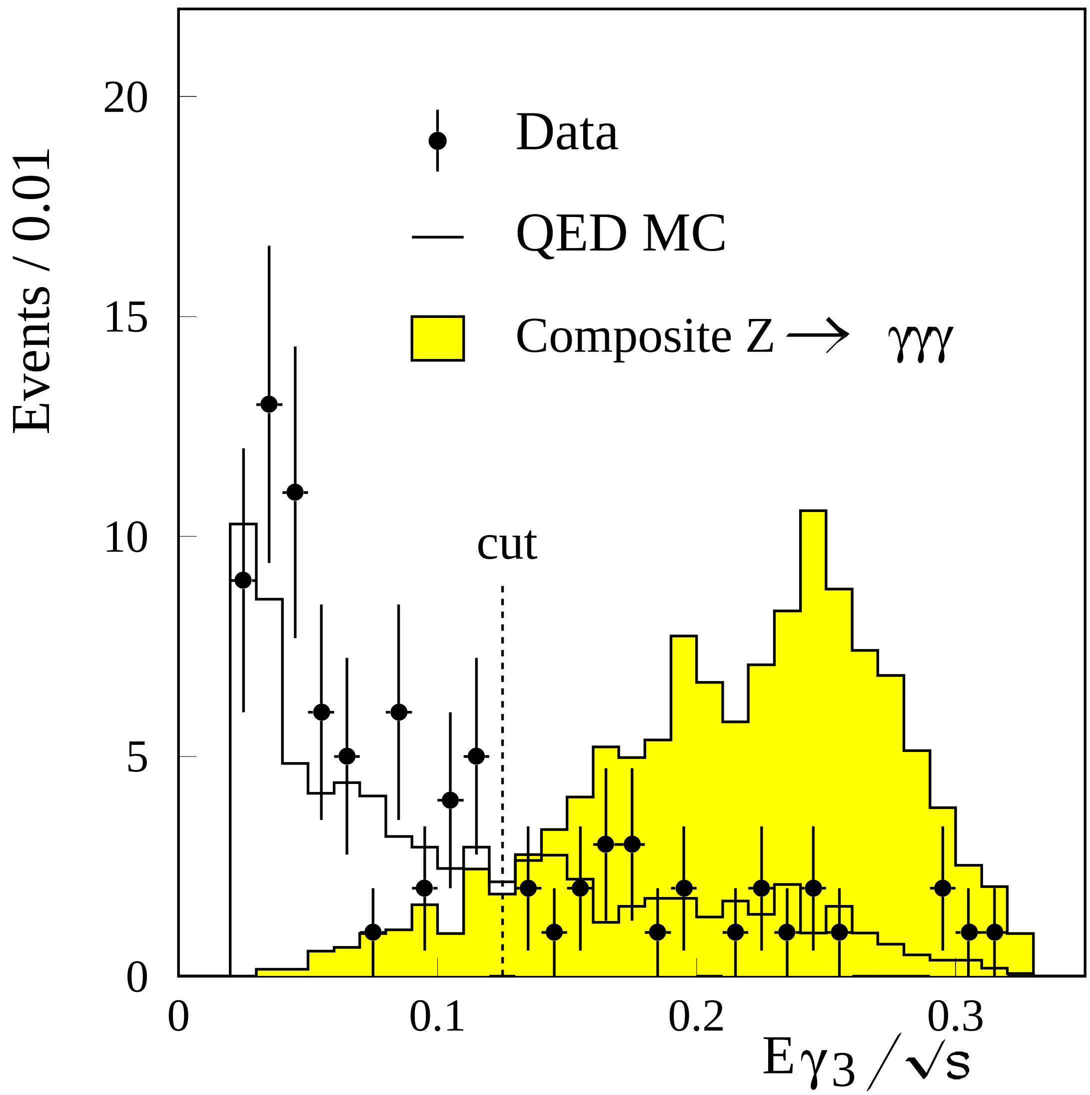

Run # 489702 Event # 1431
γ
30.5 GeV
γ
31.8 GeV
TEC
ECAL
HCAL
γ
27.1 GeV

Figure 1



Events / 0.01
20
15
10
5
0
0
0.1
0.2
0.3
Data
QED MC
Composite Z ⟶ γγγ
cut
$E_{\gamma_3}/\sqrt{s}$

Figure 2

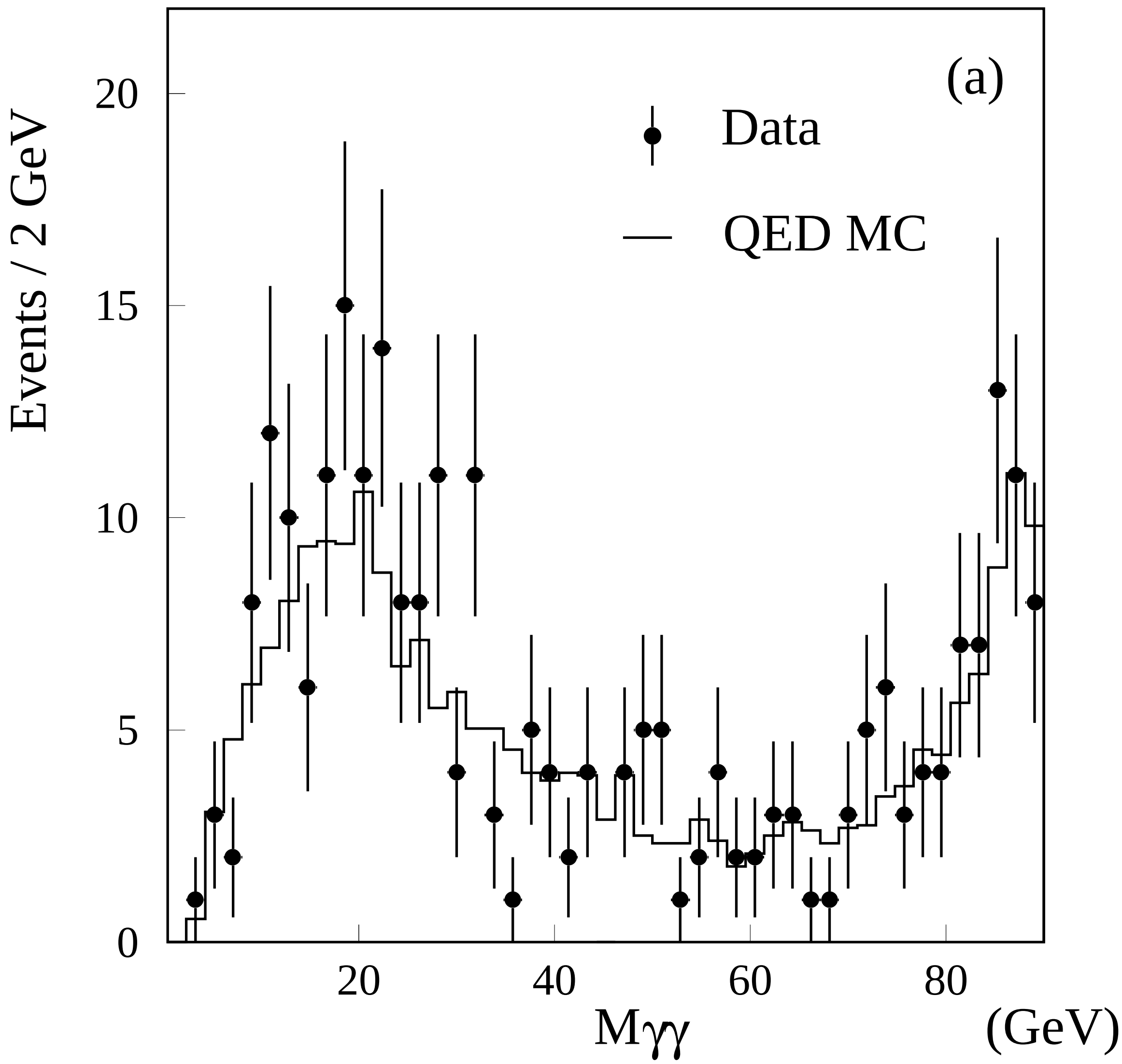


Figure 3a

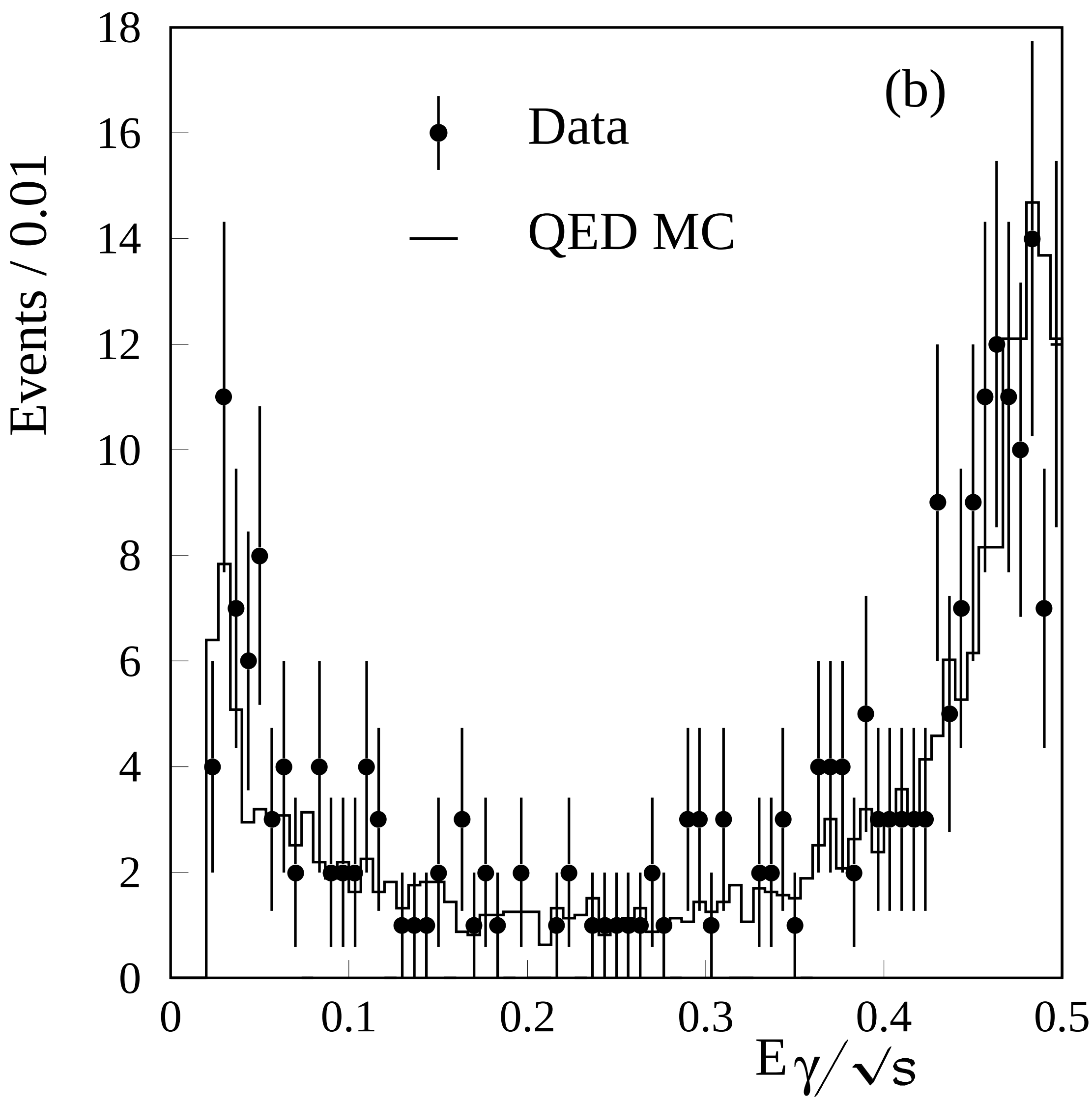


Figure 3b

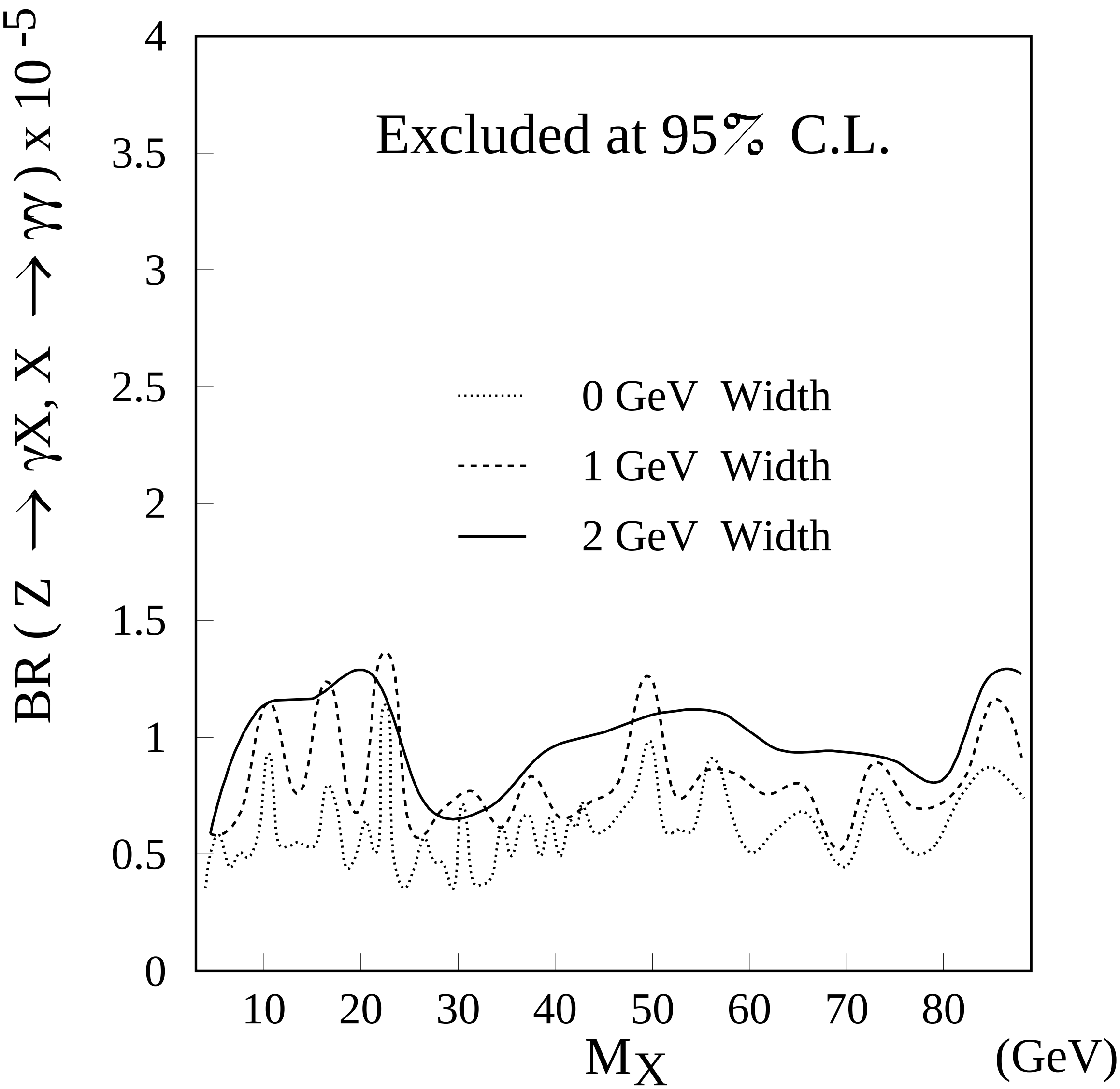

BR (Z → γX, X → γγ) x 10 -5
Excluded at 95% C.L.
0 GeV Width
1 GeV Width
2 GeV Width
4
3.5
3
2.5
2
1.5
1
0.5
0
10
20
30
40
50
60
70
80
MX
(GeV)

Figure 4

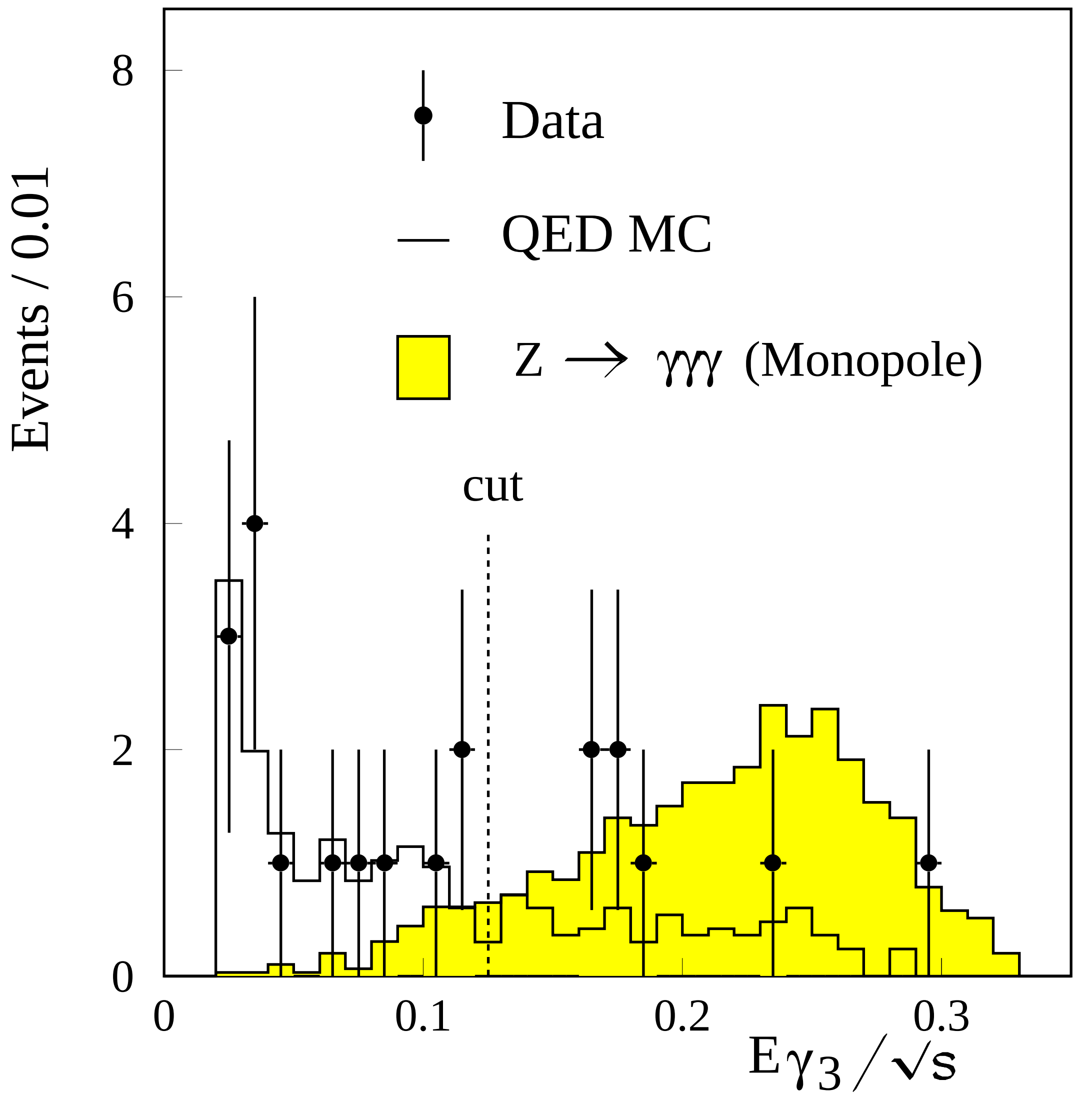


Figure 5