Limits on compositeness from lepton and photon channels at LEP ¹

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Abstract

Combined data of the four LEP experiments are used to set limits on non-standard processes. A total width of a new process larger than 36 MeV and an invisible width larger than 16 MeV are excluded at 95 % confidence level from Z lineshape parameters. Limits are given on masses and couplings of excited leptons: e^* , μ^* , τ^* and ν^* , on the QED cutoff parameter Λ , and on the branching ratios of Z decays into $\pi^0\gamma$, $\eta\gamma$ and $\gamma\gamma\gamma$. No evidence for an anomalous $Z\gamma\gamma\gamma$ coupling is found.

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1 Introduction

Compositeness is a possible solution to standard model puzzles such as the fermion spectrum and mass generation. It supposes an underlying structure of fermions and perhaps also of gauge bosons. Effects of this substructure are expected to be manifest at a large energy Λ called the compositeness scale, but could be detectable in precision experiments at much lower energies. Clean and precise measurements at LEP provide a good opportunity to search for compositeness effects and to tighten existing limits on excited particles masses and couplings. Recent reviews of the LEP data on compositeness can be found in [1]. The present paper concentrates on some aspects where results from four LEP experiments can be combined and better limits obtained. The following subjects are discussed:

- limits on allowed exotic Z decay widths from Z lineshape measurements,
- search for deviations from QED in the reaction $e^+e^- \rightarrow \gamma\gamma$,
- search for excited leptons and limits on their couplings to ordinary leptons and gauge bosons,
- limits on Z decays into $\pi^0\gamma$ and $\eta\gamma$,
- search for an anomalous $Z\gamma\gamma\gamma$ coupling.

2 Width limits from Z lineshape

Although Z lineshape parameters measured at LEP agree very well with standard model predictions, some room is still left for non-standard Z decay modes. In this section the maximum allowed width for such decays is estimated taking into account experimental errors and uncertainties in theoretical predictions..

Standard model predictions are calculated [2] allowing the parameters to vary within the following ranges: $89 < m_t < 200 \text{ GeV}/c^2$, $50 < m_{\text{Higgs}} < 1000 \text{ GeV}/c^2$, $0.107 < \alpha_s(m_Z) < 0.123$. The range of α_s is the one standard deviation limit of the all-LEP average obtained from jet rates, energy correlations and event shapes [3].

The Z lineshape parameters used in this analysis are the averages [4] of the values determined by the individual LEP experiments from fits to hadron and lepton cross sections. The following variables are considered: the total width Γ_Z , the hadronic peak cross section σ_h^0 , the hadron to lepton width ratio R and the ratio of invisible to leptonic width. The allowed range of each variable is determined at 95% confidence level, assuming a gaussian measurement error and restricting the physical region by a theoretical bound defined as the most conservative standard model prediction for this variable. The results are then translated into a limit on the allowed width Γ^X of a new channel following the method described in detail in ref. [5].

The maximum allowed width of a non-standard channel is $\Gamma^X = 36 \text{ MeV}$, corresponding to a 1.5% limit on the branching ratio. This result is derived from the total Z width and valid for any decay mode. The variables σ_h^0 and R allow limits to be deduced on Γ^X as a function of topological branching ratios x_h , x_l and x_{inv} , satisfying $x_h + x_l + x_{inv} = 1$, defined as the fraction of X decays which would be classified as hadronic, leptonic or neither

by experimental selection criteria. Fig. 1 (a) shows the contour lines of Γ^X in the plane x_l, x_h . In Figs 1 (b) and (c) the limit is plotted as a function of x_h and x_l , respectively.

Figure 1: Limits at 95% c.l. on the width of a new process as a function of topological hadronic and leptonic branching ratios.

From the measurement of the width ratios Γ_{inv}/Γ_l the maximum allowed “invisible” width is derived: $\Gamma_{inv} = 0.1 \cdot \Gamma_\nu = 16 \text{ MeV}$.

Table 1 summarises the limits on widths and branching ratios for some distinct topologies, obtained from the Z lineshape. To a large extent, the sensitivity of the method is limited by uncertainties of the standard model predictions.

Topology	Source	Width limit (MeV)	Br.ratio limit (%)
any	Γ_t	36	1.5
non-hadronic	σ_h^0	18	0.7
purely leptonic	R	2	0.1
invisible	Γ_{inv}/Γ_l	16	0.7

Table 1: Maximum allowed values of widths and branching ratios for non-standard Z decays, at 95 % c.l., derived from Z lineshape parameters measured by LEP.

3 Excited fermion mass limits

Results presented in the previous section are now used to extract limits on excited fermion masses. The decay of the Z boson into a pair of excited fermions is expected to proceed via the standard model couplings. The variation of the $Z \rightarrow f^* \bar{f}^*$ width with f^* mass is

plotted in fig 2 for excited quarks, charged leptons and neutrinos of Dirac and Majorana types. The prediction of the model of Hagiwara et al [6] for ν^* is also shown.

Figure 2: Variation of the width $Z \rightarrow f^* \bar{f}^*$ as a function of f^* mass. The horizontal lines show the total, non-hadronic and invisible width limits.

Table 2 gives the mass limits inferred from the total width limit which are therefore valid independent of excited fermion decay topology. A fourth Dirac-type neutrino giving an incoherent contribution to the Z width is excluded for masses up to $43.7 \text{ GeV}/c^2$, and that of Majorana type up to $36.4 \text{ GeV}/c^2$. More stringent limits on excited lepton masses given in the last column of the table are deduced under the assumption that their decays are purely radiative; however this popular assumption could be false [7].

Excited fermion	any decay topology	topology-dependent limit
u-type quark	41.7	-
d-type quark	44.7	-
charged lepton	29.8	36.7
Dirac neutrino	43.7	45.2
Majorana neutrino	36.4	40.5
neutrino of Hagiwara et al. [6]	45.4	45.5

Table 2: Limits on excited fermion masses in GeV/c^2 . Masses between 0 and the value given in the table are excluded at 95% confidence level. The first limit is valid for any decay mode, the second one assumes radiative decays of excited leptons.

4 Search for deviations from QED

The reaction $e^+e^- \rightarrow \gamma\gamma$ provides a clean test of QED since it is dominated by purely electromagnetic processes. The four LEP collaborations [5,8,9,10] have measured the angular distribution and have compared it with the theoretical predictions calculated up to order α^3 [11]. fig. 3 shows the ratio of measured to expected signal as a function of $\cos \theta$ from each experiment. The errors plotted in the figure are statistical; in addition there is a small systematic normalisation error. Good agreement between QED and the data is observed.

Figure 3: Angular distributions for the reaction $e^+e^- \rightarrow \gamma\gamma$.

The angular distributions measured by the four experiments, expressed in terms of the number of events, were combined. Similarly, the distributions of expected number of QED events after detector simulation and selection cuts, estimated by each experiment,

were also combined. The ratio of the obtained angular distributions is plotted in fig.4. No systematic deviation from QED is seen. The total number of detected events is 634 while 611 are expected. The overall normalisation error for the combined sample is taken as the sum of systematic errors of individual experiments; the relative error is $\Delta n = 2.4\%$.

Figure 4: Angular distribution of $e^+e^- \rightarrow \gamma\gamma$. The curves correspond to the maximum allowed values of the QED cutoff parameters $\Lambda_+^{\text{QED}} = 114 \text{ GeV}$, $\Lambda_-^{\text{QED}} = 140 \text{ GeV}$ at 95% c.l.

A new interaction would modify the differential cross section as follows [12] :

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s} \frac{1 + \cos^2 \theta}{1 - \cos^2 \theta} \left(1 \pm \frac{s^2}{2(\Lambda_{\pm}^{\text{QED}})^4} (1 - \cos^2 \theta) \right)$$

where $\Lambda_{\pm}^{\text{QED}}$ is called the QED cutoff parameter. The limit on $\Lambda_{\pm}^{\text{QED}}$ is set by the maximum likelihood fit assuming the Poisson probability of observing $N^{\text{DATA}}(k)$ events while $N^{\text{QED}}(k)$ are predicted in the $\cos \theta$ bin k . The likelihood function has the form

$$\mathcal{L} = \frac{1}{\sqrt{2\pi}\Delta n} \exp \left(-\frac{1}{2} \left(\frac{1-n}{\Delta n} \right)^2 \right) \prod_{k=1}^{10} P(N^{\text{DATA}}(k), n, N^{\text{QED}}(k)).$$

The overall normalisation factor n was allowed to vary in the fit with the standard deviation Δn . The predicted number of events integrated over the bin k is given by the expression

$$N^{\text{QED}}(k) = \sum_{i=1}^7 N_i^{\text{QED}}(k, s_i) \left(1 + \epsilon \frac{s_i^2}{2} f(k) \right),$$

where $f(k) = \int (1 + \cos^2 \theta) d\cos \theta / \int ((1 + \cos^2 \theta)/(1 - \cos^2 \theta)) d\cos \theta$ and the integrals are calculated over the $\cos \theta$ bin k . In order to calculate $N_i^{\text{QED}}(k, s_i)$, the expected number of

QED events is determined by each experiment is distributed over the seven LEP energy points according to a $1/s$ law and to the collected luminosities. The QED cutoff parameter is replaced in the fit by $\epsilon = 1/(\Lambda_{\pm}^{\text{QED}})^4$ since the error on ϵ is expected to have a distribution close to gaussian. The fit gives $\epsilon = (0.14_{-0.40}^{+0.44}) \cdot 10^{-8} \text{GeV}^{-4}$ where the errors are one-sided 95% c.l. limits. This excludes the values of the QED cutoff parameters smaller than

$$\Lambda_{+}^{\text{QED}} = 114 \text{ GeV}, \quad \Lambda_{-}^{\text{QED}} = 140 \text{ GeV}.$$

The corresponding curves showing the maximum allowed deviations from QED are drawn in fig. 4. The limits obtained are better than those reported in e^+e^- experiments at lower energies (for a complete list of references see [5]). The improvement with respect to individual LEP experiments is small since the limit on Λ^{QED} increases proportionally to the number of events to the power $1/8$. For this reason, no significant update is expected to come from LEP in the near future.

5 Excited leptons

Excited lepton mass limits determined from the Z width limits in Section 2 can be improved by direct searches of Z decays into an excited lepton pair. Negative searches for the final states $\ell^*\bar{\ell}^* \rightarrow \ell\bar{\ell}\gamma\gamma$ and $\nu^*\bar{\nu}^* \rightarrow \nu\bar{\nu}\gamma\gamma$ reported at LEP [1] push the excited lepton mass limits up to about $m_Z/2$, provided that ℓ^* and ν^* decays are radiative.

Single production of excited fermions at LEP extends the range of accessible masses almost up to the Z mass and allows for the first time a study of the couplings of excited leptons to the Z boson, $Z\ell^*\ell$ and $Z\nu^*\nu$. The transition between excited and ordinary fermions is assumed to be magnetic and inversely proportional to the parameter Λ called the compositeness scale [13]. In the $SU(2) \times SU(1)$ invariant model (ref.[6]), the couplings c of leptons to the gauge bosons γ , Z or W are expressed in terms of two unknown parameters f and f' , and of the Weinberg angle θ_W :

$$\begin{aligned} c_{\gamma\ell^*\ell} &= -\frac{1}{4}(f + f') & c_{\gamma\nu^*\nu} &= \frac{1}{4}(f - f') \\ c_{Z\ell^*\ell} &= -\frac{1}{4}(f \cot \theta_W - f' \tan \theta_W) & c_{Z\nu^*\nu} &= \frac{1}{4}(f \cot \theta_W + f' \tan \theta_W). \\ c_{W\nu^*\ell} = c_{W\ell^*\nu} &= \frac{f}{2\sqrt{2} \sin \theta_W} \end{aligned}$$

In this model the differential cross section for the reaction $e^+e^- \rightarrow \ell^*\bar{\ell} + \ell\bar{\ell}^*$ via the dominant process of s-channel Z exchange is

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{s} \frac{c_{Z\ell^*\ell}^2}{\Lambda^2} \frac{1}{|D_Z(s)|^2} \left[(a^2 + b^2) (m^{*2}(s - m^{*2}) + 2tu) + 4ab m^{*2}(t - u) \right],$$

where $|D_Z(s)|^2 = (s - m_Z^2)^2 + m_Z^2\Gamma_Z^2$, a and b are the standard model couplings of the electron: $a = (4 \sin \theta_W \cos \theta_W)^{-1}$, $b = (1 - 4 \sin^2 \theta_W)(4 \sin \theta_W \cos \theta_W)^{-1}$. The same expression is valid for ν^* production, with $c_{Z\ell^*\ell}$ replaced by $c_{Z\nu^*\nu}$.

Excited leptons can decay into a photon or a virtual Z or W boson, with unknown probabilities. Therefore results of direct searches provide limits on the quantity $(c/\Lambda)B^{1/2}$, where B is the branching ratio for the studied excited lepton decay mode.

Excited charged leptons were searched for by all LEP collaborations in the reaction $e^+e^- \rightarrow \ell^*\bar{\ell} + \ell\bar{\ell}^* \rightarrow \ell\bar{\ell}\gamma$, where $\ell = e, \mu$ or τ . No ℓ^* signal has been found, the data being compatible with the expected background from radiative lepton pair production. Limits were extracted on $Z\ell^*\ell$ coupling versus the ℓ^* mass m^* for masses almost up to the kinematical limit. The quantity on which the limit is set was not the same for each group and the relation $f = f'$ was assumed in most cases. All results can be interpreted as a limit on $k(c_{Z\ell^*\ell}/\Lambda)B^{1/2}(\ell^* \rightarrow \ell\gamma)$, with the following values of k : $k = 4/(\cot\theta_W + \tan\theta_W) = 3.15$ in references [14] and [15], $k = 2\sqrt{2}/(\cot\theta_W + \tan\theta_W)$ in [16] and [17], and $k=1$ in [5]. The advantage of expressing the results in terms of the coupling $c_{Z\ell^*\ell}$ rather than f/Λ is that the assumption $f = f'$ is avoided. When the limits are brought to the common form, they are similar. For example, for $m^* = 50 \text{ GeV}/c^2$, the best limits on $(c_{Z\ell^*\ell}/\Lambda)B^{1/2}(\ell^* \rightarrow \ell\gamma)$ are $(7 \text{ TeV})^{-1}$ for e^* and μ^* , and $(5 \text{ TeV})^{-1}$ for τ^* , at 95% confidence level. Results published by the LEP experiments cannot be easily combined since the $\ell\gamma$ mass resolution is generally different in each experiment.

Searches for excited neutrinos in the reaction $e^+e^- \rightarrow \nu^*\bar{\nu} + \nu\bar{\nu}^* \rightarrow \nu\bar{\nu}\gamma$ were published by two LEP collaborations. No ν^* candidates were found and thus the limits corresponding to 3 observed events were set on $k(c_{Z\nu^*\nu}/\Lambda)B^{1/2}(\nu^* \rightarrow \nu\gamma)$, with $k = 1$ in [18,5] and $k = 2\sqrt{2}$ in [19]. After redefining the latter with $k = 1$, the two limits (denoted L_1 and L_2) are combined according to the formula $L^{-2} = L_1^{-2} + L_2^{-2}$ and the result is plotted in fig.5 as a function of the ν^* mass.

Figure 5: Limits on the excited neutrino coupling to the ordinary neutrino and the Z boson at 95% c.l..

The values of $(c_{Z\nu^*\nu}/\Lambda)B^{1/2}(\nu^* \rightarrow \nu\gamma)$ larger than $(10 \text{ TeV})^{-1}$ are excluded for ν^* masses around $50 \text{ GeV}/c^2$; the limit is weaker for higher m^* masses. The L3 collaboration has also searched for ν^* decays into an electron and a virtual W boson, and obtained the limit curve shown in the same figure. No searches are reported yet on excited leptons

decaying via a virtual Z boson.

The $e^*e\gamma$ coupling can be studied at LEP by looking for excited electrons produced via photon exchange in the t -channel. This process leads to a specific topology $e(e)\gamma$, where one of the electrons is emitted at a very small angle and escapes detection. The t -channel cross section for reaction $e^+e^- \rightarrow e^*\bar{e} + e\bar{e}^*$ is [20,6]:

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{s} \frac{c_{\gamma e^*e}^2}{\Lambda^2} \frac{1}{st} [2us + m^{*2}(s - m^{*2}) - 2m_e^2 m^{*4}/t].$$

Previously, searches for excited electrons were reported by e^+e^- experiments at lower energies where both topologies, $ee\gamma$ and $e(e)\gamma$ are dominated by photon exchange in the s and t channels respectively. The limits on the $e^*e\gamma$ coupling were expressed in terms of the parameter $\lambda/m^* \equiv \sqrt{2}c_{\gamma e^*e}/\Lambda$.

LEP data are compatible with the expected background of virtual Compton scattering and extend the existing limits to e^* masses up to 90 GeV/ c^2 . When expressed in the form $k(\lambda/m^*)B^{1/2}(e^* \rightarrow e\gamma)$, the limits published by the LEP collaborations correspond to the following values of k : $k = 1$ in references [16], [17] and [14], $k = \sqrt{2}$ in [15] and $k = 1/\sqrt{2}$ in [5]. Again the limits are similar and cannot be easily combined. The most stringent limit for $m^* = 50$ GeV/ c^2 is $(\lambda/m^*)B^{1/2}(e^* \rightarrow e\gamma) < (2 \text{ TeV})^{-1}$.

Excited electron masses can be explored beyond the kinematic limit of single e^* production since the virtual e^* exchange is expected to contribute to the reaction $e^+e^- \rightarrow \gamma\gamma$ and to modify the angular distribution predicted by QED as follows [12]:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s} \frac{1 + \cos^2 \theta}{1 - \cos^2 \theta} \left(1 + \frac{s^2}{2} \left(\frac{\lambda}{m^{*2}} \right)^2 (1 - \cos^2 \theta) H(\cos \theta) \right)$$

where

$$H(\cos \theta) = \left(1 + \frac{s}{2m^{*2}} \frac{1 - \cos^2 \theta}{1 + \cos^2 \theta} \right) \left(\left(1 + \frac{s}{2m^{*2}} \right)^2 - \left(\frac{s}{2m^{*2}} \right)^2 \cos^2 \theta \right)^{-1}.$$

The cross section depends on two unknown parameters, the e^* mass m^* and the previously discussed parameter λ . A limit on λ/m^* is set for several fixed values of m^* using a maximum likelihood fit to the combined $\gamma\gamma$ angular distribution. The fitting technique was similar to that described in section 4. As an example, fig. 6 shows the results of the fit for $m^* = 100$ GeV/ c^2 ; the curve represents the maximum allowed contribution of the e^* propagator at 95 % c.l..

The boundary of the excluded region in the plane λ/m^* versus m^* is plotted in fig. 7 together with the curve $\lambda = 1$ considered as an upper limit of the validity of the model. The intersection point corresponds to $m^* = 114$ GeV/ c^2 . The LEP curve is slightly more stringent than the best previous limit from CELLO [21]. Opal has reported [10] a limit valid up to $m^* = 116$ GeV/ c^2 obtained using the full formula of ref.[12].

Figure 6: Angular distribution of $e^+e^- \rightarrow \gamma\gamma$ for combined LEP data. The curve shows the maximum allowed contribution (at 95% c.l.) due to the t-channel exchange of an excited electron of mass $100 \text{ GeV}/c^2$.

Figure 7: Limits on the excited electron coupling to the ordinary electron and the photon at 95% c.l. from combined LEP data on the reaction $e^+e^- \rightarrow \gamma\gamma$.

6 Z decays into $\pi\gamma$ and $\eta\gamma$

Z decays into a pseudoscalar and a vector particle are expected to occur with a probability of 10^{-9} . However recently several authors [22] have discussed the possibility that the branching ratio may be considerably larger and thus detectable at LEP. The final states $\pi^0\gamma$ and $\eta\gamma$ are indistinguishable from $\gamma\gamma$ (unless a refined analysis is performed [5]), and would show up as a resonant peak on the top of the smooth $1/s$ variation of the $\gamma\gamma$ cross section expected from QED. The data collected by the four LEP collaborations [5,8,9,10] are presented in fig.8 in the form of the ratio of the measured to expected number of events.

Figure 8: Energy variation for the reaction $e^+e^- \rightarrow \gamma\gamma$.

The combined data are shown in figure 9. The curve shows the maximum allowed resonant contribution determined by the likelihood method at 95% c.l. Taking into account the combined detection efficiency (39% for $\pi^0\gamma$ and 21% for $\eta\gamma$), the result is translated into upper limits on the branching ratios:

$$BR(Z \rightarrow \pi^0\gamma) < 1.3 \cdot 10^{-4}, \quad BR(Z \rightarrow \eta\gamma) < 1.9 \cdot 10^{-4}.$$

Figure 9: Energy variation for the reaction $e^+e^- \rightarrow \gamma\gamma$ for combined LEP data. The curve shows the maximum allowed contribution of Z decay into $\pi\gamma$ or $\eta\gamma$.

A better limit on the $\eta\gamma$ decay mode is found in ref [5]: $BR(Z \rightarrow \eta\gamma) < 5.1 \cdot 10^{-5}$. The result is based on the measurement of the shape of electromagnetic energy deposits, expected to be wider for neutrals from η decay than for single photons. In addition, an improvement comes from a negative search for the decay channel $\eta \rightarrow \pi^+\pi^-\pi^0$.

7 Search for an anomalous $Z\gamma\gamma\gamma$ coupling

If the Z boson is composite, then new couplings can generate anomalous Z decays or considerably enhance decays allowed by the standard model. The $Z \rightarrow \gamma\gamma\gamma$ decay branching ratio is predicted by the standard model to be 10^{-9} [23]. It may become significantly higher if the Z is a bound state of its charged subconstituents or if a new 4-boson interaction described by a residual contact term occurs with sufficient strength [24,25].

The four LEP collaborations [5,8,9,10] have detected 24 $\gamma\gamma\gamma$ events while 24.7 are expected from the QED calculation based on the Monte Carlo generator of ref.[11] and detector simulation. The energy variation of the cross section for the combined data is

shown in fig.10. No anomaly is observed. A maximum likelihood fit is performed assuming an incoherent mixture of QED and of resonant Z contribution. The curve in fig.10 indicates the maximum signal compatible with the data. The limit on the $Z \rightarrow \gamma\gamma\gamma$ decay branching ratio at 95% c.l. is $BR(Z \rightarrow \gamma\gamma\gamma) < 2.4 \cdot 10^{-5}$.

Figure 10: Energy variation for the reaction $e^+e^- \rightarrow \gamma\gamma\gamma$ for combined LEP data. The curve shows the maximum allowed contribution of Z decay into $\gamma\gamma\gamma$.

When a contact $Z\gamma\gamma\gamma$ coupling is assumed [24] and experimental cuts are optimised, then a better limit is obtained in ref. [5]:

$$BR(Z \rightarrow \gamma\gamma\gamma) < 1.9 \cdot 10^{-5}.$$

It corresponds to a limit of $\Lambda > 24.4$ GeV for the compositeness scale.

8 Conclusions

The measurements of the Z lineshape parameters at LEP lead to the following limits on non-standard Z decays at 95 c.l.:

$$\Gamma^{tot} < 36 \text{ MeV}, \quad \Gamma^{inv} < 16 \text{ MeV},$$

where the first result is independent of the decay mode(s), and the second refers to “invisible” decays.

The maximum allowed mass of a heavy neutrino giving an incoherent contribution to the Z width and having purely neutral decays is $45.2 \text{ GeV}/c^2$ for the Dirac-type ν and $40.5 \text{ GeV}/c^2$ for the Majorana type ν .

A test of QED was performed using the reaction $e^+e^- \rightarrow \gamma\gamma$. Possible deviations were parametrised by the QED cut-off parameter Λ^{QED} and a 95% c.l. limit on this parameter was deduced from the combined angular distribution data of four LEP collaborations:

$$\Lambda_+^{\text{QED}} = 114 \text{ GeV}, \quad \Lambda_-^{\text{QED}} = 140 \text{ GeV}.$$

No evidence has been found for pair-produced excited leptons. This excludes the mass region up to about half of the Z mass, under the assumption of purely radiative decays of excited leptons.

LEP has set first limits on the couplings of excited charged and neutral leptons to the ordinary ones and the gauge boson Z , and has extended existing limits on the $e^*e\gamma$ coupling to the mass region up to $90 \text{ GeV}/c^2$. For excited leptons of mass $m^* = 50 \text{ GeV}/c^2$ the best limits at 95 % c.l. are:

$$\begin{aligned} (c_{Ze^*e}/\Lambda)B^{1/2}(e^* \rightarrow e\gamma) &< (5 \text{ TeV})^{-1}, \\ (c_{Z\mu^*\mu}/\Lambda)B^{1/2}(\mu^* \rightarrow \mu\gamma) &< (5 \text{ TeV})^{-1}, \\ (c_{Z\tau^*\tau}/\Lambda)B^{1/2}(\tau^* \rightarrow \tau\gamma) &< (7 \text{ TeV})^{-1}, \\ (c_{Z\nu^*\nu}/\Lambda)B^{1/2}(\nu^* \rightarrow \nu\gamma) &< (10 \text{ TeV})^{-1}, \\ (\lambda/m^*)B^{1/2}(e^* \rightarrow e\gamma) &< (2 \text{ TeV})^{-1}. \end{aligned}$$

Searches for the effects of the e^* propagator in the reaction $e^+e^- \rightarrow \gamma\gamma$ have led to improved limits on the $e^*e\gamma$ coupling in the e^* mass region up to $116 \text{ GeV}/c^2$.

The energy variation of the cross section for the reactions $e^+e^- \rightarrow \gamma\gamma$ and $e^+e^- \rightarrow \gamma\gamma\gamma$ shows no deviation from QED. Upper limits on the branching ratios of rare Z decays are (at 95% c.l.):

$$\begin{aligned} BR(Z \rightarrow \pi^0\gamma) &< 1.3 \cdot 10^{-4}, \\ BR(Z \rightarrow \eta\gamma) &< 5.1 \cdot 10^{-5}, \\ BR(Z \rightarrow \gamma\gamma\gamma) &< 1.9 \cdot 10^{-5}. \end{aligned}$$

No evidence for an anomalous $Z\gamma\gamma\gamma$ coupling is found.

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