# LEP 2 $e^+e^- \to f\overline{f}$, $\gamma\gamma(\gamma)$: results and interpretations

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Results on LEP 2 $e^+e^- \to f\overline{f}$ and $\gamma\gamma(\gamma)$ production are presented. These are compared with Standard Model predictions, and then used to set limits on various New Physics models, including Low Scale Gravity. Finally the status of the LEP beam energy determination from radiative return events is summarised.

## 1 Introduction

During the LEP 2 programme of 1995–2000 approximately $700\,\mathrm{pb}^{-1}$ per experiment were collected at $e^+e^-$ centre-of-mass energies between 130 and 207 GeV. How this integrated luminosity was distributed is indicated in figure 1. As well as allowing precise studies of 4 fermion final states, and the search for the Higgs boson and supersymmetry, these data have been exploited in the examination of 2 fermion and hard gamma production, and it is this work which is reported here. A collection of final and preliminary results are presented, and these are interpreted in the context of the Standard Model and alternative theories.

### *1.1 Selection*

The topologies of the $q\overline{q}$, $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ and $\gamma\gamma\,(\gamma)$ final states are sufficiently distinctive for samples to be selected with high efficiency and purity. With these samples cross-sections, forward-backward asymmetries, and differential cross-sections have been measured. Within the $q\overline{q}$ sample, lifetime information from vertex detectors, together with other discriminating variables, has been used to isolate $b\overline{b}$ and $c\overline{c}$ events. These have been used to measure the heavy quark branching ratios $R_{b,c} = \sigma_{b\overline{b},\,c\overline{c}}/\sigma_{q\overline{q}}$ and corresponding forward-backward asymmetries, $A_{\mathrm{FB}}^{b,c}$.

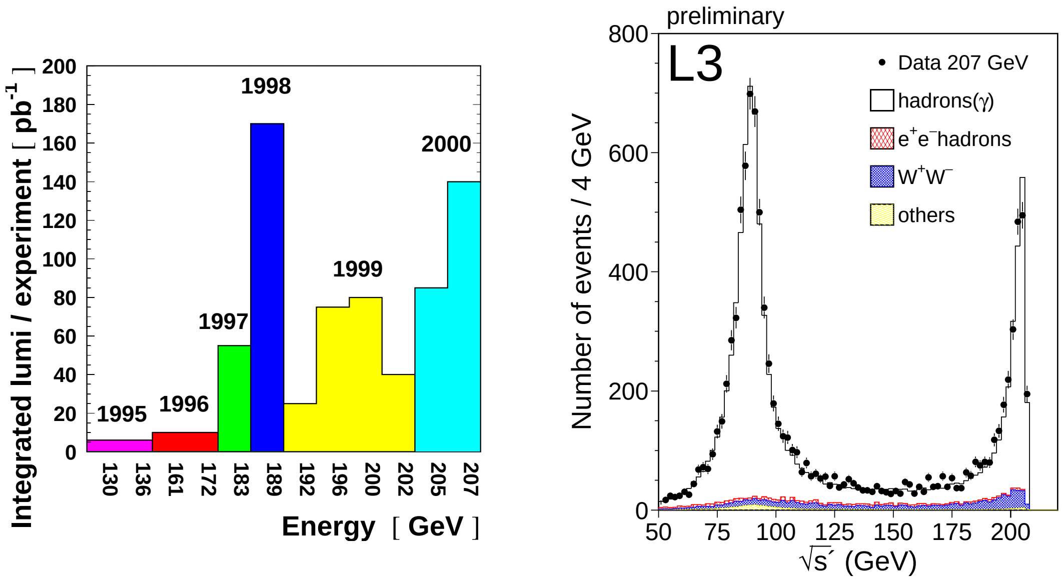


Figure 1: Left: approximate integrated luminosity at LEP 2. Right: example $\sqrt{s'}$ distribution in the $q\overline{q}$ channel.

### *1.2 $s'$ reconstruction*

At LEP 2 energies the emission of initial photons is very probable. Therefore the variable $\sqrt{s'}$ is defined, which is the centre-of-mass energy of the $e^+e^-$ system after initial state radiation. Experimentally this is reconstructed from the direction of the final state fermions, under the assumption that a single photon was emitted undetected along the beam pipe. More sophisticated treatments allow for the emission of multiple photons and account for any observed radiation. The resulting spectrum in $\sqrt{s'}$ is shown in figure 1 for the L3 $q\overline{q}$ analysis. Two clear peaks are visible: that at $\sqrt{s'} \sim \mathrm{m_Z}$ comes from the so-called *radiative return* events, whereas that at $\sqrt{s'} \sim \sqrt{s}$ consists of high energy, *non-radiative* events. It is the non-radiative events which are of most interest in testing the Standard Model and other theories. In contrast, the radiative return events are used as a calibration tool, as explained in section 4

### *1.3 LEP wide combination*

To achieve the best possible precision, efforts have been made to average the published and preliminary results of the 4 collaborations. This has been done for all the avaliable $\mu^+\mu^-$, $\tau^+\tau^-$, $q\overline{q}$ and heavy quark cross-section and asymmetry measurements. In performing this average careful attention has to be paid to correlated systematics, and to ensuring that the signal definition is the same between the experiments. (The latter requirement is not always satisfied, for instance in the definition of non-radiative samples or $\sqrt{s'}$. In this case appropriate corrections have been applied prior to combination.)

Table 1 shows the precision now achieved for the three most important cross-section measurements, expressed in terms of deviation from the Standard Model prediction. The total experimental uncertainty is given, and the corresponding uncertainty coming from theory. The fact that the theoretical uncertainties are small is the result of much effort invested at the time of the LEP 2 Monte Carlo workshop [1]. At present the corresponding uncertainties in the $e^+e^-$ channel are more significant at $\sim 2\%$, and therefore no LEP wide combination as yet been performed. The total uncertainty on the asymmetries are dominated by statistics, and are 0.012

Table 1: Approximate LEP wide precision on 2-fermion cross-sections.

| Uncertainty | $q\overline{q}$ | $\mu^+\mu^-$ | $\tau^+\tau^-$ |
|---|---|---|---|
| Experimental | 1.0 % | 1.6 % | 2.2 % |
| Theoretical | 0.3 % | 0.4 % | 0.4 % |

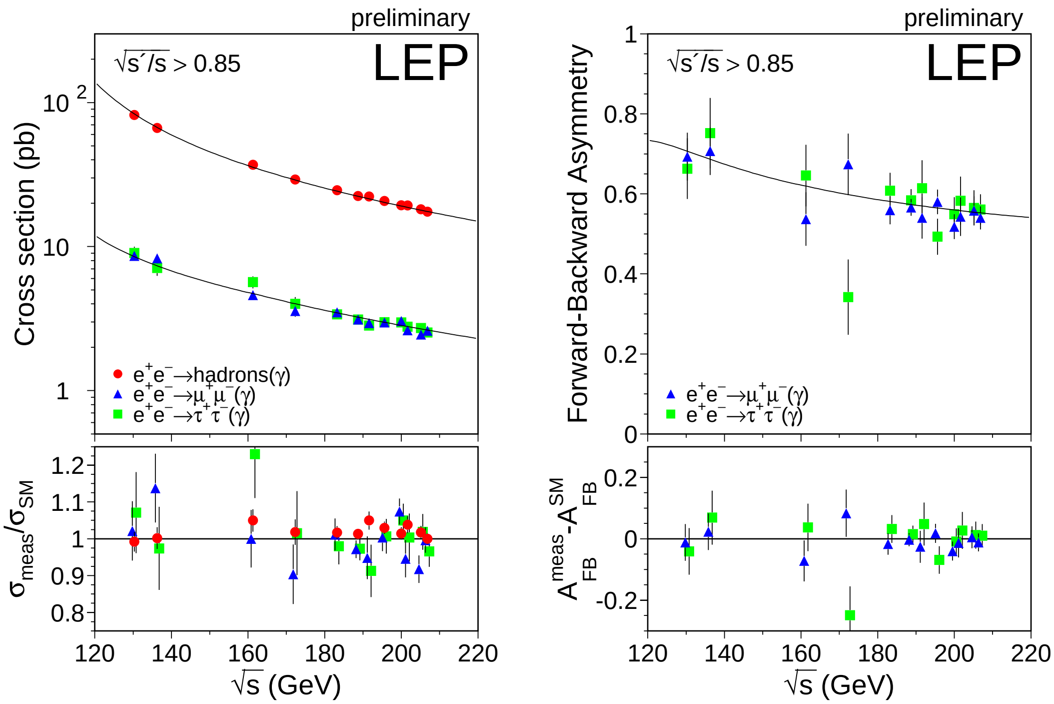


Figure 2: Cross-section results for the channels $e^+e^- \to q\overline{q}$, $\mu^+\mu^-$ and $\tau^+\tau^-$, and forward-backward asymmetries for $e^+e^- \to \mu^+\mu^-$ and $\tau^+\tau^-$, all with $\sqrt{s'/s} > 0.85$.

for the muons and 0.015 for the taus.

Similar combinations are being made of the differential cross-sections, although this work is at a preliminary stage. LEP wide averages exist for the heavy flavour results and the $\gamma\gamma$ ($\gamma$) channel. For the former it is the $b\overline{b}$ channel which is presently most precise with a relative uncertainty of 2.5% on $R_b$, averaged over all energies, and 0.06 on the asymmetry. The $\gamma\gamma$ ($\gamma$) cross-section is precise to 1.2%.

## 2 Results and Comparison with Standard Model Predictions

Figure 2 show the LEP averaged cross-section and forward backward asymmetry results for the non-radiative samples ($\sqrt{s'/s} > 0.85$) as a function of $\sqrt{s}$, together with the Standard Model prediction from ZFITTER [2]. Published and preliminary results from all experiments and all energy points are included [3]. The agreement is generally good, although the $q\overline{q}$ cross-sections are on average almost 2 sigma higher than expectation.

Figure 3 shows the LEP combined results on $R_b$ and $A^b_{\mathrm{FB}}$. These include published and preliminary measurements from all experiments and energy points [3], apart from ALEPH 2000 and OPAL 1999 and 2000, where no results have yet been announced. Again there is satisfactory agreement with expectation, but with a tendency for the data to prefer a slightly lower $R_b$.

Cross-section results from all significant data sets and experiments have been combined for

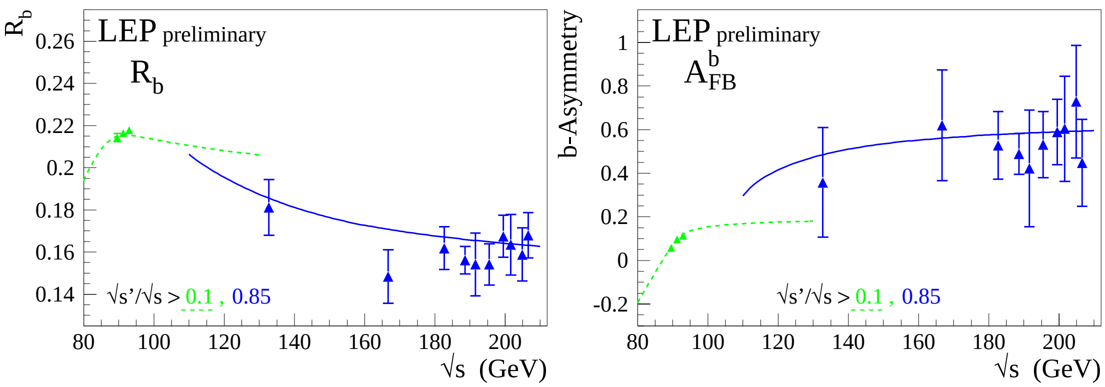


Figure 3: LEP combined $R_b$ and $A_{\rm FB}^b$ results against energy.

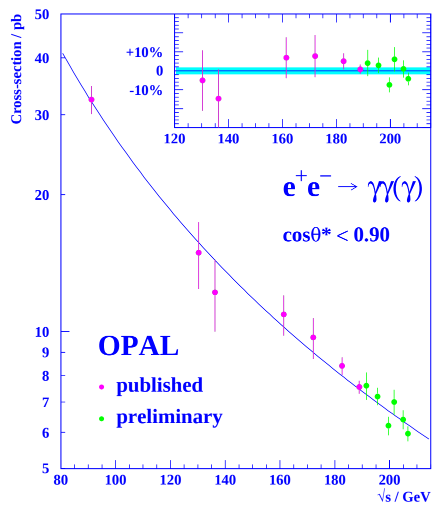


Figure 4: OPAL measurements of the cross-section for $e^+e^- \to \gamma\gamma(\gamma)$, against $\sqrt{s}$.

$e^+e^- \to \gamma\gamma(\gamma)$ [4]. When averaged over energy these give a result of $\sigma_{\rm meas}/\sigma_{\rm QED} = 0.982 \pm 0.012$, where $\sigma_{\rm QED}$ is the theorerical prediction, which is known with a precision of 1%. Figure 4 shows the results of OPAL alone, and their dependence on energy.

## 3 Indirect Searches for New Physics

Having first established the consistency of the fermion pair and $\gamma\gamma(\gamma)$ results with the Standard Model, it is then natural to use the same results to establish limits on New Physics. Here three possibilities are explored.

### *3.1 $Z'$ bosons*

Many Standard Model extensions predict the existence of additional massive neutral bosons, which are generically known as $Z'$s. These bosons have a mass $M_{Z'}$ and mix with the $Z^0$ with a mixing angle $\theta_{ZZ'}$. The $Z'$s' coupling to fermions vary depending on the model in which they arise, but in general have the potential to modify the cross-sections and asymmetries at LEP

Table 2: LEP limits on the mass of $Z'$ bosons.

| Model | $\chi$ | $\psi$ | $\eta$ | LR | SSM |
|---|---|---|---|---|---|
| $M_{Z'} >$ [GeV] | 678 | 463 | 436 | 800 | 1890 |

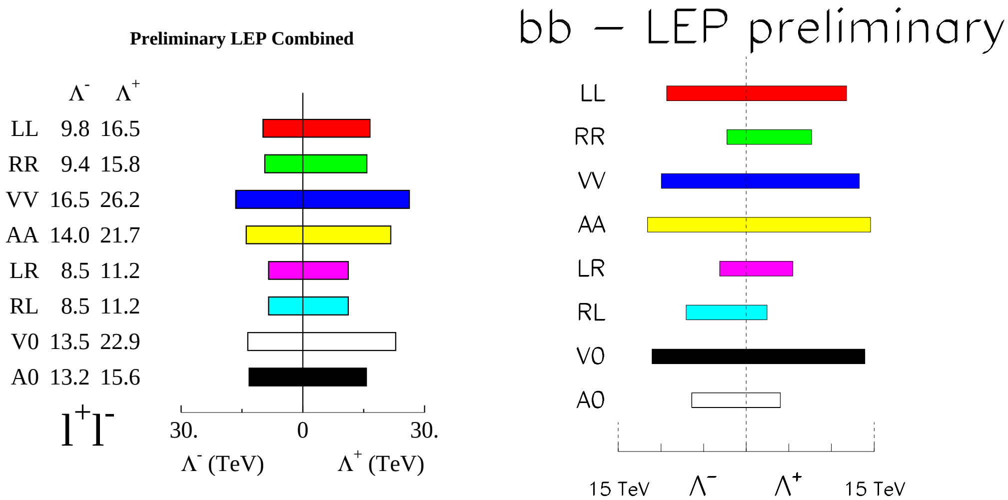


Figure 5: 95% limits on the contact interaction New Physics scale $\Lambda$ for various helicity structures, for leptons (left) and b quarks (right).

energies.

The LEP 2 two fermion results have been used to set limits on $Z'$ bosons. It turns out that the LEP 1 data are more sensitive to the mixing angle and constrain this to be very small for all models. Therefore here $\theta_{ZZ'}$ is set to 0, and the LEP 2 data used to place limits on $M_{Z'}$. The results at 95% confidence level are shown in table 2, for a variety of string inspired models, and the Sequential Standard Model (SSM). In the latter the couplings are the same as in the Standard Model, and it is for this model that the best limits are obtained.

### *3.2 Contact Interactions*

Four fermion contact interactions parameterise New Physics, such as heavy particle exchange or compositeness, in terms of an effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{i,j=L,R} \eta_{ij} \overline{e_i} \gamma_\mu e_i \overline{f_j} \gamma^\mu f_j,$$

where $\delta = 1$ when $f = e$ and 0 when $f \neq e$. $\Lambda$ represents the characteristic energy scale of this New Physics. Its coupling strength is unknown, so by convention $g$ is chosen such that $g^2/4\pi = 1$.

Fits to the $e^+e^- \to l^+l^-$ data have been performed with $\epsilon = 1/\Lambda^2$ as a free parameter, so that $\epsilon = 0$ represents the limit of no new physics. Models have been considered with different helicity structures (LL,RR etc). No evidence of physics beyond the standard model has been found, and limits have been obtained on $\Lambda$ of between 8.5 and 26.2 TeV, as shown in figure 5. The figure also includes the corresponding limits for contact interactions between electrons and b quarks. The superscript on $\Lambda$ signifies constructive (+) or destructive (-) interference with the Standard Model.

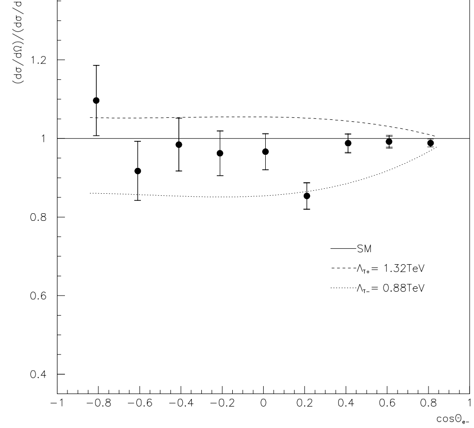


Figure 6: ALEPH $e^+e^-$ differential cross-sction, normalised to the Standard Model prediction. Superimposed are the deviations expected for the fitted 95% CL lower limits on $\Lambda_s$ ($\equiv$ $(\pi/2)^{0.25} \times M_s$).

### *3.3 Low Scale Gravity (LSG)*

A long standing problem in physics is the huge difference in magnitude between the electroweak scale ($M_{\rm ew} \sim 10^2$ GeV) and that of gravity ($M_{\rm Planck} \sim 10^{19}$ GeV). Various possible solutions have been advanced, most notably SUSY. Recent proposals [5], however, suggest that the scale of the electroweak and gravitational interactions are in fact similar, but the latter appears diluted due to graviton exchange occuring in more dimensions that the 4 in which the Standard Model particles propagate. In this scheme the true gravity scale $M_D$ ($\sim M_{\rm ew}$) is related to its apparent scale by

$$M^2_{\rm Planck} \;=\; (M_D)^{2+n}\, R^n.$$

Here $n$ is the number of extra dimension, and $R$ is their characteristic size. It can be seen that assuming if, for instance, $n = 2$, then the radius of the compactified new dimensions will be 0.1 mm, which is large compared with the predictions of more orthodox string theories.

If correct, this proposal makes plausible the possibility that LEP 2 two fermion production receive a contribution from virtual graviton exchange. In this case the differential cross-section would assume the form:

$$\frac{d\sigma}{d\cos\theta} \;=\; A(\cos\theta) + B(\cos\theta)\left[\frac{\lambda}{M_S^4}\right] + C(\cos\theta)\left[\frac{\lambda}{M_S^4}\right]^2,$$

where the $A(\cos\theta)$ is the Standard Model contribution, the $B(\cos\theta)$ term represents graviton–Standard Model interference, and the $C(\cos\theta)$ term represents pure graviton exchange. $M_S$ ($\sim M_D$) is the cutoff energy for LSG, and $\lambda$ are other possible model dependencies, which are chosen to be $\pm 1$ to allow for different signs of interference.

The experiments have interpreted their two fermion data in this context. The best sensitivity is available from the $e^+e^-$ channel, because of interference between LSG and the Standard Model t-channel diagram. Figure 6 shows the observed ALEPH $e^+e^-$ differential cross-section, normalised to the pure Standard Model expectation. The data are consistent with this description. Superimposed are the deviations resulting from the 95% CL limit on $M_S$, which are 1.18 TeV and 0.81 TeV for $\lambda = +1$ and $\lambda = -1$ respectively.

LSG can also affect boson pair production, where it is mainly seen in a modification of the total cross-section. A LEP combined analysis of the $\gamma\gamma(\gamma)$ events sets a limit of $M_s^{\lambda=+1} >$ 0.97 TeV and $M_s^{\lambda=-1} > 0.94$ TeV [4]. Individual experiments have included other channels in combined analyses [6]. Work is still required, however, to produce a LEP combined limit.

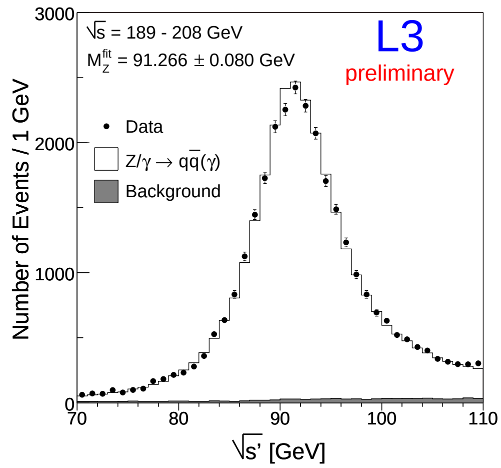


Figure 7: L3 fitted $q\overline{q}$ radiative return peak for use in the $E_b$ determination.

Table 3: $E_b$ determination from radiative returns, compared with the machine estimate.

| Measurement | $\Delta E_b$ [MeV] |
|---|---|
| ALEPH '97 $q\overline{q}$ | $-76 \pm 103$ |
| OPAL all | $-31 \pm 54$ |
| DELPHI $\mu^+\mu^-$ | $+76 \pm 96$ |
| L3 $\geq$ '98 $q\overline{q}$ | $-83 \pm 84$ |

## 4 Determination of the LEP Beam Energy through Radiative Returns

An important systematic error in the LEP $m_W$ measurement [7] is the uncertainty in the LEP beam energy, $E_b$. $E_b$ is presently determined through machine based analyses [8], and is known to a precision of $\sim 20\,\mathrm{MeV}$. The two fermion radiative return events provide a complementary way for the experiments to cross-check this number with their own data. As the mass of the Z is extremely well known from LEP 1, the position of the radiative-return peak can be used to determine $E_b$, and compared with the estimate of the energy model used in the $m_W$ analysis. In practice, however, the analysis is extremely delicate, requiring in the hadronic channel excellent knowledge of the jet reconstruction in the forward region, where the events are generally found, and for all channels good understanding of the initial and final state radiation processes.

Figure 7 shows the fitted radiative return peak from a new L3 $q\overline{q}$ analysis. Table 3 gives a summary of available results [9], where $\Delta E_b$ is the radiative return estimate of $E_b$ minus that coming from the standard procedure. No combination is yet available taking account of the significant correlated systematics. It can be seen that there is no evidence of a disagreement within the accuracy of the measurements.

## 5 Conclusions

The high integrated luminosity delivered by LEP 2 at energies up to and beyond 200 GeV have allowed a precise study of two fermion and hard photon production, and a detailed comparison with Standard Model predictions. No significant deviation has been found. The same results have been used to set limits on various New Physics models, including $Z'$s, contact interactions and Low Scale Gravity.

A significant amount of work is required to finalise these studies. Final publications are expected from each of the experiments, and these results must then be correctly averaged. There is scope for improvements in the theoretical understanding, particularly in the $e^+e^-$ channel.

Initial results from radiative return analyses indicate that measurements on the full data set from all experiments would produce a very interesting cross-check on the LEP beam energy.


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