Fermion Pair and Photon Pair Production at LEP2*

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Abstract

Preliminary results on fermion pair and photon pair production at LEP2 are presented, for which the measurements of the four LEP collaborations have been combined. This allows precise tests of the Standard Model at the $\approx 1\%$ level. From the observed agreement with the Standard Model predictions limits are derived for physics beyond the Standard Model like contact interactions, models with additional Z' bosons and such with gravity in extra dimensions.

1 Introduction

Fermion pair ($f\bar{f}$) production is the dominant process in e^+e^- annihilation at LEP2 center-of-mass energies (130-207 GeV). Large cross-sections for these processes allow precise tests of the Standard Model, for which theoretical predictions exist with uncertainties below 1%. Therefore they also a high sensitivity is provided to detect physics beyond the Standard Model, which would be seen in significant deviations from those predictions.

The production of photon pairs arises from a nearly pure QED process, which is well calculable including radiative corrections. Deviations from the prediction can be interpreted in terms of physics beyond the Standard Model as well.

Measurements of these processes have been performed by the four LEP collaborations, and their results have been combined by the LEP Electro-Weak Working Group. These combined results - still preliminary - are presented in this report in comparison with the Standard Model predictions, and limits on new physics are derived.

2 Data selection

2.1 Data sets

In the years 1995 until 2000 the LEP collaborations **A**LEPH, **D**ELPHI, **L**3 and **O**PAL collected data at center-of-mass energies between 130 and 207 GeV corresponding to an integrated luminosity of about 700 pb^{-1} for each experiment. Various final states have been analyzed by the four experiments, for which total cross-sections (σ), differential cross-sections ($d\sigma/dcos\theta$) and forward-backward asymmetries (A^f_{FB}) have been measured.

The combined measurements [1, 2] presented here are listed in Table 1. The averages take into account all statistical and systematic uncertainties of the individual measurements including their correlations. Good agreement was found between the results of the different experiments, e.g. for the total cross-sections and forward-backward asymmetries of $f\bar{f}$ pairs a $\chi^2 = 160/180$ was found.

The results presented in this report are still preliminary, however, they contain nearly the full statistics available. Some measurements have finally been published, the other final results and their combination are expected for 2004.

2.2 Radiative corrections from initial state radiation (ISR)

For $f\bar{f}$ production at center-of-mass energies above the Z resonance large radiative corrections occur due to photon radiation from the initial state. For a significant amount of the observed events, so called *Radiative Z Returns*, the effective center-of-mass energy $\sqrt{s'}$ of the final state and of the Z/γ propagator corresponds after ISR approximately to the mass of the Z boson. Such events are of no

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Final State	measured quantity	LEP experiments included
$q\bar{q}$	σ	ADLO
e^+e^-	$d\sigma/dcos\Theta$	ALO
$\mu^+\mu^-$	σ, A_{FB}, $d\sigma/dcos\Theta$	ADLO
$\tau^+\tau^-$	σ, A_{FB}, $d\sigma/dcos\Theta$	ADLO
$b\bar{b}$	$R_b = \sigma^{b\bar{b}}/\sigma^{q\bar{q}}$, A_{FB}	ADLO
$c\bar{c}$	$R_c = \sigma^{c\bar{c}}/\sigma^{q\bar{q}}$, A_{FB}	ADO
$\gamma\gamma$	σ, $d\sigma/dcos\Theta$	ADLO

Table 1: Data sets included in the combination.

interest for the physics discussed here. They are removed nearly completely from the data sample by a cut on the effective center-of-mass energy, which is reconstructed from the measured momenta of the initial and final state particles with constraints from energy and momentum conservation. An example is shown in Figure 2.2 for muon pairs measured in DELPHI.

For all $f\bar{f}$ results presented here a common cut $\sqrt{s'/s} > 0.85$ has been applied, except for the e^+e^- final state, for which an equivalent cut on the acollinearity of the final state leptons $\Theta_{acol} < 10^\circ$ was chosen instead.

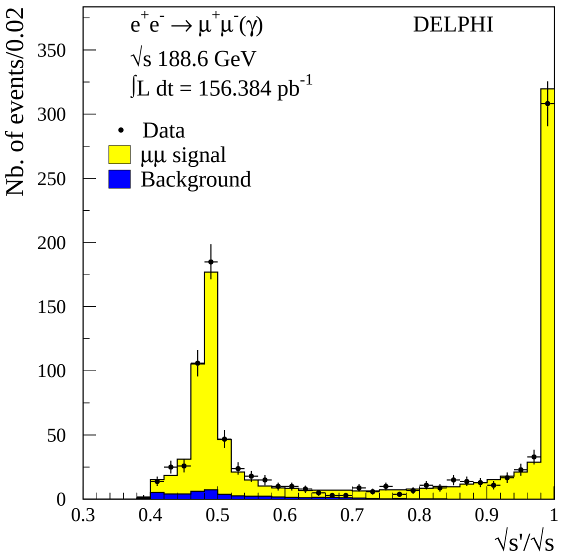

Figure 1: Reconstructed effective center-of-mass energy $\sqrt{s'/s}$ for muon pairs.

2.3 Selection efficiencies and backgrounds

The selection efficiencies for $f\bar{f}$ events are large, typically $\approx 90\%$, except for the $\tau^+\tau^-$ final state, for which they are $\approx 50\%$. Backgrounds from other processes, among which 4-fermion production is the main contribution, are in the range of $1 - 10\%$.

3 Results and their comparison with the Standard Model

3.1 Cross-sections and asymmetries of fermion pairs

The measurements of the total cross-sections for $q\bar{q}$ pairs, as well as cross-sections and forward-backward asymmetries for $\mu^+\mu^-$ and $\tau^+\tau^-$ pairs are shown in Figure 3.1. Good agreement with the Standard Model predictions of ZFITTER[3] is observed. Such good agreements is also observed for the differential cross-sections of the (three) lepton pairs.

The largest difference to the Standard Model prediction is observed for the hadronic cross-sections, for which the measured average is 1.7 standard deviations above the prediction.

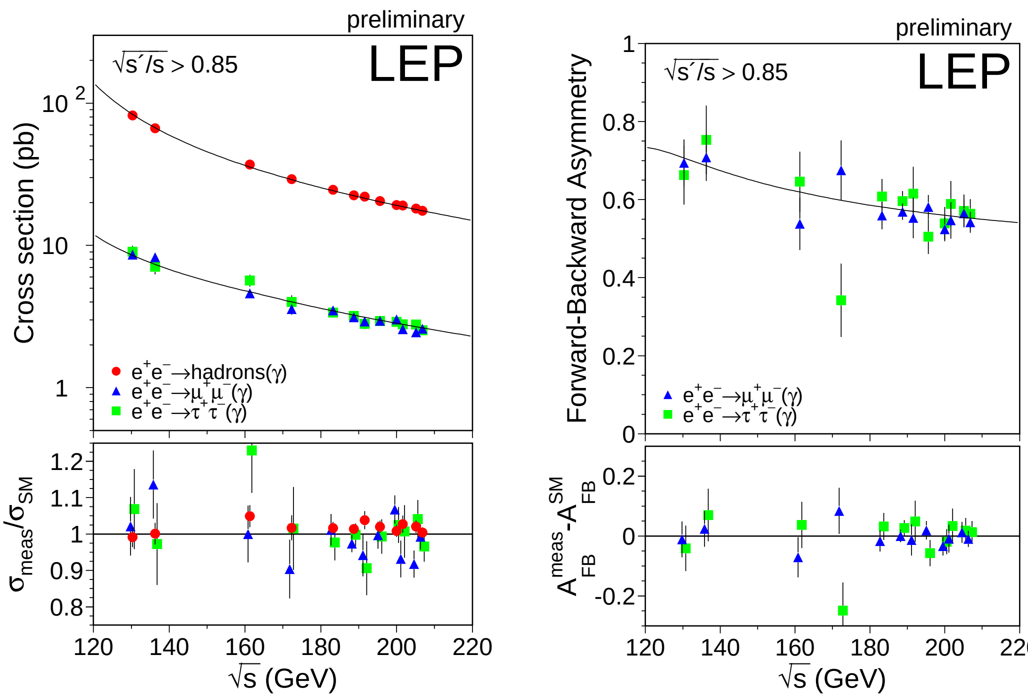

Figure 2: Preliminary LEP results on cross-sections for $q\bar{q}$, cross-sections and forward-backward asymmetries for $\mu^+\mu^-$ and $\tau^+\tau^-$ final states as function of the center-of-mass energy. The Standard Model predictions shown as curves are computed with ZFITTER.

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The results for quark jets identified as b- or c-quarks are shown in Figure 3.1. Both the cross-section ratios $R_{b/c}$ and the forward-backward asymmetries $A_{FB}^{b/c}$ are in good agreement with the Standard Model expectations.

3.2 Cross-sections of photon pairs

Measurements of the total cross-sections $e^+e^- \to \gamma\gamma$, normalized to the QED prediction, are shown in Figure 3.2. The LEP combined result, averaged over all center-of-mass energies, is

$$\sigma_{meas}/\sigma_{QED} = 0.982 \pm 0.01(\text{exp.}) \pm 0.01(\text{theor.}),$$

where a theoretical uncertainty of 0.01 is estimated for the $\mathcal{O}(\alpha^3)$ computation of the QED cross-section.

4 Limits for new physics

Because the results presented in the previous section show no evidence for physics beyond the Standard Model, limits can be derived for various models of new physics. Three examples are presented here.

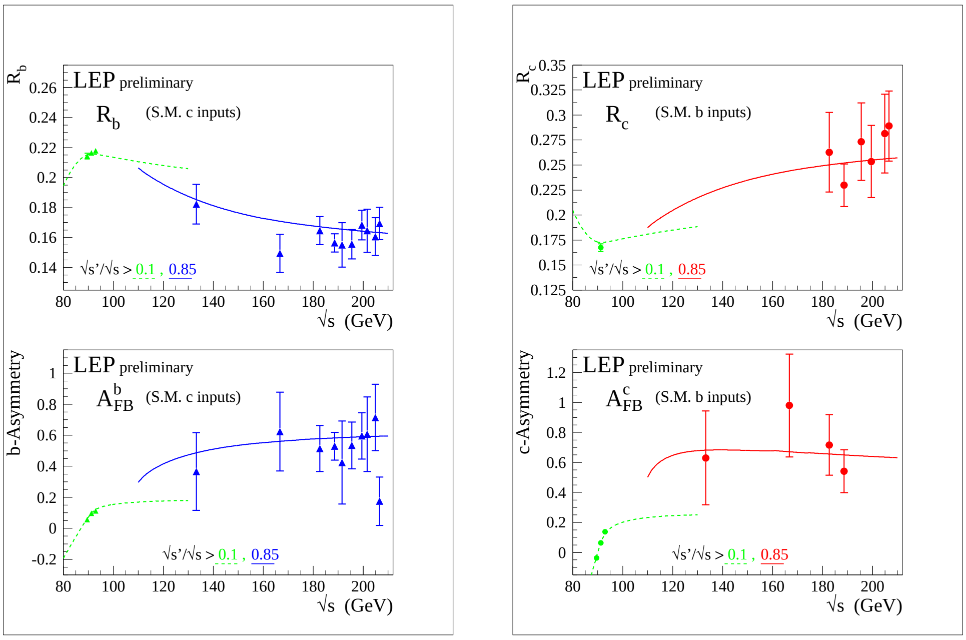

Figure 3: Preliminary LEP results for R_b, A^b_{FB}, R_c and A^c_{FB} as function of the center-of-mass energy. The Standard Model predictions shown as curves are computed with ZFITTER.

4.1 Contact interactions

Contact interactions can be parameterized using an effective Lagrangian $\mathcal{L}_{eff}$, which is added to the Standard Model Lagrangian. For fermion pairs in the final state it can be written as

$$\mathcal{L}_{eff} = \frac{g^2}{(1+\delta) * \Lambda^2} \sum_{i,j=L,R} \eta_{ij} (\bar{e}_i \gamma_\mu e_i)(\bar{f}_j \gamma^\mu f_j),$$

where g is an unknown coupling, which is set $g^2 = 4\pi$, $\delta = 1(0)$ for $f = e(f \neq e)$ and Λ is the energy scale of the contact interaction. By the choice of η_{ij} the chiral structure of the model (LL, RR, VV, AA, LR, RL, V0, A0) is described. Fitting this ansatz to the LEP2 $f\bar{f}$ data, lower limits of the cutoff parameter Λ can be derived for each final state fermion, both for constructive and destructive interference between the Standard Model process and the contact interaction. These limits with 95% confidence level are in the range of 1-10 TeV; tables can be found in ref.[1]. The highest limits between 8.6 and 21.7 TeV, depending on the chiral structure of the model, are found for leptons, when the results for $\mu^+\mu^-$ and $\tau^+\tau^-$ are combined with the assumption of lepton universality.

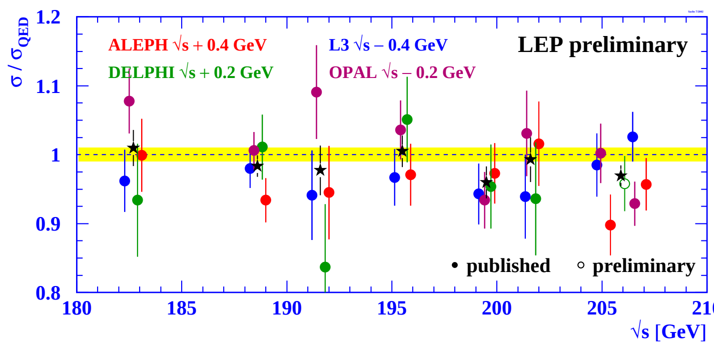

Figure 4: Cross-section ratio $\sigma_{meas}/\sigma_{QED}$ for the process $e^+e^- \to \gamma\gamma$ as function of the center-of-mass energy from the four LEP experiments (dots) and combined (stars). The measurements of the individual experiments are slightly (200 or 400 MeV) displaced from the actual energy for clarity.

For the production of photon pairs contact interactions are parameterized similarly; e.g. the differential cross-section can be described by

$$(\frac{d\sigma}{d\Omega})_{\Lambda_\pm} = (\frac{d\sigma}{d\Omega})_{Born} \pm \frac{\alpha^2 s}{2\Lambda_\pm^4}(1+cos^2\Theta).$$

The 95% confidence level limits on this cutoff parameter are $\Lambda_+ > 392$ GeV and $\Lambda_- > 364$ GeV.

4.2 Models with Z' bosons

Additional Z' boson bosons are predicted in E6 GUT and left-right symmetric models[4]. Free parameters are the mass of the new boson $M_{Z'}$ and the mixing angle $\Theta_{ZZ'}$. Whereas the mixing angle is constrained from LEP1 data close to 0, the best limits for $M_{Z'}$ can be derived from the $f\bar{f}$ production at LEP2. The excluded mass ranges are shown in Figure 4.2 for $\Theta_{ZZ'} = 0$.

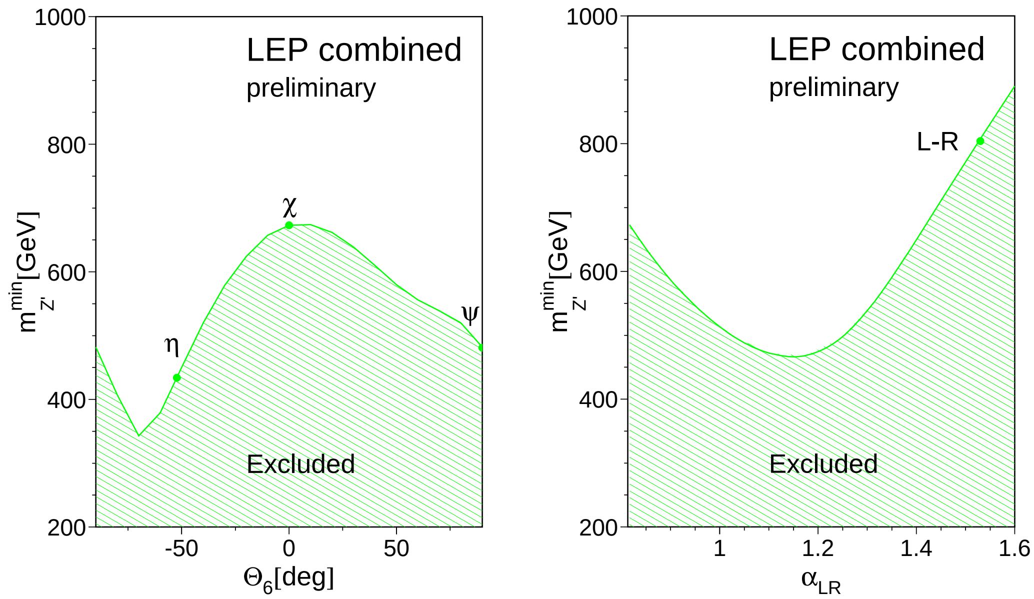

Figure 5: The 95% confidence level limits on $M_{Z'}$ as function of the model parameter Θ_6 for E_6 models and α_{LR} for left-right symmetric models. The mixing angle is fixed to $\Theta_{ZZ'} = 0$.

4.3 Gravity in extra dimensions

An approach to solve the hierarchy problem has been proposed[5], which brings the Planck scale M_{Pl} close to the electro-weak scale introducing extra spacial dimensions. In this framework the effective 4-dimensional M_{Pl} is connected to a new $M_{Pl(4+n)}$ scale in a (4+n) dimensional theory

$$M_{Pl}^2 \sim M_{Pl(4+n)}^{2+n} R^n,$$

with n compact extra dimensions of radius R. Such models predict additional contributions to fermion and photon pair production by virtual effects due to the exchange of gravitons (Kaluza-Klein excitations). The exchange of spin-2 gravitons modifies the differential cross-sections in a unique way providing clear signatures[6].

The gravitational mass scale M_s is defined to be of the order of the fundamental gravity scale in 4+n dimensions. The deviations from the Standard Model are introduced by a parameter $\epsilon = \lambda/M_s^4$, for which λ is of $\mathcal{O}(1)$ and depends on the explicit theory. In the analysis described it is set to ± 1.

The most sensitive measurements to observe deviations from the Standard Model value $\epsilon = 0$ are the angular distributions $d\sigma/dcos\theta$ of e^+e^- and of photon pairs. The 95% confidence level limits obtained for e^+e^- final states are

$$M_s > 1.20 \text{ TeV for } \lambda = +1, \qquad M_s > 1.09 \text{ TeV for } \lambda = -1.$$

For photon pairs the limits are

$$M_s > 0.93 \text{ TeV for } \lambda = +1, \qquad M_s > 1.01 \text{ TeV for } \lambda = -1.$$

5 Summary

Fermion and photon pair production in e^+e^- annihilation has been measured at LEP2 over a wide energy range. As the measurements of the four LEP experiments are in good agreement, their results have been combined taking into account all uncertainties with their correlations.

The LEP combined measurements agree with the predictions from the Standard Model at the $\approx 1\%$ level. Therefore many constraints on models describing physics beyond the Standard Model can be derived. Some limits on contact interactions, models with Z' bosons and models with gravity in extra dimensions are presented in this report.

Acknowledgments

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