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Fermion pair physics at LEP2

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Abstract. Combined measurements of the 4 LEP collaborations for the fermion pair processes $e^+e^- \to f\bar{f}$ are presented. The results show no significant deviations when compared with the Standard Model predictions and are used to set limits on contact interactions, Z′ gauge bosons and low scale gravity models with large extra dimensions.

1 Introduction

Fermion pair cross-sections, forward-backward asymmetries and R_q's have been measured by the LEP collaborators up to collision energies $\sqrt{s} \sim 209$ GeV. Initial state photon radiation (ISR) is important at LEP2 energies: the decreased center of mass collision energy enhances significantly the inclusive cross-section of the process due to the high interaction rate around the Z peak. Photon radiation also complicates the definition of the effective collision energy $\sqrt{s'}$ as final state radiation (FSR) cannot be cleanly separated from ISR and unlike LEP1 the ISR-FSR interference term is important. The $\sqrt{s'}$ can be defined as the invariant mass of the s-channel propagator with interference term subtracted or the bare invariant mass of the outgoing $f\bar{f}$ pair [1]. For the LEP combinations the first definition is adopted to classify the events into the non-radiative sample with $\sqrt{s'/s} \geq 0.85$ and inclusive sample with $\sqrt{s'/s} \geq 0.1$. Only the higher energy non-radiative sample is used for new physics searches whereas the radiative events are used for an independent beam energy measurement [2].

2 Measurements

As individual experiments have adopted different signal definitions for the difermion signal, corrections are applied to derive the results using a common signal definition for all measurements used in the averaging procedure [3]. Systematic errors are broken down in parts so as to take into account correlations between channels and experiments. Preliminary combinations for the cross-sections of the channels $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$, $e^+e^- \to q\bar{q}$ and forward-backward asymmetries for the muon and tau pairs have been performed. The averaging method used was the best linear unbiased estimator technique (BLUE) [4] using all data in the range 130-209 GeV at the same time. The agreement between the Standard Model predictions and the averaged measurements is good as can be seen in Figure 2 with the hadronic cross-section slightly above expectations ($\sim$ 1.7 standard deviations when averaged over all energies). In addition the differential cross-sections have been combined for the bhabhas using a χ^2 fit to the LEP data in the range 189-209 GeV. In a similar way the averaged differential cross-section for the muon and tau pairs have been calculated using the BLUE technique in the data set from 183 GeV up to 209 GeV. Finally, the heavy flavour measurements R_b, R_c and forward-backward asymmetries for b and c quarks were also combined in the range 130-209 GeV. All combined results for the differential cross-sections and heavy flavour measurements show no significant deviation from the Standard Model predictions.

3 Search for New Physics

The agreement between data and Standard Model predictions can be used to put constraints on the energy scale of new physics phenomena such as contact interactions, the exchange of a new Z′ gauge boson and models with large extra dimensions.

3.1 Contact Interactions

Contact interactions provide a very general framework to search for new physics from $e^+e^- \to f\bar{f}$ data. For example we can look for another deeper level of substructure in quarks and leptons or exchange of new heavy particles, assuming an effective Lagrangian similar to the one used by Fermi to describe the weak force:

$$\mathcal{L}^{contact} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{i,j=L,R} \eta_{ij} [e_i \gamma^\mu e_i][f_j \gamma^\mu f_j]$$

where $\delta = 1$ for bhabhas and 0 otherwise, $e_L(f_L)$ and $e_R(f_R)$ are chirality projections, Λ the new physics energy scale and g the unknown coupling fixed by convention

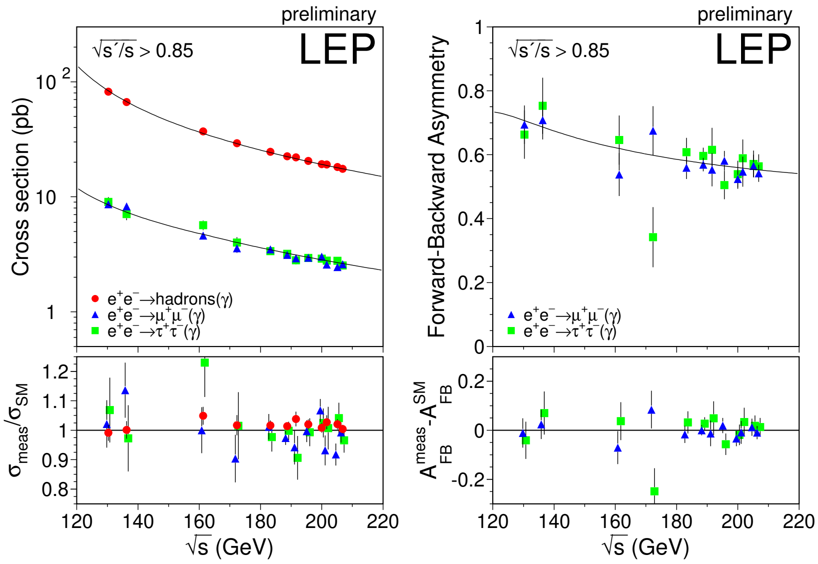

Fig. 1. Combined cross-sections for $\mu^+\mu^-$, $\tau^+\tau^-$, $\mathrm{q\overline{q}}$ final states (left) and forward-backward asymmetries for $\mu^+\mu^-$, $\tau^+\tau^-$ (right) as a function of the collision energy.

to $g^2 = 4\pi$. The η_{ij} are parameters with values ±1, 0 depending on the vector or axial-vector character of the specific model [5]. For the leptonic final states $\mathrm{e^+e^-}\rightarrow\mu^+\mu^-$, $\mathrm{e^+e^-}\rightarrow\tau^+\tau^-$ limits on the energy scale Λ can be extracted by fitting the combined cross-sections and asymmetries. For bhabhas the averaged differential cross-sections are used in the fit. The heavy flavour measurements R_b, R_c are converted to cross-sections $\sigma_{\mathrm{b\overline{b}}}$, $\sigma_{\mathrm{c\overline{c}}}$, using the $\sigma_{\mathrm{q\overline{q}}}$ results mentioned in section 2. The hadronic cross-sections are then fitted to extract the limits on contact interactions between electrons and b and c quarks (Figure 2) which are accessible only to $\mathrm{e^+e^-}$ colliders. As a fitting parameter $\epsilon \equiv 1/\Lambda^2$ is used, where $\epsilon = 0$ refers to the SM prediction. No evidence for new physics was found for all models and thus the fitted values for ϵ are converted into 95% confidence level lower limits on Λ, with Λ^+, Λ^- referring to constructive and destructive interference with the Standard Model respectively. Depending on the specific model the limits extracted are in the range 1.5-19.7 TeV.

3.2 New gauge bosons

Some GUT models where the Standard Model is embedded into a larger gauge group predict the existence of extra, neutral heavy gauge bosons For example in the $E6$ model the group breaks down as:

$$\begin{aligned} \mathrm{E}(6) &\rightarrow \mathrm{SO}(10) \times \mathrm{U}_\chi(1) \\ \mathrm{SO}(10) &\rightarrow \mathrm{SU}(5) \quad \times \mathrm{U}_\psi(1) \\ \mathrm{SU}(5) &\rightarrow \mathrm{SU_C}(3) \times \mathrm{SU_L}(2) \times \mathrm{U_Y}(1), \end{aligned}$$

where two additional neutral gauge bosons Z_χ, Z_ψ are introduced. In general, $\mathrm{Z}^{0'}$ can be a mixture of Z_χ and Z_ψ.

Model	χ	ψ	η	L-R	SSM
$\mathrm{M_{Z'}}$ (GeV)	673	481	434	804	1787

Table 1. The 95% confidence level lower limits on $\mathrm{M_{Z'}}$ for various models.

Several models exist depending on the mixing angle Θ_E (e.g χ, ψ, η models have Θ_E=0, $\pi/2$, $-\arctan\sqrt{5/3}$ respectively). The observed particles Z, Z′ could be a mixture of Z^0 and $\mathrm{Z}^{0'}$ with mixing angle $\Theta_{\mathrm{ZZ'}}$. In the Sequential Standard Model (SSM) the Z′ couplings to fermions are assumed to be the same as for Z. In Left-Right symmetric model (L-R) an additional $SU_R(2)$ is introduced [5]. The mass of the Z′ and the mixing angle $\Theta_{\mathrm{ZZ'}}$ are free parameters but the latter is constrained by LEP1 data to be close to zero. By assuming $\Theta_{\mathrm{ZZ'}}$ equals zero, 95% confidence level limits can be obtained for $\mathrm{M_{Z'}}$ for several models, by fitting the combined hadronic and leptonic cross-sections and the leptonic asymmetries (Table 1).

3.3 Extra Dimensions

The difference of many orders of magnitude between the electroweak ($M_{EW} \sim 10^3$ GeV) and Planck scale ($M_{Pl} \sim 10^{18}$ GeV) where gravity becomes as strong as gauge interactions, is a puzzle for physicists. While electroweak interactions have been tested experimentally to very short distances (M_{EW}^{-1}), gravity has only been probed to the submillimeter range [6]. Recent proposals attempt to explore the possibility that the only fundamental short range scale in nature is the experimentally tested M_{EW}^{-1} [7]. M_{Pl} can arise by assuming that there are n extra compact spatial

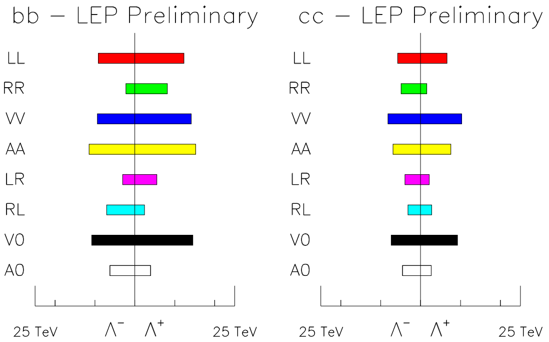

Fig. 2. 95% confidence level limits on the energy scale $\Lambda^{\pm}$ of $e^+e^-\to b\bar{b}$ (left) and $e^+e^-\to c\bar{c}$ (right) contact interactions for various models using the heavy flavour LEP results from 133 GeV to 207 GeV.

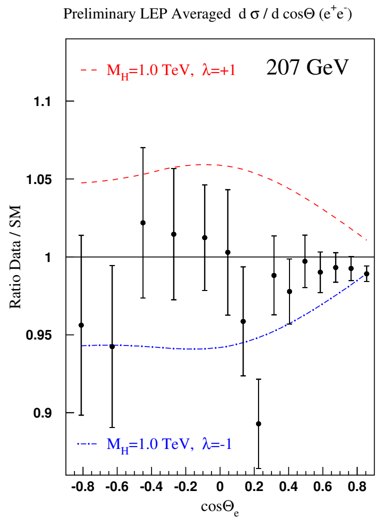

Fig. 3. Ratio of the LEP averaged differential cross-section for $e^+e^- \to e^+e^-$ at 207 GeV compared to the SM prediction. Effects from graviton exchange are also shown for $\lambda \pm 1$ and $M_H = 1$ TeV.

dimensions of radius R. According to this model, gravity is propagating to extra 'large' compact dimensions, while the rest of gauge interactions are confined to the usual space-time. The propagation of Standard Model particles in extra dimensions is severely constrained by electroweak measurements. By comparing the gravitational potential dictated by Gauss's law in (4+n) dimensions and the usual space-time in distances $r \gg R$ we can derive the following relation between the Planck scale in (4+n) dimensions $M_{Pl(4+n)}$ and M_{Pl}:

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

For example for $n = 2$ the model predicts $R \sim \mathcal{O}(1\,\mathrm{mm})$. The exchange of spin-2 virtual gravitons via the process $e^+e^- \to G^* \to f\bar{f}$ would modify the differential cross-sections of the fermion pairs. The graviton contribution can be parametrised as a function of $\epsilon \equiv \lambda/M_H^4$, where M_H is the gravitational mass scale and λ is unknown parameter depending on full knowledge of quantum gravity theory. In this case, λ was set to ±1 in order to study both positive and negative interference with SM. Bhabhas are the most sensitive channel due to interference of graviton exchange with t-channel (Figure 3). The fitted value for ϵ using the averaged difermion differential cross-sections is compatible with the Standard Model and is converted into 95% confidence level lower limits on M_H:

$$M_H \geq 1.20\,\mathrm{TeV}, \quad \text{for} \quad \lambda = +1$$

$$M_H \geq 1.09\,\mathrm{TeV}, \quad \text{for} \quad \lambda = -1$$

4 Conclusions

Preliminary combined LEP results for fermion pair processes show no significant deviation from Standard Model. The results are used to set limits on models with contact interactions in the range 1.5-19.7 TeV, mass of new Z$'$ boson up to ~ 1.7 TeV and low scale gravity with large extra dimensions ($M_H \sim 1$ TeV).

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