PROCEEDINGS

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Fermion Pair Production Above the Z^0 Resonance

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Abstract: Measurements of the process $e^+e^- \to f\bar{f}$ at energies above the Z^0 resonance at LEP II provide a test of the Standard Model to $\mathcal{O}(1\%)$ and can be used to constrain physics beyond the Standard Model. The determination of the energy of the LEP e^+e^- beams from study of the *radiative return* process is discussed.

1. Introduction

Measurements of the process $e^+e^- \to f\bar{f}$ at energies above the Z^0 provide a test of the Standard Model at the $\mathcal{O}(1\%)$ level and can be used to place tight constraints on physics beyond the Standard Model. In addition, so called, *radiative return* events have been used to determine the energy of the LEP e^+e^- beams. LEP data taking is now over and, although results are still preliminary, many of the measurements now include the full data set. In addition, certain results from individual LEP experiments have been combined. Further details can be obtained from the submissions to this conference [1], [2] and [3] and from [4].

2. Features of $e^+e^- \to f\bar{f}$ above the Z^0 resonance

Within the Standard Model ($\mathcal{SM}$), the process $e^+e^- \to f\bar{f}$ at energies above the Z^0 resonance is mediated by Z^0 and γ exchange. The cross-sections are typically 2-3 orders of magnitude smaller than at the Z^0 resonance and the forward-backward asymmetries[1] are typically larger. QED radiative corrections are significant, leading to a substantial enhancement of the total cross-section. These effects come predominantly from the process of *radiative return* in which an initial state photon is emitted, reducing the invariant mass of the hard scattering ($\sqrt{s'}$) from the e^+e^- invariant mass ($\sqrt{s}$) to approximately the mass of the Z^0 (M_Z). Kinematic quantities can be used to separate these events from *non-radiative* events where $\sqrt{s'} \sim \sqrt{s}$.

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[1]The forward backward asymmetry A_{FB} is defined as $\frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$ where σ_F and σ_B are the cross-sections for the scattering of the final state fermion in to the same hemisphere as the incoming electron direction and the opposite hemisphere respectively.

3. Analysis of $e^+e^- \to f\bar{f}$ at LEP II

The LEP II programme delivered approximately 700 pb^{-1} of integrated luminosity per experiment at centre-of-mass energies from $\sqrt{s} \sim 130$ to $\sqrt{s} \sim 207$ GeV. The analyses of $e^+e^- \to f\bar{f}$ processes at LEP II have follow very closely those used to analyse data at $\sqrt{s} \sim$ M_Z at LEP I. Modifications were made to take into account falling signal cross-sections and increasing backgrounds, including new background from W^+W^- and ZZ production, and to distinguish between *radiative return* and *non-radiative* samples of events. Individual experiments have made measurements for *non-radiative* samples of events and for *inclusive* samples, which include *radiative return* events. In addition, measurements for *non-radiative* samples of events have been averaged to give LEP combined results [4].

3.1 Cross-sections and leptonic asymmetries

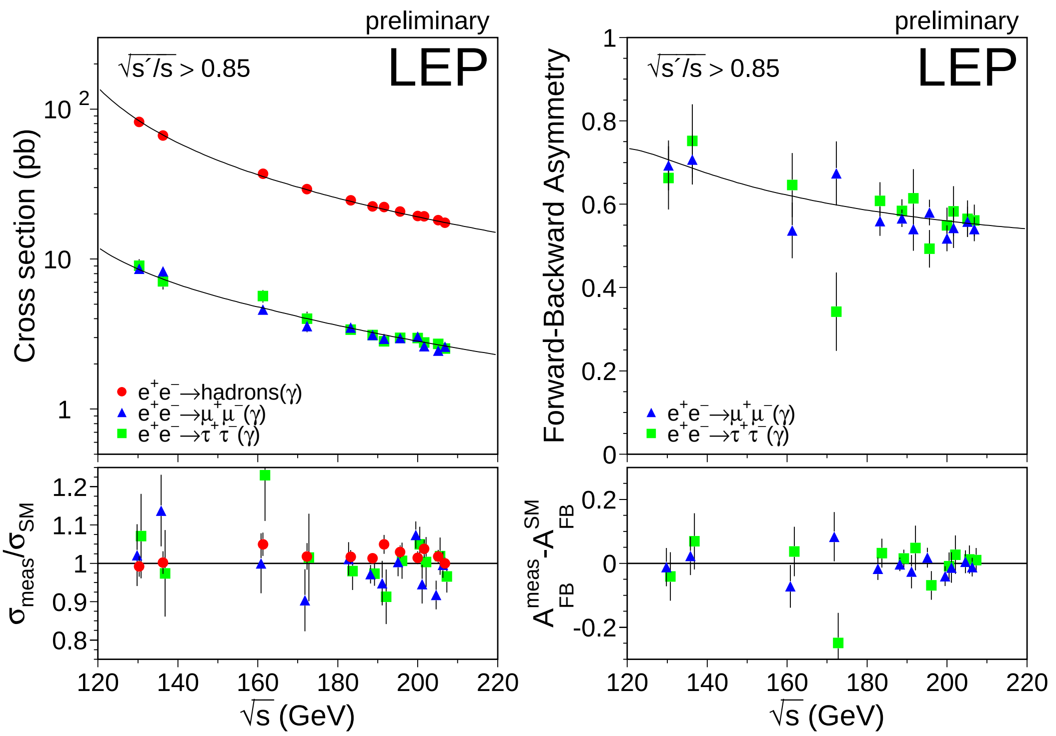

Figure 1: Preliminary LEP combined cross-section and forward-backward asymmetry results

Cross-section and asymmetries for selections of *non-radiative* $\mu^+\mu^-$ and $\tau^+\tau^-$ and hadronic final states from the individual LEP experiments have been combined. Details of the LEP averaging procedure can be found in [4]. Preliminary results presented here are from an average of data at all LEP II energies, from 130 - 207 GeV. The averaging procedure provides a full set of averaged results and a full correlation matrix; these can be found at [5]. The preliminary results of the averaging procedure are shown in Figure 1.

Correlations between hadronic cross-section results at different energies are significant, in the region of $15 - 30\%$ of the errors. Other correlations are smaller. Combining the measurements over all energies, the precision of the *non-radiative* hadronic cross-section determinations is 1.0%. Similarly for $\mu^+\mu^-$ and $\tau^+\tau^-$ production cross-sections the precisions are 1.6% and 2.2% respectively. These compare to the theoretical precisions of 0.2% and 0.4%0.2% [6] for the hadronic and leptonic cross-sections respectively. The hadronic cross-sections are ~ 1.8 standard deviations above the predictions of ZFITTER [7].

3.2 Heavy flavour results

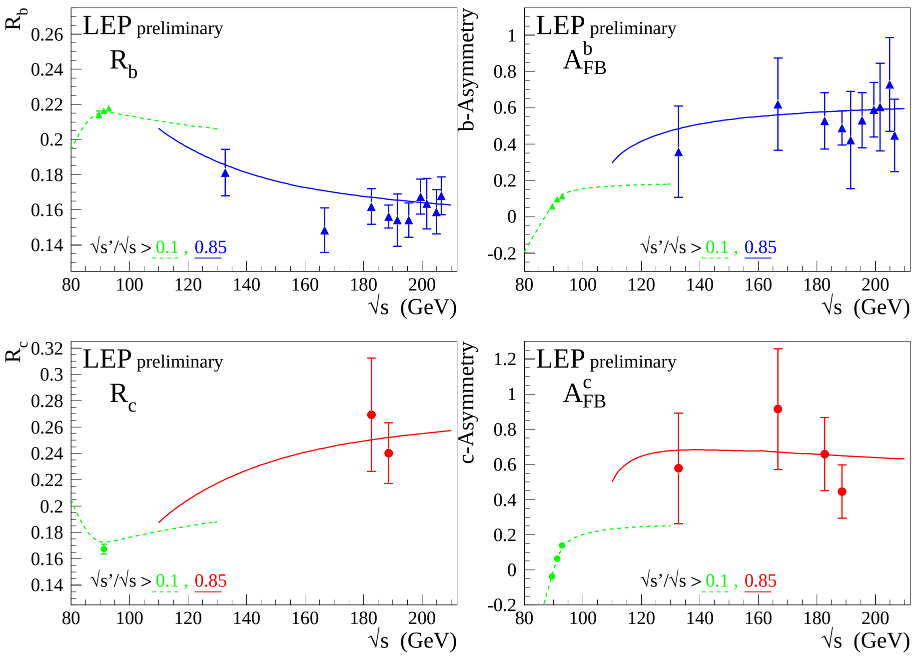

Figure 2: Preliminary LEP combined cross-section ratio andforward-backward asymmetry results for $b\bar{b}$ and $c\bar{c}$ production.

The LEP experiments have made measurements of b and c quark production at LEP II. Results on the ratios of the heavy quark production cross-section to the total hadronic cross-section ($R_{\rm q}$) and the heavy quark forward-backward asymmetries ($A^{\rm q}_{\rm FB}$) have been reported. The measurements use similar techniques to those used at LEP I [4, 2]. The available heavy flavour results have been combined [4] using a technique similar to that used to combine LEP I heavy flavour results. The preliminary combined measurements of $R_{\rm q}$ and $A^{\rm q}_{\rm FB}$ are shown in Figure 2. Averaging the data over all energies, $R_{\rm b}$ is determined to a precision of $\sim 2.5\%$ and $A^{\rm b}_{\rm FB}$ to ~ 0.06.

4. Interpretation

Precise measurements of the $e^+e^- \to f\bar{f}$ process can be used to directly test the $\mathcal{SM}$ using the S-Matrix formalism, and the data can also be used to search for physics beyond the Standard Model in a wide variety of models. Typically the sensitivity to these new phenomena come from the interference of the new physics with the $\mathcal{SM}$ processes in the virtual exchange of new particles, and the samples of *non-radiative* events have the highest sensitivity.

4.1 S-Matrix

The S-Matrix formalism parameterises the energy dependence of the total cross-section and forward backward asymmetry for $e^+e^- \to f\bar{f}$ in terms of the exchange of a massless and a massive neutral gauge boson. For example, the Born level cross-section for $f\bar{f}$ production, is given by:

$$\sigma^0_{tot}(s) = \frac{4}{3}\pi\alpha^2 + \left[\frac{\mathrm{g_f^{tot}}}{s} + \frac{\mathrm{j_f^{tot}}(s - \overline{\mathrm{m}}_\mathrm{Z}^2) + \mathrm{r_f^{tot}}s}{(s - \overline{\mathrm{m}}_\mathrm{Z}^2)^2 + \overline{\mathrm{m}}_\mathrm{Z}\overline{\Gamma}_\mathrm{Z}^2}\right].$$

The parameter of interest is $\mathrm{j_{had}^{tot}}$ which determines the strength of the $\mathrm{Z}^0 - \gamma$ interference for inclusive hadron production - the value of this parameter can be predicted in the $\mathcal{SM}$. Data taken during the LEP I programme at $\sqrt{s} \sim \mathrm{M_Z}$ does not give good experimental constraints on this parameter. Measurement at energies either above or below $\sqrt{s} \sim \mathrm{M_Z}$ can be used to put tighter constraints on $\mathrm{j_{had}^{tot}}$, providing a consistency check of the standard electroweak fits [8].

LEP experiments use cross-section and forward-backward asymmetry results from $\sqrt{s} \sim \mathrm{M_Z}$ and LEP II. OPAL and L3 have reported preliminary results which are given in Table 1, and are compared to the value obtained by VENUS [9] using data at $\sqrt{s} \sim 60$ GeV and preliminary LEP I S-Matrix results. The results are consistent with each other, and with the $\mathcal{SM}$ prediction $\mathrm{j_{had}^{tot}} = 0.22$.

Expt	Data	$\mathrm{j_{had}^{tot}}$
L3:	LEP I + LEP II	0.30 ± 0.10
OPAL:	LEP I + LEP II	0.21 ± 0.12
VENUS:	VENUS + LEP I	0.20 ± 0.08

Table 1: Measurements of $\mathrm{j_{had}^{tot}}$

4.2 Contact interactions

The combined LEP data has been used to search for four fermion contact interactions [4]. The effective Lagrangian for such interactions [10] can be written as:

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

The parameter of interest is Λ, the energy scale associated with the interactions. Different models correspond to different choices of the parameters η_{ij} which determine the helicity states for the e^+e^- and $f\bar{f}$ currents involved in the interactions. The parameter δ_{ef} is 0 for $f \neq e$ and 1 for $f = e$.

Preliminary 95% confidence lower limits on Λ are derived assuming a coupling $g^2 = 4\pi$. The limits obtained depend on the model considered. For a combination of $\mu^+\mu^-$ and $\tau^+\tau^-$ final states limits on Λ range from 8.5 to 26.2 TeV for contact interaction in the process $e^+e^- \to l^+l^-$. While for the process $e^+e^- \to b\bar{b}$ limits range from 2.2 to 14.6 TeV.

4.3 Z′ bosons

An extra, heavy, neutral gauge boson, Z′, is predicted in a number of extensions of the Standard Model [11]. Different models predict different coupling of the Z′ to fermions. Individual experiments have search for Z′ bosons using both LEP I and LEP II cross-section and forward-backward asymmetry results. The LEP I data constrain the mixing of the Z′ field with the $\mathcal{SM}$ Z^0 field ($\theta_{ZZ'}$) and the LEP II data constrain the mass of the Z′ ($M_{Z'}$) Results from individual experiments indicate that the mixing of the Z′ field with the $\mathcal{SM}$ Z^0 field ($\theta_{ZZ'}$) should be small. LEP combined limits on Z′ mass ($M_{Z'}$) have been obtained using just the combined LEP II cross-section and forward-backward asymmetry results, assuming $\theta_{ZZ'} = 0$ [4]. The largest preliminary 95% confidence limit, $M_{Z'} > 1890$ GeV is found for the Sequential Standard Model (SSM), where the Z′ couplings to fermions are taken to be identical to the $\mathcal{SM}$ Z^0 couplings.

4.4 Gravity in extra dimensions

The idea that gravitational interactions in large extra dimensions can give rise to significant effects in high energy colliders should, by now, be well known [12]. The LEP experiments have searched for such phenomena in $e^+e^- \to f\bar{f}$ and other channels. In $e^+e^- \to f\bar{f}$ gravitational effects arise from the exchange of large numbers of gravitons, leading to a modification of the differential cross-sections for $e^+e^- \to f\bar{f}$, which can be parameterised as

$$\frac{d\sigma}{d\cos\theta} = A + B\left[\frac{\lambda}{M_s^4}\right] + C\left[\frac{\lambda}{M_s^4}\right]^2 .$$

The functions $A(\cos\theta)$, $B(\cos\theta)$ and $C(\cos\theta)$ parameterise, the $\mathcal{SM}$ processes, the interference between $\mathcal{SM}$ and gravity and the purely gravitational process. M_s set the scale for gravity in large extra dimensions. The coupling λ is taken to be either $+1$ or -1.

	M_s[TeV] (95% C.L.)	
	$\lambda = -1$	$\lambda = +1$
ALEPH	> 0.80	> 1.18
L3	> 0.98	> 1.06
OPAL	> 1.15	> 1.00

Table 2: Preliminary 95% confidence lower limits on the scale M_s from $e^+e^- \to e^+e^-$.

The best preliminary limits on M_s from LEP come from measurements of the $e^+e^- \to e^+e^-$ process in individual experiments, these are shown in Table 2. There is no combined LEP result as yet, but due to the $\frac{1}{M_s^4}$ dependence of the differential cross-section, combining LEP results will only give a modest improvement in the sensitivity to M_s.

5. Determination of the LEP beam energy

Determining the LEP beam energy (E_{BEAM}) is critical to the measurement of the mass of the W boson (M_W) - a central part of the LEP II program. At LEP I, the beam energy could be determined to $\mathcal{O}(1\ \mathrm{MeV})$ [13] at LEP II, the precision of the LEP determination is limited to $\mathcal{O}(20\ \mathrm{MeV})$ [14].

An alternative means of determining E_{BEAM} has been developed by the experiments, using radiative return $e^+e^- \to f\bar{f}$ events. In the case that a single ISR photon is emitted collinear to the incoming e^+ or e^-, the ratio $\sqrt{s'}/\sqrt{s}$ can be found from the polar angle of the fermion and anti-fermion with respect to the e^- direction. So, for radiative return events, assuming $\sqrt{s'} \sim \mathrm{M_Z}$, yields an estimate of the LEP centre-of-mass energy $(\sqrt{s})^2$, with an intrinsic event-by-event resolution determined by the width of the Z. In practice, the experiments use either the polar angles alone or constrained kinematic fits to obtain event-by-event estimates of the centre of mass energy. The distribution of the estimates can be fitted to determine a central value, which is usually quoted as the difference between the centre-of-mass energy determined from the $e^+e^- \to f\bar{f}$ events and the LEP measurements (ΔE_{BEAM}). A preliminary combination of the values presented in [3], taking into account common systematic uncertainties, gives

$$\Delta E_{\mathrm{BEAM}} = -12 \pm 37(\mathrm{stat.}) \pm 29(\mathrm{syst.})\mathrm{MeV},$$

which is consistent with 0, providing a significant cross-check of the LEP beam energy determination. These are non-trivial measurements, relying on good alignment and calibration of the LEP detectors' tracking and calorimetry in the forward and backward regions of the detectors.

6. Summary

The LEP II $e^+e^- \to f\bar{f}$ data provide a test of the Standard Model at the $\mathcal{O}(1\%)$ level. Preliminary data are in good agreement with predictions, and provide tight constraints on physics beyond the Standard Model. The radiative return events can also be used to cross-check the determination of the LEP beam energy. Data taking is now over, some of the results presented here use data from the full LEP II data set. The LEP collaborations are working to finalise their analyses, and also combined final results. In some areas small improvements can be expected, in others, particular the measurements of heavy flavours production, more substantial improvements are possible.

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