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Fermion pair production at LEP2

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In 1995-2000 the LEP collider was operated at the energies significantly above the region of Z resonance. I present the results of the four LEP experiments on the measurement of the fermion pairs at the highest energy (up to 209 GeV). The experiments have studied the production of leptons, inclusive quark pairs and pairs of tagged heavy quarks. Production cross-sections and asymmetries were measured. No sign of the "new physics" have been observed and stringent constrains were imposed on the theories beyond the Standard Model.

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The LEP (Large Electron-Positron) collider was operated in 1989-2000 in CERN (Geneva). The collision products were registered by the four general-purpose detectors - ALEPH, DELPHI, L3 and OPAL. The dominant process in the electron-positron annihilation was the production of fermion-antifermion pairs: $e^+e^- \to Z/\gamma \to \mathrm{f}\,\bar{\mathrm{f}}$.

In the initial phase (LEP1, 1989-1995) LEP was operated at the energies around Z resonance. About 20 millions of Z decays were recorded by the LEP experiment, resulting in a very precise determination of the Standard Model parameters. In the second phase (LEP2, 1995-2000) the energy of electron-positron collisions was boosted to the world highest values, up to 209 GeV. Although the collected statistics of the fermion pairs was approximately 100 times smaller than at the LEP1, the high annihilation energy allowed the experiments to perform precision tests of the Standard Model and to impose stringent constrains on the theoretical models involving the so-called "new physics".

A characteristic feature of the fermion pair production at LEP2 is the effect of *radiative return* to the Z resonance. If the initial state radiation (ISR) photon is emitted with the high enough energy, the electron-positron collision may happen at the actual energy close to the Z resonance (91 GeV). The probability of such radiative return is greatly enhanced by the fact that the annihilation cross-section at the resonance is hundreds times higher than at the typical LEP2 energies.

The actual annihilation energy ($\sqrt{s'}$) can be reconstructed experimentally from the directions of the final state fermions (which are measured much more precisely than the fermion energies). An example of the reconstructed $\sqrt{s'}$ spectrum is presented in fig.1 (left). One can see that there are two distinct classes of events: *non-radiative* events (with $\sqrt{s'}$ almost equal to the nominal collision energy) and the radiative return events. It is natural to expect that the possible effects of the "new physics" would manifest themselves at the highest actual annihilation energy. Therefore the results on fermion pair production at LEP2 are quoted separately for the two event classes: for the non-radiative events ($\sqrt{s'/s} < 0.85$) and for the *inclusive* event class (which includes almost all values of $\sqrt{s'}$).

The following observables were measured by all four LEP experiments: the fermion pair production cross-section; the forward-backward charge asymmetry (A_{FB}) for the leptonic pairs; and the angular differential cross-section for the leptonic pairs. The lepton production angle is defined as the angle between the directions of the beam electron and the negatively charged final state lepton. The same convention is used for the definition of the forward-backward charge asymmetry. The differential cross-sections were measured only for the non-radiative event samples.

The examples of the measurements of the total cross-section and A_{FB} are presented in fig.1 (middle and right). The differential leptonic cross-sections are presented in fig.2. No significant

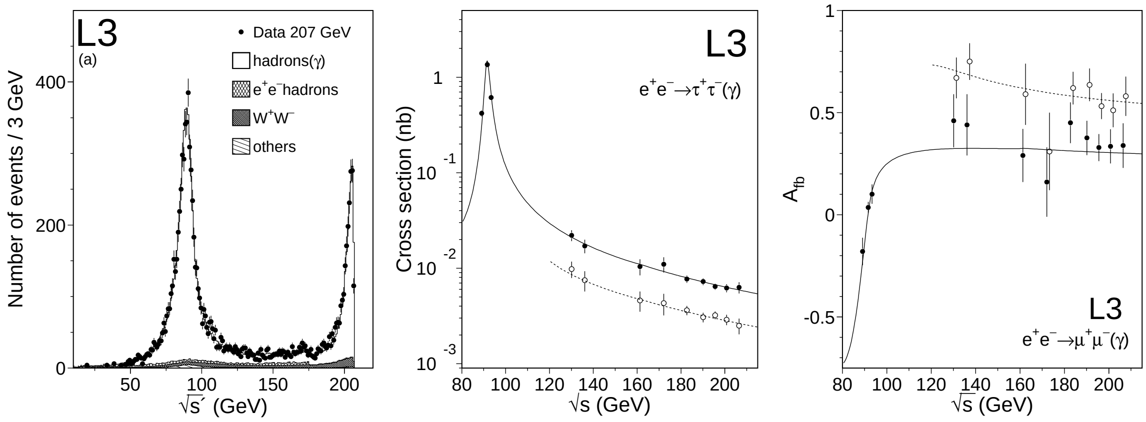

Figure 1: Left: reconstructed $\sqrt{s\prime}$ for the ee$\to$qq(γ) process. Middle: energy dependence of the measured cross-section of the ee$\to$ $\tau\tau(\gamma)$ process. Right: energy dependence of the measured forward-backward asymmetry of the ee$\to$ $\mu\mu(\gamma)$ process. Open circles represent non-radiative samples, black circles are for the inclusive samples. The curves show the predictions of the Standard Model.

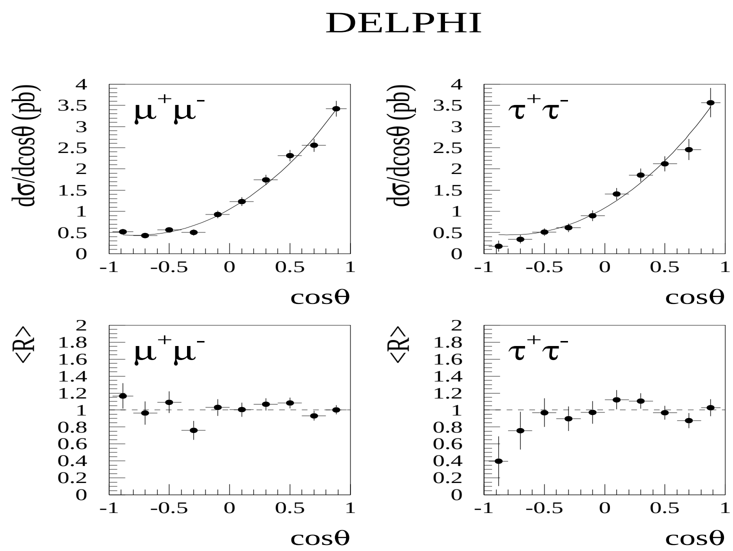

Figure 2: Upper plots: the measured differential cross-section of muon (left) and tau (right) pair production. The curves show the Standard Model predictions. Lower plots: the ratio of the measurements and the Standard Model predictions.

deviation from the predictions of the Standard Model was observed neither in the results of the individual experiments, nor in the combined LEP results.

In addition to the measurement of the flavor-inclusive process ee$\to$qq, one can also measure cross-sections and asymmetries of the flavor-tagged heavy quark pairs ee$\to$bb and ee$\to$cc. The heavy quarks can be tagged in different ways: using the reconstructed secondary decay vertex, leptons from the semi-leptonic decays or the kinematic differences between decays of the heavy quarks and the fragmentation of the light quarks.

The measured flavor-tagged cross-sections are usually presented in terms of the so-called "R ratio", i.e. the fraction of the heavy quark pairs in the inclusive sample of hadronic final states. At this conference OPAL has presented the recent measurement of R_b, i.e. the "R ratio" for the tagged b-quark pairs. The energy dependence of R_b is presented in fig.3 (left). Only the non-radiative events were used. The measurements are in a good agreement with the Standard Model prediction.

In addition to the cross-sections and asymmetries, DELPHI has performed a measurement of the tau lepton polarisation at LEP2 energies. The energy spectra of the tau decay products were used as the polarisation analyzers. The tau polarisation was measured for the events with rather high actual annihilation energy: $\sqrt{s'/s} < 0.92$ The measurements are presented in fig.3 (right). One can see that the results agree well with the Standard Model.

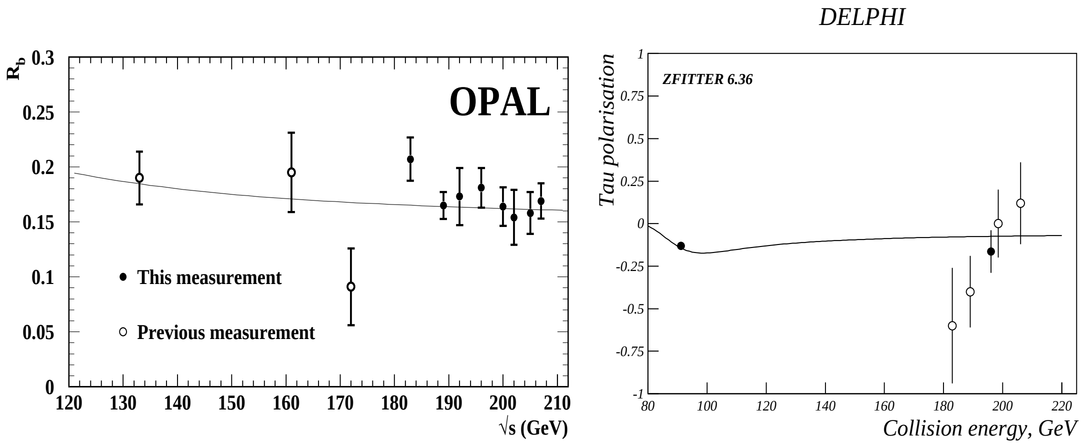

Figure 3: Left: energy dependence of the "R_b ratio". Right: tau polarisation measurements at LEP1 and at LEP2. On both plots the curves show the predictions of the Standard Model.

The LEP experiments have used their measurements of the fermion pair production to test various theoretical models beyond the Standard Model. In particular were tested the theories of four-fermion contact interactions; models involving additional Z-bosons (Z'); R-parity violating s-neutrino exchange; existence of large (millimeter-scale) extra dimensions; interactions involving leptoquarks. In all cases the experimental results were consistent with the predictions of the Standard Model and as a consequence no sign of the "new physics" was found. Stringent limits were set on the parameters of the tested theories. For example, the lower limits on the energy scales of the contact interactions are typically 10-15 TeV.

To summarize, all four LEP experiments have performed the precision measurements of fermion pair production at the energies up to 209 GeV. Typical experimental precision was at the level of 1-3%. All results were in a good agreement with the Standard Model. Various theoretical models were tested, but no sign of the "new physics" was found. Stringent constrains were imposed on the parameters of theories beyond the Standard Model.