RESEARCH AT CERN LARGE ELECTRON-POSITRON COLLIDER. L3 EXPERIMENT

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The world's biggest accelerator complex – Large Electron-Positron Collider (LEP) – was constructed in the 80s at the European Centre for Nuclear Research – CERN. The electron and positron beams are accelerated up to the energies of about 45 GeV[1] in a 50–170 m deep, 27 km long tunnel. The Z^0 bosons, the weak interaction carrier particles, are born in the collisions of these beams.

The four detectors located in the underground halls at the beams intersection points are aimed at the comprehensive study of the phenomena taking place at such high energies. The largest of the four detectors – L3 – was created by the joint efforts of physicists and engineers of 15 countries of Western and Eastern Europe, Asia, and USA. Starting from 1986, PNPI also participates in the L3 experiment.

The main specific feature of the L3 detector is its high (the best among the LEP experiments) energy resolution at photon and lepton registration. This was the main priority in the detector design.

The L3 Detector

The L3 magnet is the largest ever used in the scientific research: its magnetic field volume is about $12 \times 12 \times 12$ m^3. Almost all the detector elements are located inside a 7800 ton magnet. The magnetic field along the beam axis is about 0.5 T. The cross section of the detector is presented in Fig. 1.

The detector elements are supported with a 45 m long, 4.45 m diameter steel tube. The muon spectrometer is mounted outside the tube, while the muon filter, hadron calorimeter, electromagnetic calorimeter, central and forward-backward trackers[2] are located inside the tube.

Muon detector

The muon detector consists of two 6 m long "wheels". Each of them, in turn, contains eight independent structures – octants. Each octant comprises five drift chambers measuring the track coordinates in the plane perpendicular to the Z-axis (i.e. electron beam direction): the outer layer contains two chambers with 16 wires in each, the middle one – two chambers (24 wires), and the inner layer consists of one chamber with 16 signal wires in it. Besides, both inner and outer layers are surrounded by the drift chambers measuring the coordinates along the Z-axis. As the trajectory of a muon with the energy above 3 GeV does not get out of one octant, the high precision alignment is only carried out within an octant. The alignment systematic error does not exceed 30 μm. The precision of the muon spectrometer measurements is cross-checked by the determination of the Z^0-boson mass in the decay $Z^0 \to \mu^+\mu^-$. The muon momentum resolution observed is $\sigma(P_\mu/E_{beam}) = 2.5\%$.

[1] In 1996 the LEP-2 program started with the beam energies reaching 100 GeV.

[2] In 1993 – 1995 the endcap muon chambers and the silicon vertex detector were also implemented in the L3 detector.

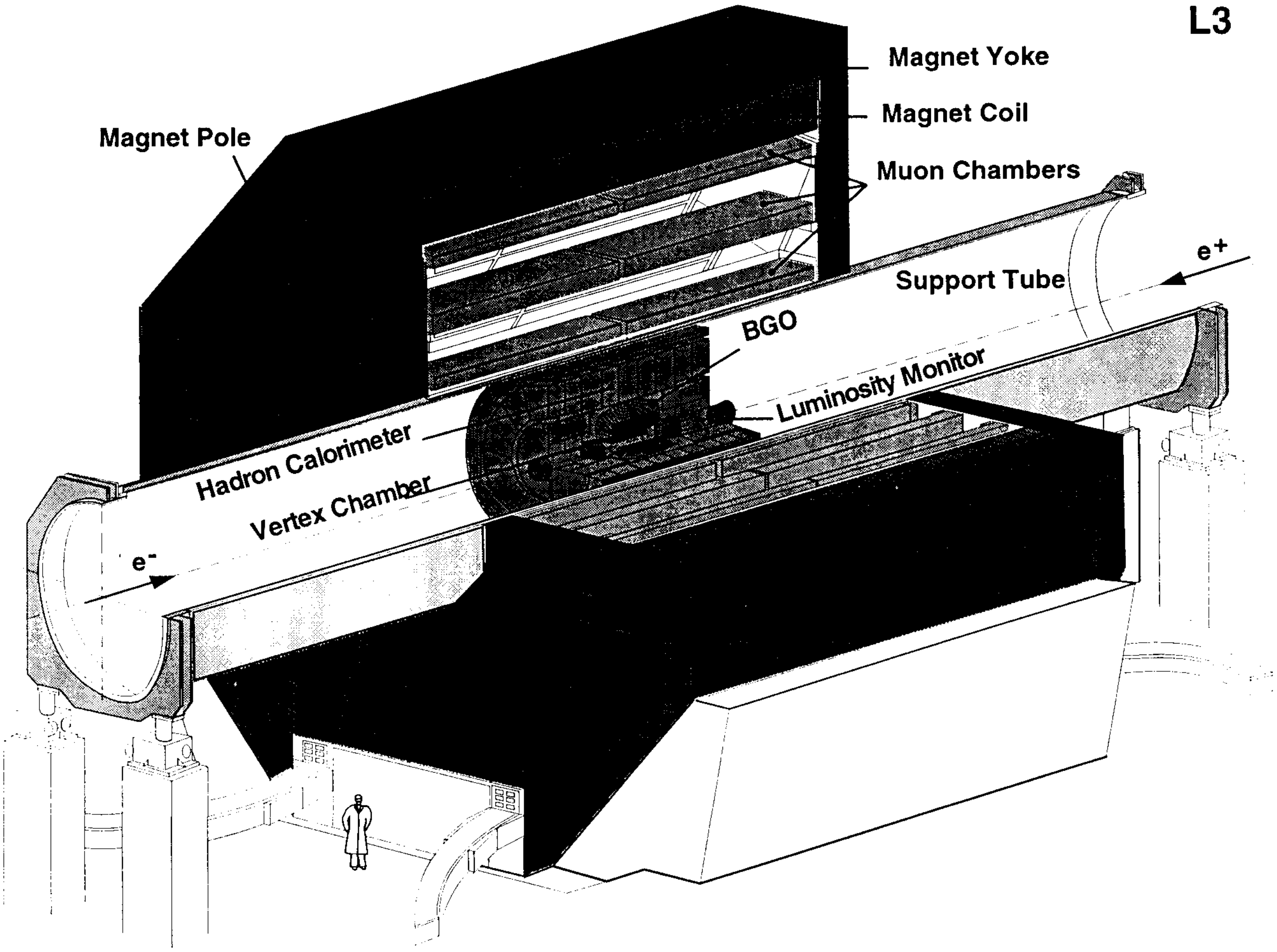

Fig. 1. Cross section of the L3 detector.

Hadron calorimeter and muon filter

The energy of hadrons produced in the e^+e^- collisions is measured by the total absorption method with the electromagnetic and hadron calorimeters. The uranium plates interleaved with the multiwire proportional chambers are used as the absorber. The calorimeters also serve as a filter allowing only the minimum ionizing particles to reach the muon spectrometer. The total length of the electromagnetic and hadron calorimeters corresponds to 6–7 nuclear absorption lengths.

The signals coming from wires of the proportional chambers of the hadron calorimeter are grouped in a way to measure the energy flow in so-called towers "looking" towards the interaction point at the solid angle with $\Delta\theta = 2°$, $\Delta\varphi = 2°$. The towers segmentation in the radial direction is provided by grouping wires within each of the ten calorimeter layers. The detailed information on the space distribution of the energy in hadron showers allows to determine the shower axis direction with the precision of about 2.5°. The total energy deposited in the hadron decays of Z^0 boson can be measured with the error not exceeding 10%.

The muon filter is located inside the supporting tube and adds about one nuclear absorption length. It consists of six brass absorber layers interleaved with the five layers of pipe-shaped proportional counters parallel to the Z-axis.

The hadron calorimeter and muon filter are also very effective in the minimum ionizing particle registration thus allowing to improve substantially the muon identification.

Electromagnetic calorimeter

The L3 electromagnetic calorimeter has high energy and space resolutions in a wide energy range (from 100 MeV up to 100 GeV). It consists of 11,000 bismuth germanium oxide (BGO) crystals. Each crystal is shaped as a 27 cm long truncated pyramid, inner and outer base areas being 2×2 cm^2 and 3×3 cm^2, respectively. The calorimeter energy resolution is equal to 5% at the electron energy 100 MeV and 1.5% at high energies. The spatial resolution at 2 GeV is about 2 mm. The calorimeter allows reliable identification of the electrons and photons: the hadronic admixture does not exceed 0.1%.

Central tracker

The full length of a charged particle track in the central tracker is about 30 cm. To determine the charge signature at the energy of 50 GeV, at least 50 measurements are required with the precision of 50 μm. This goal was achieved by creation of a dedicated drift chamber – Time Expansion Chamber (TEC). The signal wires parallel to the Z-axis are put in a high electric field. The wires are separated from the low-field area (where the drift of electrons mostly takes place) by a grid. The usage of a gas mixture [3] with low diffusion at high pressure (1.2 bar) and low drift velocity (6 μm/ns) has allowed to solve the above problem successfully.

The central tracker is surrounded by two cylindrical proportional chambers with the cathode read-out allowing to measure Z-coordinate of the track with the precision of 300 μm that corresponds to the polar angle measurement with the precision of ~ 1 mrad.

The central tracker provides high-precision measurements of the track parameters in the polar angle range $45^\circ - 135^\circ$. Beyond this range, the precision of the polar angle determination falls down substantially ($\sigma_\theta \approx 10$ mrad). The number of measurements of the track coordinates getting smaller, the precision of the momentum determination lowers too.

The Forward-backward Tracking Chambers – FTC

Measurement of the charged particle track in the polar angles range $14^\circ - 35^\circ$ and $145^\circ - 166^\circ$ is carried out jointly by TEC and the Forward-backward Tracking Chambers (FTC). The FTC subdetectors occupy about 100 mm space along the beam between the TEC flanges (about one radiation length thick) and the electromagnetic calorimeter. The precision in measurement of the two track coordinates (X and Y) by FTC is better than 200 μm.

FTC consists of four disks each containing 26 rectangular cells of four-wires drift chambers determining the track coordinates in the plane perpendicular to the Z-axis by the drift time measurements. Besides, the measurement of the signal amplitudes from both ends of the wires allows to determine the track coordinate along the wire by the charge division method.

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[3] 80% CO_2 + 20% C_4H_{10}.

Fig. 2 presents an example of dependence of the spatial resolution on the drift time. The resolution is getting worse at small drift times because of fluctuations in the ionization process. At larger drift times the resolution is also getting somewhat spoiled by the electron cloud diffusion. A thorough shaping of the quasi-uniform electric field (Fig. 3) allowed to reduce substantially the edge effects inevitable in such small drift cells [1].

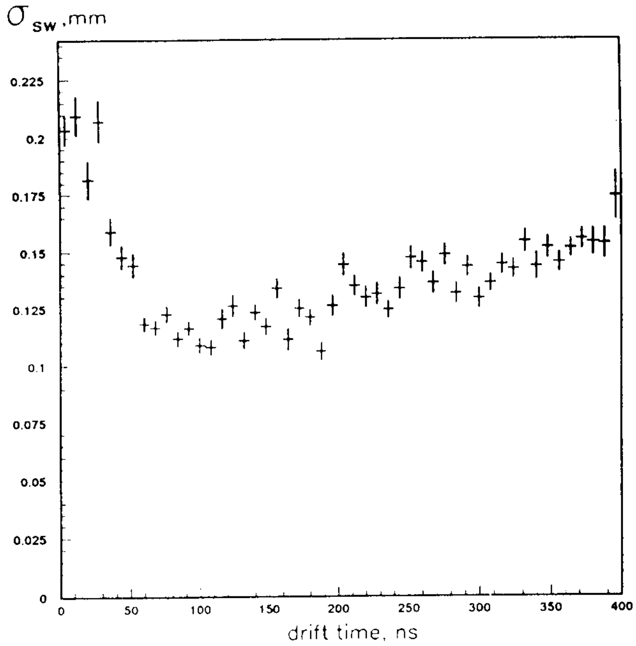

Fig. 2. FTC single wire spatial resolution vs drift time.

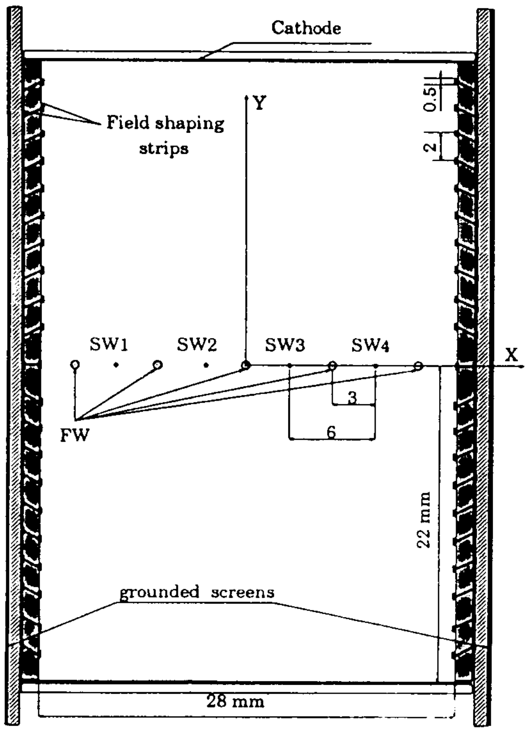

Fig. 3. FTC cell layout. Shown are the field-shaping strips to form the quasi-uniform electric field. SW – signal wires, FW – field-shaping wires.

The minimum distance of the tracks separation is also predefined by the detector layout. The measured value (2.5–2.7 mm) corresponds to the expectations. While measuring the coordinate by the charge division method the resolution proved to be about 20 mm, which is a good result for a standard low-Ohm wires used in the FTC.

The quality of the FTC calibration and alignment can be illustrated with an example of the two-particle decay $Z^0 \rightarrow \mu^+\mu^-$. The muons produced in this decay have large momenta (~ 45 GeV/c). In the polar angle ranges $14° - 35°$ and $145° - 166°$ the number of TEC-measured points is 1.5–2 times smaller than that in the central region of the detector. That is why the probability of the charge sign determination to be wrong is close to 50% when the TEC information is only used. Although precision of the coordinate measurement by FTC is somewhat lower than by TEC, the muon path length in the magnetic field is here approximately 1.5 times larger (the precision of the track curvature measurement is proportional to the length squared). Fig. 4 shows the distribution of the azimuthal angles difference of the muon trajectories as measured by FTC: the two peaks correspond to the two different directions of the negatively charged muons – to the forward or backward hemispheres. The figure shows that the probability of error in the charge sign determination is low.

The high precision of the polar angle θ measurement by FTC is quite evident: the distance to the L3 detector centre is provided by the geodesic measurements, and the coordinates of the FTC disks intersection points for the particle tracks are determined with at least a 200 μm precision; hence $\sigma_{FTC}(\theta) \approx 0.5$ mrad. However, at the momenta lower than 15 GeV/c the multiple scattering in the TEC flanges limits the precision of the polar angle determination.

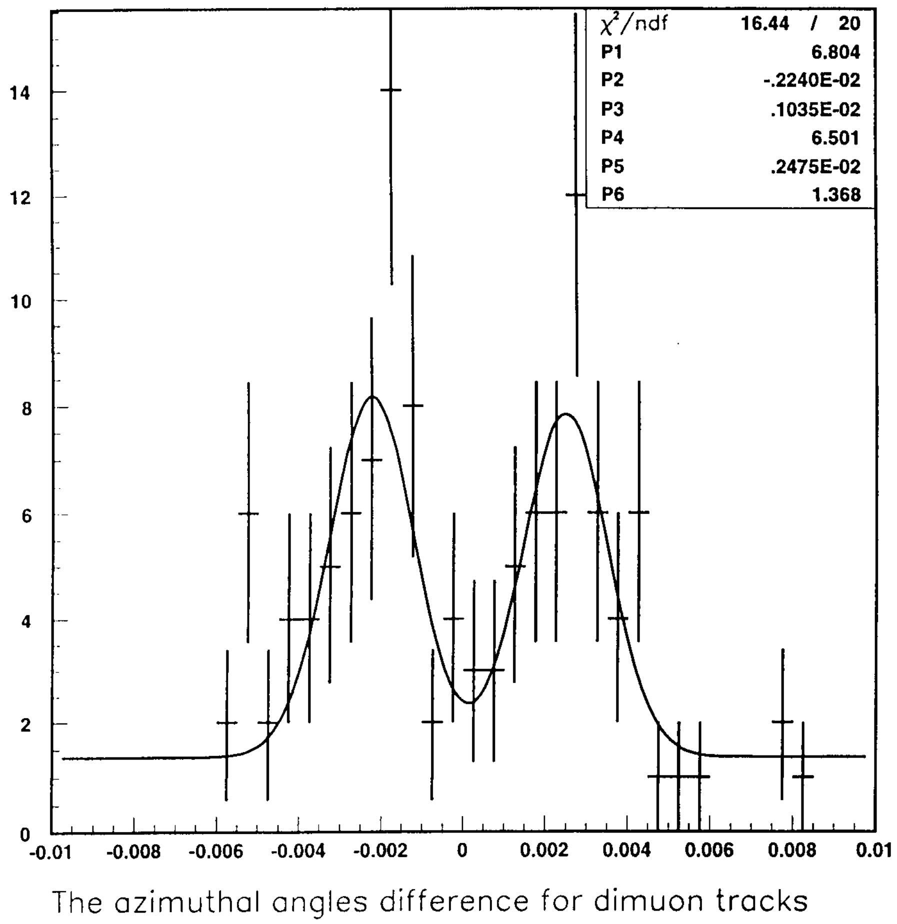

Fig. 4. The difference in radians of the azimuthal angles in the dimuon events as measured by FTC.

Main results

Since 1989, the L3 detector has registered about 5 millions of the Z^0-boson decays. The data processing is still under way. There is no reason, however, to expect the final analysis to bring any significant changes to the already published fundamental physical conclusions.

Electroweak parameters and test of the Standard Model

The electroweak parameters have been determined from the measurements of the reactions $e^+e^- \to \text{hadrons}(\gamma)$, $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^- \to \tau^+\tau^-(\gamma)$, $e^+e^- \to e^+e^-(\gamma)$. All measurements support the hypothesis of lepton universality. The properties of the Z^0 boson were obtained from the hadronic and leptonic cross section data:

$$m_Z = 91195 \pm 9 \text{ MeV},$$
$$\Gamma_Z = 2494 \pm 10 \text{ MeV},$$
$$\Gamma_{\text{had}} = 1748 \pm 10 \text{ MeV},$$
$$\Gamma_l = 83.49 \pm 0.46 \text{ MeV}.$$

The corresponding invisible width of 496.5 ± 7.9 MeV constrains, within the Standard Model, the number of light neutrino species to be

$$N_\nu = 2.981 \pm 0.050.$$

A direct determination of the number of light neutrino families N_ν was performed by measuring the cross section of the radiative process $e^+e^- \to \nu\bar{\nu}\gamma$:

$$N_\nu = 3.14 \pm 0.24(\text{stat}) \pm 0.12(\text{syst}).$$

Including the leptonic forward-backward asymmetries and the average τ polarization, the effective neutral weak current coupling constants for charged leptons were found to be

$$\bar{g}_{Vl} = -0.0378^{+0.0045}_{-0.0042},$$
$$\bar{g}_{Al} = -0.4998 \pm 0.0014.$$

Within the framework of the Standard Model and including L3 measurements of the $Z^0 \to b\bar{b}$ forward-backward asymmetry and partial decay width, an effective electroweak mixing angle of

$$\sin^2 \bar{\theta}_W = 0.2326 \pm 0.0012$$

was derived. An estimate for the top-quark mass of

$$m_t = 158^{+32}_{-40} \pm 19(\text{Higgs}) \text{ GeV}$$

was also obtained. The mass of the W-boson was estimated to be

$$m_W = 80.22 \pm 0.22 \text{ GeV}$$

Analysis of isolated hard photons (direct photons) produced in the hadronic decays of the Z^0 boson allowed to constrain the effective electroweak couplings of quarks to the Z^0 boson

$$c_{u,d} = 4(\bar{g}_V^2 + \bar{g}_A^2)_{u,d},$$

where the subscripts u and d denote quarks with charge $+2/3$ (u-type) and with charge $-1/3$ (d-type), respectively. Combining the obtained result with an independent constraint from L3 measurement of the total hadronic width of the Z^0 boson, the following values were found:

$$c_u = 0.92 \pm 0.22, \quad c_d = 1.63 \pm 0.15.$$

These results are consistent with the Standard Model prediction:

$$c_u = 1.156 \pm 0.014, \quad c_d = 1.486 \pm 0.015.$$

For lepton flavour violating decays of the Z^0 boson the following limits (95% C.L.) have been obtained:

$$B(Z^0 \to e\mu) < 0.6 \cdot 10^{-5},$$
$$B(Z^0 \to e\tau) < 1.3 \cdot 10^{-5},$$
$$B(Z^0 \to \mu\tau) < 1.9 \cdot 10^{-5}.$$

Search for new particles

The existence of the Higgs boson H^0 in the Minimal Standard Model has been excluded (95% C.L.) in the mass range $0 \leq m_{H^0} < 57.7$ GeV. No indication for the production of neutral and charged Higgs bosons predicted in the non-minimal models has been found.

There is no indication for the existence of the additional heavy gauge boson Z'; the fitted $Z - Z'$ mixing angle is compatible with zero for all models considered.

A sample of events with one or two isolated hard photons was used to look for new processes involving photon emission. For production of excited quarks, the following limits (95% C.L.) were found:

$$\sigma(e^+e^- \to Z^0 \to q^*q) \times B(q^* \to q\gamma) < 10 \text{ pb},$$
$$\sigma(e^+e^- \to Z^0 \to q^*q^*) \times B^2(q^* \to q\gamma) < 2 \text{ pb}.$$

No signal has been observed in the search for neutralinos. This leads to upper limits of a few times 10^{-5} on the branching ratios $Z^0 \to \chi\chi'$ and $Z^0 \to \chi'\chi'$. In the framework of the Minimal Supersymmetric Standard Model the lightest neutralino χ was excluded with m_χ less than 18 GeV if either $\tan\beta > 2$ or the gluino mass $m_{\tilde{g}} > 100$ GeV.

The three types of isosinglet neutral heavy leptons N_e, N_μ, N_τ, that are expected in many extensions of the Standard Model, have been directly searched for. No evidence for the signal has been found. The limit

$$B(Z^0 \to \nu_l N_l) < 3 \cdot 10^{-5}$$

at the 95% C.L. was set for the mass range from 3 GeV up to m_Z.

The hadronic lineshape of the Z^0 boson has been analyzed for an evidence of new, narrow vector resonances in the Z^0-mass range. No evidence for new states was found, and it was possible to exclude (95% C.L.) a quarkonium state in the mass range from 87.7 to 94.7 GeV.

Four-fermion events were used to search for new particles coming from the process $e^+e^- \to Z^0 \to XZ^*$, where X or Z^* decays into ll or qq pair. The number of observed events and their kinematics distributions were found to be consistent with calculations based on the Standard Model. No significant structure was seen in the dilepton invariant or in the recoil mass spectra.

No signal was observed in the search for single-photon events with $E_\gamma > \frac{1}{2}E_{beam}$. From this result it was found that the parameter β, used to characterize the strength of the Z^0 electric dipole transition, is less than 0.80 (95% C.L.) and that the existence of a superlight gravitino with mass less than 10^{-14} GeV is ruled out in a wide region of the supersymmetric parameter space.

A lower mass limit of 510 GeV was obtained for a magnetic monopole coupled to the Z^0 boson.

Test of QED

The total and differential cross sections of the reaction $e^+e^- \to \gamma\gamma(\gamma)$ have been measured at the centre-of-mass energies around 91 GeV. The results are in good agreement with the QED predictions. The lower limits (95% C.L.) were set on the energy scale parameter of the contact interaction ($\Lambda > 602$ GeV), on the mass of the excited electron ($m_e^* > 146$ GeV), and on the QED cut-off parameters ($\Lambda_+ > 149$ GeV and $\Lambda_- > 143$ GeV).

The following upper limits (95% C.L.) were also set for radiative decays of the Z^0 bosons:

$$B(Z^0 \to \gamma\gamma) < 5.2 \cdot 10^{-5},$$
$$B(Z^0 \to \pi^0\gamma) < 5.2 \cdot 10^{-5},$$
$$B(Z^0 \to \eta\gamma) < 7.6 \cdot 10^{-5},$$
$$B(Z^0 Z^0 \to \gamma\gamma\gamma) < 3.3 \cdot 10^{-5}.$$

Determination of α_s

The strong coupling constant α_s has been determined by three different methods: from the study of the global event shape, from the heavy jet mass, and from the energy-energy jets correlations. The combined result was found to be

$$\alpha_s(91.2 \text{ GeV}) = 0.125 \pm 0.003(\text{exp}) \pm 0.008(\text{theor}).$$

Inclusive production of hadrons in Z^0-decays

From the measurement of inclusive production of J and χ_c in hadronic Z^0-decays the following branching ratios have been determined:

$$B(Z^0 \to J + X) = (3.6 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})) \cdot 10^{-3},$$
$$B(b \to J + X) = (1.3 \pm 0.2(\text{stat}) \pm 0.2(\text{syst})) \cdot 10^{-2},$$
$$B(Z^0 \to \chi_{c1} + X) = (7.5 \pm 2.9(\text{stat}) \pm 0.6(\text{syst})) \cdot 10^{-3},$$
$$B(b \to \chi_{c1} + X) = (2.4 \pm 0.9(\text{stat}) \pm 0.2(\text{syst})) \cdot 10^{-2},$$

An upper limit (90% C.L.) was set on J meson production from excited gluons:

$$B(Z^0 \to q\bar{q}g^*;\ g^* \to J + X) < 7.0 \cdot 10^{-4}.$$

The inclusive production of neutral hadrons π^0, η, K_s^0, and Λ from Z^0-decays has also been measured. Comparing the obtained results with low energy e^+e^- data, it was shown that QCD describes the shape and energy evolution of the hadron spectra.

B physics

From the sample of the $Z^0 \to q\bar{q}$ events the ratio $R_b = \Gamma_{b\bar{b}}/\Gamma_{\mathrm{had}}$ has been measured:

$$R_b = 0.222 \pm 0.003(\mathrm{stat}) \pm 0.007(\mathrm{syst}).$$

Using a sample of $Z^0 \to b\bar{b}$ events, the following quantities have been determined.
The average b hadron lifetime:

$$\tau_b = 1535 \pm 35(\mathrm{stat}) \pm 28(\mathrm{syst})\ \mathrm{fs}.$$

The inclusive production ratio of B^* mesons relative to B mesons:

$$N_{B^*}/(N_{B^*} + N_B) = 0.76 \pm 0.08(\mathrm{stat}) \pm 0.06(\mathrm{syst}).$$

The inclusive $b \to \tau\nu X$ branching ratio:

$$B(b \to \tau\nu X) = 0.024 \pm 0.007(\mathrm{stat}) \pm 0.008(\mathrm{syst}).$$

The time integrated $B^0 - \bar{B}^0$ mixing parameter that corresponds to the composition of the B_s^0 and B_d^0 states produced in Z^0 decays was determined to be

$$\chi_B = 0.123 \pm 0.012(\mathrm{stat}) \pm 0.008(\mathrm{syst}).$$

Combining this measurement with the B_d^0 mixing value measured by the CLEO Collaboration, a value for the B_s^0 mixing parameter was extracted:

$$\chi_s = 0.43^{+0.26}_{-0.17}.$$

The $b\bar{b}$ forward-backward asymmetry at the effective centre-of-mass energy $\sqrt{s} = 91.30$ GeV was measured to be

$$\mathrm{A}_{b\bar{b}} = 0.087 \pm 0.011(\mathrm{stat}) \pm 0.004(\mathrm{syst}).$$

This corresponds to the effective electroweak mixing angle

$$\sin^2 \bar{\theta}_W = 0.2335 \pm 0.0021.$$

No evidence for a signal was found in the search for the electromagnetic penguin decay $b \to s\gamma$, for decays $B^0_{d,s} \to \gamma\gamma$, and for the rare charmless decays of $B^0_{d,s}$ mesons in the neutral exclusive channels $\eta\eta$, $\eta\pi^0$ and $\pi^0\pi^0$. The following upper limits (90% C.L.) have been set:

$$\begin{aligned}
B(b \to s\gamma) &< 1.2 \cdot 10^{-3}, \\
B(B_d^0 \to \gamma\gamma) &< 3.9 \cdot 10^{-5}, \\
B(B_s^0 \to \gamma\gamma) &< 14.8 \cdot 10^{-5}, \\
B(B_d^0 \to \eta\eta) &< 4.1 \cdot 10^{-4}, \\
B(B_s^0 \to \eta\eta) &< 1.5 \cdot 10^{-3}, \\
B(B_d^0 \to \eta\pi^0) &< 2.5 \cdot 10^{-4}, \\
B(B_s^0 \to \eta\pi^0) &< 1.0 \cdot 10^{-3}, \\
B(B_d^0 \to \pi^0\pi^0) &< 6.0 \cdot 10^{-5}, \\
B(B_s^0 \to \pi^0\pi^0) &< 2.1 \cdot 10^{-4}.
\end{aligned}$$

Properties of τ leptons

For the hadronic one-prong τ decays the following branching ratios have been measured:

$$B(\tau \to \pi/K\ \nu_\tau) = 0.1182 \pm 0.0026(\mathrm{stat}) \pm 0.0043(\mathrm{syst}),$$
$$B(\tau \to \pi/K\ \pi^0\ \nu_\tau) = 0.2505 \pm 0.0035(\mathrm{stat}) \pm 0.0050(\mathrm{syst}),$$
$$B(\tau \to \pi/K\ 2\pi^0\ \nu_\tau) = 0.0888 \pm 0.0037(\mathrm{stat}) \pm 0.0042(\mathrm{syst}),$$
$$B(\tau \to \pi/K\ 3\pi^0\ \nu_\tau) = 0.0170 \pm 0.0024(\mathrm{stat}) \pm 0.0038(\mathrm{syst}).$$

The branching ratios for τ decays with neutral kaons have also been obtained:

$$B(\tau^- \to \nu_\tau \pi^- \bar{K}^0) = 0.0095 \pm 0.0015(\mathrm{stat}) \pm 0.0006(\mathrm{syst}),$$
$$B(\tau^- \to \nu_\tau \pi^- \pi^0 \bar{K}^0) = 0.0041 \pm 0.0012(\mathrm{stat}) \pm 0.0003(\mathrm{syst}),$$
$$B(\tau^- \to \nu_\tau \pi^- K^0 \bar{K}^0) = 0.0031 \pm 0.0012(\mathrm{stat}) \pm 0.0004(\mathrm{syst}).$$

From the measured polarization of the τ leptons $P_\tau(\cos\theta)$ the quantities

$$A_l = 2g_{Vl}g_{Al}/(g_{Vl}^2 + g_{Al}^2), \quad l = \mathrm{e}, \tau$$

were obtained:

$$A_\tau = 0.150 \pm 0.013(\mathrm{stat}) \pm 0.009(\mathrm{syst}),$$

$$A_\mathrm{e} = 0.157 \pm 0.020(\mathrm{stat}) \pm 0.005(\mathrm{syst}).$$

This corresponds to the following ratio of vector to axial-vector weak neutral couplings for electrons

$$g_{V\mathrm{e}}/g_{A\mathrm{e}} = 0.0791 \pm 0.0099(\mathrm{stat}) \pm 0.0025(\mathrm{syst})$$

and for τ's

$$g_{V\tau}/g_{A\tau} = 0.0752 \pm 0.0063(\mathrm{stat}) \pm 0.0045(\mathrm{syst})$$

consistent with the hypothesis of $e - \tau$ universality. Assuming universality of the $e - \tau$ neutral current, the effective electroweak mixing angle was determined:

$$\sin^2\bar{\theta}_W = 0.2309 \pm 0.0016.$$

The analysis of a sample of the energetic single-photon events ($E_\gamma > 15$ GeV) allowed to set the upper limit of $4.1 \cdot 10^{-6} \mu_B$ (90% C.L.) on the magnetic moment of the τ neutrino.

Gamma-gamma physics

The reaction $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-K_s^0K_s^0$ has been studied and formation of the $f_2'(1525)$ resonance was observed. The radiative width times the branching ratio was measured to be

$$\Gamma_{\gamma\gamma}(f_2') \times B(f_2' \to K\bar{K}) = 0.093 \pm 0.018(\mathrm{stat}) \pm 0.022(\mathrm{syst})\ \mathrm{keV}.$$

The mixing angle of the tensor meson nonet

$$\theta = (29.4^{+1.4}_{-1.6})^\circ$$

was determined.

A study of twelve distinct decay channels of η_c produced in two-photon collisions has also been performed. Summing all channels, 28 candidate events have been identified, with an estimated background of 11 events. The two-photon radiative width was evaluated to be

$$\Gamma_{\gamma\gamma}(\eta_c) = 8.0 \pm 2.3(\mathrm{stat}) \pm 2.4(\mathrm{syst})\ \mathrm{keV}.$$

The PNPI contribution

The L3 experiment is one of the largest in the high energy physics. PNPI has significantly contributed to the L3 experimental complex: a half of the electromagnetic calorimeter crystals have been made by joint efforts using the materials supplied by PNPI; the muon spectrometer high-voltage monitor has been designed, produced and installed by the PNPI group; all the L3 data taking and experimental control electronics (about 1000 CAMAC and FASTBUS crates) are installed in the water-cooled racks (250 racks) designed (jointly with CERN) and made at PNPI; finally, the forward-backward FTC detectors, together with the electronics, have been designed and produced at PNPI. The PNPI physicists perform the FTC exploitation, including its calibration and alignment. The whole amount of the PNPI-supplied materials and equipment is evaluated as 10 millions of Swiss francs.

A large group of the PNPI High Energy Physics Division took part in the L3 physics program development, software creation, detector installation, data taking and processing, and in physical results analysis:

G. Alkhazov, V. Andreev, Vl. Andreev, A. Atamanchuk, A. Bykov, O. Fedine, G. Gavrilov, A. Krivshich, A. Kulbardis, P. Levtchenko, V. Maleev, A. Nadtotchi, S. Patrichev, D. Prokofiev, O. Prokofiev, N. Sagidova, V. Schegelsky, A. Schetkovsky, L. Shipunov, N. Smirnov, V. Suvorov, I. Tkach, A. Tsaregorodtsev, S. Volkov, A. Vorobyov, An. Vorobyov, N. Zaitsev, A. Zalite, Yu. Zalite.

An essential contribution to the electronics design and production has been made by the HEPD Electronics Department (E. Spiridenkov) and by the HEPD Hybrid Technologies Department (V. Ivochkin). Many PNPI divisions took part in the L3 experiment preparation. The general supervising of the financial and technical problems was carried out by the PNPI deputy director N. Abrossimov. The timely supply of the materials and equipment was due to the Supply Division (L. Zhigunova). The Central Design Shops (V. Razmyslovich) and the Experimental Workshops (L. Rabinsky, E. Ivanov) have been working hard during the four years of the L3 construction.

A big amount of work on the FTC chambers and electronics has been made by the PNPI Automatization Department (Yu. Ryabov, A. Kudin, G. Shablij). Last but not least, all the equipment produced at PNPI has been delivered to Geneva by the institute's transport (V. Gugneshov).

Conclusions

The LEP–1 experimental program has been completed in 1995. The L3 detector has detected more than 5 millions of Z^0-boson decays. More than 100 papers have been published [4]. The processing of the data obtained will take two or three years more. Each of the other three LEP experiments – ALEPH, DELPHI, and OPAL – has accumulated approximately the same statistics. The results of all the four experiments are quite consistent.

The main result of the LEP–1 program is the high precision confirmation of the validity of the Standard Model. No fact is found which could not be explained in the framework of this theory. The number of the leptons families is measured experimentally. In the framework of the Standard Model, the t-quark mass has been estimated on the base of the measured radiative corrections. The observation of the t quark and the measurement of its mass (consistent with the LEP predictions) at the FNAL proton-antiproton collider was just another contribution to the Standard Model triumph.

The LEP–2 program started in 1996. The beam energy is to rise firstly up to 80–85 GeV, and then to reach 100 GeV in 1997–1998. At these energies, the W-boson mass determination is practically model-independent and can be measured with about 100 MeV precision. At higher energies, it will be possible to study the inter-boson coupling, i.e. to explore the WZW and $W\gamma W$ interactions. One of the main aims of the energy rise up to 100 GeV is the Higgs boson search: the Standard Model supersymmetric extension allows the existence of both charged and neutral Higgs bosons with mass lower than 100 GeV.

According to the existing plans, the LEP accelerator complex will be operating till the years 1999–2000, and the L3 experiment will remain at the front edge of the fundamental research in the high energy physics.

References

[1] *G.E. Gavrilov, A.G. Krivshych, M.K. Jarmarkin.* // Nucl. Instr. Meth., 1995. V.A356. P.189.

[2] L3 preprints 001 $\div$ 035,
CERN-PPE/91-232,
CERN-PPE/92-40, 50, 58, 83, 84, 87, 99, 121, 128, 131, 132, 140, 152, 163, 164, 185, 209,
CERN-PPE/93-30, 31, 37, 44, 53, 60, 68, 126, 150, 151, 157, 158, 166, 172, 207,
CERN-PPE/94-45, 53, 68, 89, 143, 145, 164, 178, 186, 187, 216,
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CERN-PPE/96-17, 24, 29, 38, 46, 48, 49, 50.

[4] For the sake of brevity, the references are made on preprints of the papers published in Nuclear Instruments and Methods, Physics Reports, Physics Letters journals