Abstract
In 1989 DELPHI collected about 13000 $Z^0$ decays. From these I will present results on QCD studies, mass and width of the $Z^0$ and new particle searches.
1. Introduction

In August 1989 the large electron positron collider LEP at CERN came into operation. The first period until December 1989 was devoted to a scan about the Z resonance to measure precisely its mass and width. In this contribution I shall report on results that the DELPHI collaboration obtained at LEP from this running period. We collected an integrated luminosity of 600 nb$^{-1}$ corresponding to about 13000 detected Z decays.

2. DELPHI

DELPHI was designed to measure precisely charged tracks and neutral energy in a large fraction of the full solid angle and to provide particle identification over a large momentum range. For this purpose we designed a RICH counter for hadron identification and a high density projection chamber (HPC) as electromagnetic calorimeter to measure electromagnetic showers with extremely high granularity to obtain electron pion separation already from the shower shape. A sketch of the detector is given in Figure 1. A detailed description can be found in [1]. The tracking system performed well from the start and all other detectors came into operation during the course of the run. At the end of the running period we obtained first results with our RICHs. Figure 2 shows the $\theta$ distribution of Cherenkov photons produced in the liquid radiator for 7 tracks with a momentum of larger than 6 GeV. Above this momentum the Cherenkov photons are expected to be at the maximum Cherenkov angle independent of the particle species. A clear signal at the predicted angle can be seen.

To trigger Z decays we used several coincidences of the ID and OD drift chambers, the electromagnetic calorimeters and the TOF counters. With these we have redundant triggers for all the different decay channels of the Z. Due to a technical problem the first third of our data were taken with a magnetic field of 0.69 T. The rest was taken with our nominal field of 1.2 T.

Fig. 1. The DELPHI detector: 1: Vertex detector (Si-strips); 2: inner drift chamber (ID); 3: time projection chamber (TPC); 4, 13: ring imaging Cherenkov counter (RICH); 5: outer drift chamber (OD); 6, 12, 15: electromagnetic calorimeters (high density projection chamber HPC; luminosity monitor SAT; lead-glass counters FEMC); 7: superconducting solenoid; 8, 17: scintillators; 9: hadron calorimeters; 10, 16: muon counters; 11, 14: forward drift chambers.
3. QCD Studies

In order to compare our data to the predictions of QCD we selected events that are unambiguously defined as hadronic Z decays and well contained in the detector. For this we used charged tracks fulfilling the following criteria [2]:

- impact parameter in rφ relative to the centre of the beam spot < 5 cm;
- impact parameter in z relative to the centre of the beam spot < 10 cm;
- track length inside the TPC > 20 cm;
- momentum > 0.1 GeV.

For the event we required at least 2 GeV in each hemisphere, a total seen energy of at least 15 GeV, more than 5 tracks and a measured sphericity axis in the range 40° < θ < 140°. In the analysis we restricted ourselves to the data taken with a magnetic field of 0.69 T, which left us with 2109 selected events. The only background in our data sample was 0.24% τ+τ- events. We corrected for detector acceptance and radiative effects on a bin by bin basis using the Lund parton shower MC which describes our data well. We thus obtained correction factors which are in the range 0.85 < c < 1.15. We compared our results to the following event generators tuned at lower energies by the MARK II collaboration at PEP [3]:

- Jetset 6.3 parton shower with string fragmentation [4]
- Jetset 6.3 with 2nd order matrix elements (GKS) with string fragmentation [4]
- Jetset 6.3 with 2nd order matrix elements (ERT) with optimized scale tuned by JADE [5] to jet multiplicities
- Herwig 3.4 parton shower with cluster fragmentation [6]
Figure 3 a) shows the distribution of the minor value of our data together with the different MC predictions. It can be seen that both parton shower models, and especially the Lund model, are in agreement with our data. The QCD matrix element prediction disagree with them independently of the renormalisation scale and need to be retuned. This behaviour is qualitatively the same in all distributions and it appears very clearly in the the rapidity distribution (Figure 3 b). Here it is shown in addition that retuning of the matrix element model [7] can cure the problem.

\[ \frac{E_{\text{miss}}}{E_b} > 0.75 \text{ in both arms} \]
• acoplanarity < 20°
• cluster size ≥ 3 in both arms
• energy fraction in the most inner ring < 50%

The last cut was used to suppress electrons that enter the SAT in its inner back corner from below the mask. Figure 4 shows the energy distribution in both arms for data and MC. Apart from background with low energy on both sides coming from off momentum electrons the data are reproduced well by the simulation. With these cuts our effective cross section for Bhabha scattering events is 26.6 nb. The first third of our data was taken with a lead mask ranging only to 48 mrad. The effective cross section for this period was 32.5 nb. The systematic error is estimated to be 2.4% [8].

Figure 4: Energy distribution in the SAT for data and MC

4.2 Hadronic event counting

To count hadronic events we relied on charged tracks that similar criteria as for the QCD studies. To identify a hadronic $Z$ decay we require at least 3 charged tracks in one hemisphere and a sum of the $p_t^2$ of all tracks relative to the beam axis of larger than 9 GeV$^2$. Figure 5 a) shows this distribution with the prediction of the simulation. Apart from 1.3% contamination from $\tau^+\tau^-$ events our selected sample is free from background. From Monte Carlo studies and from the analysis of the trigger pattern in our data we know that for $\cos\theta < 0.65$ our efficiency is very close to 100%. To calculate our total efficiency we fit the theoretical prediction $\mathcal{f}(\cos\theta) = a(1 + (1 - \frac{8}{3\pi})\cos^2\theta)$ [9] to the data in this region and extrapolate it to the full phase space. The efficiency is estimated by the ratio of the number of found events in the full solid angle and the prediction of the fit. A small smearing correction (3%) is calculated using our Monte Carlo which describes the angular distribution of our data (Figure 5 b). We obtain a total efficiency of $\varepsilon = 93.5 \pm 1\%$.
4.3 Results

The cross section we obtain from about 11000 events with the procedure described above is given in Table I on page 7. To fit our data we used the analytical formula by Borrelli et al. [10] and the semi analytical formula by Burgers et al. [11]. Both formulae give the same output values. From a fit leaving as free parameters only the $Z$ mass and an arbitrary normalisation factor to account for the uncertainty in the normalisation we obtain:

$$M_Z = 91.171 \pm 0.030 \pm 0.030 \text{ GeV} \quad (n = 1.005 \pm 0.013, \chi^2/NDF = 4.0/6)$$

The first error on $M_Z$ represents our experimental error the second error is the uncertainty in the energy calibration of the machine and is common to all LEP experiments.

Assuming the standard model with an unknown number of light neutrino species we get

$$M_Z = 91.170 \pm 0.030 \text{ GeV} \quad N_v = 2.97 \pm 0.26 \quad (\chi^2/NDF = 4.0/7)$$

where the error on the number of neutrinos is mainly due to the 2.6% error on the luminosity (2.4%) and acceptance for hadronic events (1%). If we allow the product of the electronic and hadronic width and the total width to vary independently we obtain:

$$M_Z = 91.171 \pm 0.030 \text{ GeV} \quad \Gamma = 2.511 \pm 0.065 \text{ GeV} \quad \Gamma_e \Gamma_h = 0.148 \pm 0.006 \text{ GeV}^2$$

Figure 6 shows our cross sections together with the result of the 2nd fit and the standard model prediction for 2 and 4 neutrino species.
Table 1: cross section for $e^+e^- \rightarrow$ hadrons

<table>
<thead>
<tr>
<th>centre of mass energy [GeV]</th>
<th>$\sigma$ [nb]</th>
<th>$\Delta\sigma$ [nb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.284</td>
<td>4.74</td>
<td>0.32</td>
</tr>
<tr>
<td>89.284</td>
<td>9.42</td>
<td>0.50</td>
</tr>
<tr>
<td>90.283</td>
<td>19.51</td>
<td>0.73</td>
</tr>
<tr>
<td>91.036</td>
<td>29.15</td>
<td>0.89</td>
</tr>
<tr>
<td>91.283</td>
<td>31.02</td>
<td>0.89</td>
</tr>
<tr>
<td>91.536</td>
<td>29.97</td>
<td>0.76</td>
</tr>
<tr>
<td>92.286</td>
<td>20.92</td>
<td>0.96</td>
</tr>
<tr>
<td>93.284</td>
<td>11.57</td>
<td>0.55</td>
</tr>
<tr>
<td>94.284</td>
<td>8.54</td>
<td>0.57</td>
</tr>
<tr>
<td>95.042</td>
<td>6.19</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Figure 6: Hadronic line shape
5. Leptonic Channels

5.1 Event selection

For the analysis of the leptonic decay channels of the $Z^0$ we restricted ourselves to the angular region $50° < \theta < 130°$ [12]. This was done in order to have at least two redundant triggers for every channel.

5.1.1 Electrons

To identify $e^+ e^-$ events we required one energy cluster of at least 25 GeV in the HPC and another cluster with more than 10 GeV in the hemisphere opposite to the first one. To ensure a well understood efficiency we required that the clusters were well separated from the module boundaries of the HPC. In addition we asked at most three charged tracks with no more than two in each hemisphere. The acoplanarity had to be less than 10°. Our trigger efficiency for these events was computed from the redundancy of our trigger and found out to be 100%. The probability to accept an event inside the selected angular region was calculated with the event generator BABAMC [13] and our detector simulation and was found to be (69±2)%. The only remaining background comes from $\tau^+ \tau^-$ events and was calculated to be (6±2)%.

5.1.2 Muons

To select $Z \rightarrow \mu^+ \mu^-$ events we required 2 charged track with $p > 15$ GeV coming from the interaction region with an acolinearity of less than 10°. The tracks had to be identified as muons either by a hit in one layer of the muon chambers or by being consistent with a minimum ionizing particle in the HPC. Cosmic ray events were removed by the timing information in the TOF and the OD. Our trigger efficiency for these events was 97±2% and the acceptance 90%. The only remaining background was (4±1)% from $\tau^+ \tau^-$ events.

5.1.3 Taus

For the identification of $\tau$ decays of the $Z^0$ we selected events with one track with an isolation of at least 150° to the nearest track and 1−5 tracks in the hemisphere opposite to the isolated one. If the number of tracks was even the sum of their charges had to be zero. For 1−1 and 1−2 topologies we required in addition:

- the electromagnetic energy to be less than 30 GeV on both sides;
- at least one electromagnetic energy cluster of more than 3 GeV or no hits in the muon chambers;
- an acoplanarity larger than 1° or an acolinearity of more than 3°.
- a visible momentum of less than 60 GeV

With these requirements the acceptance was 64.5% in the selected $\theta$ region with (6±3)% background from hadronic events. The trigger efficiency was 97%. The total systematic error on the event selection is estimated to be 5.6%.
5.2 Results

Our final event sample contained 263 $e^+e^-$, 195 $\mu^+\mu^-$ and 158 $\tau^+\tau^-$ events. The $e^+e^-$ cross section was fitted using a formula by Greco \[14\] containing $s$- and $t$- channel contributions. For the missing noncolinear hard photons we corrected by comparing the formula with the $t$- channel switched off to the formula of Borrelli et. al.. We found the correction to be 9%. The $\mu^+\mu^-$ and $\tau^+\tau^-$ cross sections were fitted with the formula of Bardin et al. \[15\], assuming lepton universality. In addition the ratios of the width $\Gamma_1/\Gamma_h$ were calculated from the ratios of leptonic to hadronic events. In this ratio no universality assumption is needed and the luminosity error cancels. The result of the fits are summarized in Table 2. A general agreement with the standard model is observed.

<table>
<thead>
<tr>
<th>Lepton</th>
<th>$R_1=\Gamma_1$ [MeV]</th>
<th>$\Gamma_1/\Gamma_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons</td>
<td>83.2 ± 3.8</td>
<td>0.0502 ± 0.0036</td>
</tr>
<tr>
<td>muons</td>
<td>84.6 ± 3.8</td>
<td>0.0489 ± 0.0038</td>
</tr>
<tr>
<td>taus</td>
<td>82.6 ± 4.0</td>
<td>0.0465 ± 0.0048</td>
</tr>
<tr>
<td>mean</td>
<td>83.5 ± 2.8</td>
<td>0.0489 ± 0.0023</td>
</tr>
<tr>
<td>standard model</td>
<td>83.6</td>
<td>0.048</td>
</tr>
</tbody>
</table>

6. New particles

6.1 Selectrons

Supersymmetry predicts for every fermion a scalar partner and for every boson one with spin $\frac{1}{2}$. We searched for the partner of the electron in the decay channel $\tilde{e}\rightarrow e\chi$ where $\chi$ is the photino which is assumed to be stable and undetected. The cross section for selectron pair production is

$$\sigma(e^+e^--\tilde{e}^+\tilde{e}^-)=\frac{1}{2}\beta^3\sigma(e^+e^-\rightarrow\mu^+\mu^-) \text{ where } \beta=\sqrt{1-\frac{4m^2}{M^2}}$$

We looked for events with exactly 2 charged tracks in the detector. They were required to have a momentum larger than 2 GeV and an angle with the beam axis larger than 30°, to suppress 2 photon background. To suppress normal 2 lepton events and tracks coming from a photon conversion in the detector the acoplanarity had to be between 15° and 160°. In addition events with an isolated photon were rejected. The efficiency for selectron pairs to survive all cuts except the momentum cut is about 50%. The efficiency of the momentum cut is strongly dependent on the photino mass and varies from 100% for $m_\chi=0$ to 0 for $m_\chi=m_t$. No events with the required criteria were found. From this we derive a 95% CL. limit of 42.6 GeV on $m_\chi$, assuming $m_\mu^0=m_{\mu^+}$ and $m_t$ to be small. The excluded region of $m_\chi$ for arbitrary $m_t$ is shown in Figure 7.
6.2 Charged Higgs

Many models predict an additional Higgs doublet which contains a charged Higgs as an observable particle. It should decay predominantly in the two channels

\[ H^+ \rightarrow c\bar{s} \]
\[ H^+ \rightarrow \tau^+\nu_\tau \]

The ratio of the branching fractions depends on the ratio of the vacuum expectation values of the two Higgs doublets and is in principle a free parameter. Theorists prefer, however, \( BR(H^+ \rightarrow \tau^+\nu_\tau) > \frac{1}{3} \).

The predicted cross section for charged Higgs production is

\[ \sigma(e^+e^- \rightarrow H^+h^-) \approx 0.3 \beta^3 \sigma(e^+e^- \rightarrow \mu^+\mu^-). \]

We searched for the three different possibilities separately. For the \( \tau\tau \) channel we restricted ourselves to the one prong decays. The analysis was very similar to the selectron analysis. The efficiency for a pair of charged Higgses of about 30 GeV both decaying into \( \tau\nu \) to survive these cuts was computed to be 15%. No event was found in our data sample which gives us a limit of \( m_h > 36 \text{GeV} \) for \( BR(H^+ \rightarrow \tau^+\nu_\tau) = 1 \) at 95% cl.

For the \( \tau + \text{jets} \) channel we splitted the analysis into two different mass ranges. For an intermediate mass range we asked for exactly one charged particle in one hemisphere and more than three with momentum larger than 2 GeV in the opposite one. In addition the angle between the isolated particle and the thrust axis of the other tracks had to be larger than 20°. As for high Higgs masses the hemisphere separation becomes inefficient we looked, to exclude this region, for events with thrust < 0.9 having 2 jets and one isolated particle with momentum larger than 5 GeV. The acolinearity angle between the jets had to be between 50° and 140°. The combined efficiency of the two methods was...
around 20% for Higgs masses up to 35 GeV. No event fulfilled our criteria so that we could exclude charged Higgs masses up to 35 GeV for a branching ratio of $BR(H^+ \rightarrow \tau^+ \nu_\tau) = 0.5$

For the 4 jet channel we selected 4 jet events well contained in our detector. The jets were grouped into 2 pairs by selecting the 2 jets with the smallest opening angle as one pair. Optimizing for three different mass ranges we required certain opening angles and mass differences of the two pairs. In calculating the mass differences we corrected for missing neutrals by scaling all momenta, such that the the energy of each pair was equal to the beam energy. The efficiency to detect a charged Higgs pair in this analysis is typically around 20%. We found between 6 and 10 events in our sample and expected between 6 and 18 from normal multihadronic events. From this we derive a limit of $m_H > 32$ GeV for $BR(H^+ \rightarrow c \bar{s}) = 1$. Figure 8 shows the combined limit as a function of the $\tau \nu$ branching fraction.

Figure 8: Excluded region for charged Higgses

7. Summary

DELPHI collected in 1989 about 13000 $Z^0$ decays. They were used to obtain the $Z^0$ resonance parameters, to test QCD models, and to search for new particles. The main results are:

- The $Z$ mass was measured to be $M_Z = 91.171 \pm 0.030 \pm 0.030$ GeV and the number of light neutrino species $N_\nu = 2.97 \pm 0.26$.
- Charged Higgses were excluded up to 32 GeV independent of their decay mode.
- Selectrons were excluded up to 42.6 GeV for a not too heavy photino.
- It was checked that the parton shower models extrapolate well from PEP/PETRA energies to the $Z^0$ resonance region, but the matrix element models need retuning of some parameters.
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