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Rare and unexpected decays of the Z^0

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Recent results from the LEP experiments on searches for monojet events, radiative decays of the Z^0 into new scalar particles and on deviations from the QED are presented here. Furthermore updates of the $f\bar{f}\gamma\gamma$ and $\ell^+\ell^-V$ analysis are reported.

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Rare and unexpected decays of the Z^0

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On behalf of the LEP Experiments

Abstract

Recent results from the LEP experiments on searches for monojet events, radiative decays of the Z^0 into new scalar particles and on deviations from the QED are presented here. Furthermore updates of the $f\bar{f}\gamma\gamma$ and $\ell^+\ell^-V$ analysis are reported.

1. Introduction

Despite the good agreement between the present LEP results and the predictions of the Standard Model in the sector of the electroweak precision measurements, continuous efforts have been done by the four Collaborations to search for rare or "forbidden" Z^0 decays and deviations from the standard predictions. In this paper two distinct parts can be identified: the results of the searches for rare events and the investigations of deviations from the Standard Model predictions. With the number of events collected by the four experiments and their good performances, the present sensitivity to branching ratio is 10^{-5}, 10^{-6}.

2. Search for rare events

2.1. Monjet events

The monojet topology is commonly considered as being background free for new particle searches in e^+e^- collisions; it provides, for example, a clear signature for the production of a light Higgs boson ($e^+e^- \to H\nu\bar{\nu}$) or of the light neutralinos ($e^+e^- \to \chi\chi'$ with $\chi' \to \chi Z^*$). ALEPH searched for monojet events using all the data collected until 1993[1] (about 1.94M Z^0's hadronic decays), by taking advantage of the hermeticity, the

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M_{jet} (GeV/c^2)	P_t (GeV/c)	M_{recoil} (GeV/c^2)	particle composition
3.3	20.3	61	e^+e^-
3.2	6.6	80	*hadronic*
5.3	18.5	69	*hadronic*

Table 1. Kinematical properties of the three ALEPH monojet events.

redoundancy and the low detection thresholds of the apparatus. The monojet topology was required both in the space and in the transverse plane and after the explicit rejection of 3-prongs and candidate γ conversions monojets, three monojet events survived the selection. The contribution of the standard processes $e^+e^- \to f\bar{f}$ and $\gamma\gamma \to f\bar{f}$ has been estimated to be less than 1/100 of events. Taking into account all the four-fermion final state processes involving a Z^0 and part of those involving a W the expected number of events is 2.75 but the probability to obtain a set of events at least as unlikely as the selected one, with respect to the jet mass and transverse momentum, is only 4.8% (see table 1 and fig. 1).

A preliminary result of the searches for the same kind of events has been presented by DELPHI using the data collected in 1992 and 1993[2] (about 1.5M Z^0's hadronic decays). No monojet event candidate that cannot be

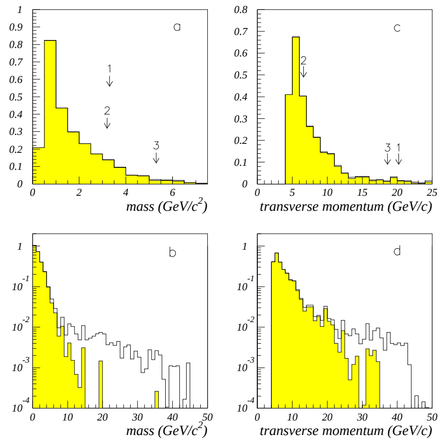

Figure 1. Expected jet mass and transverse momentum distributions for the considered "standard" processes ($Z^0 \to \gamma^* \nu\bar{\nu}$ contribution is shaded) and indication of the three events selected by ALEPH.

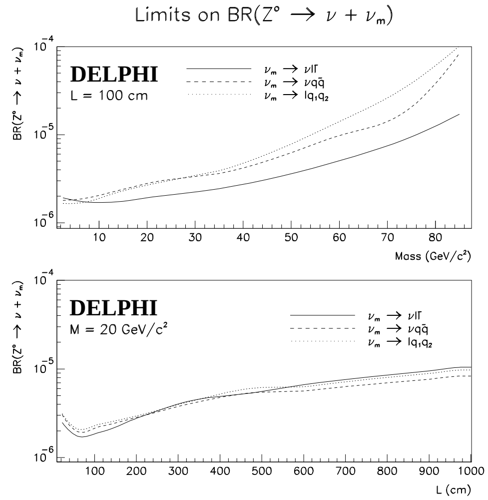

Figure 2. Limits on the heavy neutrino production branching ratio as a function of the mass or of the decay length, for different ν_m decay modes.

explained as a "standard" Z^0 decay (for example $f\bar{f}\gamma$ with missing γ or $\tau^+\tau^-$ with one "invisible" τ) has been selected, while the expected number of events from standard four fermion final state process $f\bar{f}\nu\bar{\nu}$ is ~ 0.4.

2.2. *Long lived neutral heavy particles*

Long lived neutral heavy particles were searched for in DELPHI[3], more precisely an isosinglet neutral heavy lepton ν_m, by looking for the process $Z^0 \to \nu_m \bar{\nu}$. Its branching ratio can be expressed as[4]:

$$BR(Z^0 \to \nu_m \nu) = \\ BR(Z^0 \to \nu\bar{\nu})|U|^2 \left(1 - \frac{M^2_{\nu_m}}{M^2_Z}\right)^2 \left(1 + \frac{1}{2}\frac{M^2_{\nu_m}}{M^2_Z}\right) \quad (1)$$

where M_{ν_m} is the heavy neutrino mass and $|U|^2$ can be interpreted as the coupling strength of the ν_m to the Z^0 or the mixing parameter between the heavy neutrino and its standard partner. The heavy neutrino can decay via neutral and charged weak currents and the mean decay length, function of M_{ν_m} and of $|U|^2$, is $\sim 1\ m$ for masses in the range $3 - 5\ GeV/c^2$ and production branching ratios $\sim 10^{-6}$.
This kind of process has been investigated by looking for events with monojet topology and with: a) a displaced vertex in the tracking chambers (the effective accepted transverse decay length R is between 12 and 110 cm) or b) a cluster of hits in the outer detectors spatially (and temporally) confined ($R < 300\ cm$). In the sample of events considered (equivalent to the production of about 2M Z^0's) no event has been selected and preliminary limits on the branching ratio of the order of 3×10^{-6} ($|U|^2 < 8 \times 10^{-5}$) have been established at 95% C.L. (see fig. 2).

3. Search for deviation from the standard predictions

3.1. *Search for $Z \to S\gamma$*

The decay $Z^0 \to S\gamma$, where S is a scalar particle, can have a "visible" branching ratio ($10^{-4\div5}$) both in models where Z^0 is composite and S is its scalar partner, and in extensions of the Standard Model where S is the Higgs boson and the decay $Z^0 \to H^0\gamma$ via loop is enhanced with respect to the standard prediction.
Using the data collected between 1990 and 1992 (about 1.1M Z^0's hadronic decays), ALEPH investigated this decay mode by looking for $\ell^+\ell^-\gamma$, $q\bar{q}\gamma$ and $gg\gamma$ final state events and by comparing the observed distribution of the mass recoiling against the photon with the standard Monte Carlo predictions[5]. The resolution on the recoiling mass, by rescaling the energies of the particles with the constraints of the center of mass energy and of the measured directions is (FWHM) about $0.5\ GeV/c^2$ for $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ events and $5.0\ GeV/c^2$ for $\tau^+\tau^-\gamma$ and hadronic events. Asssuming the width of S smaller than the experimental resolution the preliminary resulting limits (95% C.L.) for $BR(Z^0 \to S\gamma) \times BR(S \to f\bar{f})$ are less than 10^{-5} in the leptonic channels and 10^{-4} in the hadronic channels for S masses up to $88\ GeV/c^2$.
The hadronic channel has been investigated also by OPAL using the data collected between 1991 and 1993 (about 1.8M Z^0's hadronic decays)[6]. The mass of the hadronic system is calculated as the mass recoiling against the photon with the constraint of the center of mass energy. They obtain a resolution which decreases from $5.8\ GeV/c^2$ at $M_S = 20\ GeV/c^2$ to $0.6\ GeV/c^2$ at $M_S = 80\ GeV/c^2$. Assuming that S is scalar a

further cut is applied on the decay angle of the hadronic system and a typical (preliminary) limit for the product $BR(Z^0 \to S\gamma) \times BR(S \to q\bar{q}) < 2.5 \times 10^{-5}$ (95% C.L.) has been extracted from the resulting recoiling mass spectrum. Thinking at the Higgs boson, they searched for the decays $S \to b\bar{b}$, by tagging b quark events with their secondary vertices. The resulting tipical limit is $BR(Z^0 \to S\gamma) \times BR(S \to b\bar{b}) < 1.5 \times 10^{-5}$ (95% C.L.). OPAL has also investigated, with no assumption on the spin of S, the case in which S decays with an invisible signature[7]. Using single photon selected events, the limit for the product $BR(Z^0 \to S\gamma) \times BR(S \to inv.)$ was evaluated by comparing the resulting recoiling mass spectrum with the one expected from Standard Model. For $M_S < 64\ GeV/c^2$ the 95% C.L. limit is 4.3×10^{-6} while for $M_S < 84\ GeV/c^2$ is 1.4×10^{-5}.

3.2. *Measurement of* $e^+e^- \to \gamma\gamma(\gamma)$

In the framework of the Standard Model the reaction $e^+e^- \to \gamma\gamma(\gamma)$ is purely electromagnetic and has been proposed as a suitable process to search for deviation from QED due to new phenomena at LEP[8]. The effects of of such a breakdown of QED on the differential cross section at Born level can be parametrized as:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s}\frac{1+\cos^2\theta}{1-\cos^2\theta}(1+\delta) \qquad (2)$$

where δ contains the information about the new phenomena. It can be expressed by introducing phenomenolgical parameters as in the QED cutoff model [9], where $\delta = \pm s^2/2(1/\Lambda_\pm^4)(1-\cos^2\theta)$ and $\Lambda_\pm$ are the cutoff parameters, or by assuming the exchange in the t channel of an exited electron e^* of mass M_{e^*} and coupling λ_γ[10]; in this case $\delta = s^2\lambda_\gamma^2/(2M_{e^*}^4)(1-\cos^2\theta)H(\cos^2\theta)$ where $H(\cos^2\theta) = a[a+(1-\cos^2\theta)/(1+\cos^2\theta)]/[(1+a)^2-\cos^2\theta]$ and $a = 2M_{e^*}^2/s$.
DELPHI presented the results of the measurement of the total and differential cross sections for the reaction $e^+e^- \to \gamma\gamma(\gamma)$ using the data collected between 1990 and 1992 ($\mathcal{L} = 36.9\ pb^{-1}$)[11]. The results agreed with the QED predictions and the following lower limits were obtained at 95% C.L. on the parameters introduced above: $\Lambda_+ > 143\ GeV$, $\Lambda_- > 120\ GeV$ and $M_{e^*} > 132\ GeV/c^2$ ($\lambda_\gamma = 1$).

3.3. *Limits on the* τ*'s anomalous magnetic and electric dipole moments*

The anomalous electromagnetic couplings of the τ lepton are much less known than those of the electron and the muon, due to its short lifetime that prevents the measurement of its precession in a magnetic field.
A non-null anomalous magnetic (electric) dipole moment would lead to an additional term $F_2(q^2)/(2m_\tau)\sigma^{\mu\nu}q_\nu$ ($F_{EDM}(q^2)\sigma^{\mu\nu}\gamma_5 q_\nu$) in the τ's electromagnetic current. As a consequence the partial width of the process $Z^0 \to \tau\tau\gamma$ would become:

$$\Gamma(Z \to \tau\tau\gamma) = \Gamma_0 + \frac{\alpha^2 F_2(0)^2 m_Z^3}{64\pi \sin^2\theta_W(1-\sin^2\theta_W)m_\tau^2} \times [(c_V^2+c_A^2) - \frac{1}{9}(c_V^2-c_A^2)] \qquad (3)$$

where $c_V = 1/4 - \sin^2\theta_W$, $c_A = 1/4$ and Γ_0 is the standard width[12] (the contribution of the electric dipole moment is identical with $F_2(0)/2m_\tau$ replaced with $F_{EDM}(0)$). An important feature of this anomalous contribution is that the spectrum of the emitted photon is independent of the energy while in conventional bremsstrahlung the soft photon emission is strongly favoured.
DELPHI presented a study of $Z^0 \to \tau\tau\gamma$ events using the data collected between 1992 and 1993 (about 1.3M Z^0's hadronic decays)[13]. After the selection of $\tau^+\tau^-$ pairs with an isolated and energetic photon ($E_\gamma > 3\ GeV$), the resulting spectrum of the photon energy was compared with the one obtained with the standard Monte Carlo simulation. The agreement is

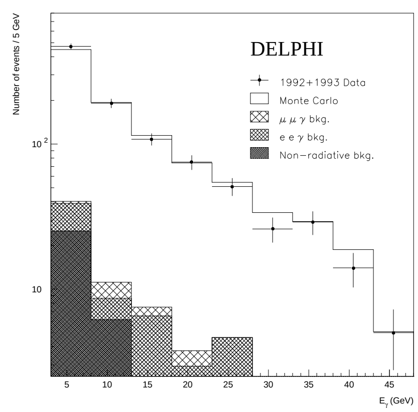

Figure 3. Distribution of the photon energy in $\tau^+\tau^-\gamma$ candidates.

good (see fig. 3) and the following preliminary limits were extracted for the anomalous dipole moments (95% C.L.):

$$F_2(q^2=0) < 0.072$$
$$F_{EDM}(q^2=0) < 4 \times 10^{-16}\ e\ cm \qquad (4)$$

It is worth noting that other limits exist for these anomalous dipole moments but they are either in different kinematical domains ($q^2 = (35\ GeV)^2$)[14], extracted from the angular distribution of the τ's pairs production at PETRA, or derived indirectly from $\Gamma(Z^0 \to \tau^+\tau^-)$, assuming the standard gauge symmetry $SU(3) \otimes SU(2) \otimes U(1)$ for the anomalous dipole couplings[15].

3.4. Search for high mass resonances in photon pairs

The interest in the search for events with photon pairs of large invariant mass was motivated by the L3 observation of four events of the type $\ell^+\ell^-\gamma\gamma$ with $m_{\gamma\gamma}$ clustered around 60 GeV/c^2[16]. DELPHI presented the results of this analysis using the data collected between 1990 and 1992[17]. The resulting limits (95% C.L.) are ($M_X = 60\ GeV/c^2$):

$$\begin{array}{rl} BR(Z^0 \to \ell^+\ell^- X)BR(X \to \gamma\gamma) & < 1.1 \times 10^{-5} \\ BR(Z^0 \to q\bar{q}X)BR(X \to \gamma\gamma) & < 1 \times 10^{-5} \\ BR(Z^0 \to \nu\bar{\nu}X)BR(X \to \gamma\gamma) & < 7.5 \times 10^{-6} \\ \Gamma_X BR^2(X \to \gamma\gamma) & < 7\ MeV \\ BR(Z^0 \to \gamma X)BR(X \to \gamma\gamma) & < 6.8 \times 10^{-6} \end{array} \quad (5)$$

These results confirm the preliminary results presented in the HEP93 conference in Marseille where a complete review of the LEP results was presented by G.W. Wilson[18].

Preliminary results, using the 1993 data, were presented by DELPHI and OPAL. DELPHI searched for high mass photon pairs in the final state $\ell^+\ell^-\gamma\gamma$, $\nu\bar{\nu}\gamma\gamma$ and $q\bar{q}\gamma\gamma$[19]. Only one candidate, identified as $e^+e^-\gamma\gamma$, was found with $m_{\gamma\gamma}$ near 60 GeV/c^2.

OPAL updated the hadronic channel and no new event was found (three events with $m_{\gamma\gamma} > 40\ GeV/c^2$), setting the following upper limit on the production branching ratio: $BR(Z^0 \to q\bar{q}X)BR(X \to \gamma\gamma) < 4 \times 10^{-6}$ for $M_X > 40\ GeV/c^2$ (95% C.L.)[6].

3.5. Study of $\ell^+\ell^- V$ events

DELPHI presented new preliminary results, using the data collected between 1992 and 1993 (about 1.5M Z^0 hadronic decays), of the study of events with two leptons and an accompanying pair of charged particles ($\ell^+\ell^- V$)[20]. They observed in each lepton channel (e, μ, τ) (40,41,18) events with an expectation of (39.0, 35.2, 10.7) signal events and (1.7, 0, 1.5) background events, demonstrating a good agreement of the $\ell^+\ell^- V$ production rate with the SM expectation. In addition 7 events have a V mass in the region including the J/ψ ($3.1 \pm 0.5\ GeV/c^2$) and 2 events in the region of the V masses around the Υ ($9.5 \pm 1.0\ GeV/c^2$) while the expectations are 3.1 and 0.5 events respectively.

4. Conclusions

Searches for Z^0 rare decays and deviations from the Standard Model gave negative results with the present sensitivity and even the ALEPH monojet event analysis require more statistics to understand the nature of the selected events. Furthermore the $f\bar{f}\gamma\gamma$ and $\ell^+\ell^- V$ anomalies reported in the past[16, 21] disappeared, revealing themselves as likely statistical fluctuations.

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