SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL AT LEP

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Abstract

The ALEPH, DELPHI, L3 and OPAL collaborations searched for evidence of physics beyond the Standard Model in the data taken by the four detectors at the LEP collider from 1989 to 2000. None of these searches has shown significant evidence for a signal. Limits have been set on the cross-sections for many processes. These cross-section limits have been interpreted in the context of many popular models, and used to exclude regions of the models' parameter space and set lower limits on the masses of additional particles they predict.

1 Introduction

Since LEP stopped taking data in 2000, the four detector collaborations have already published the results of most of their searches for evidence of physics beyond the Standard Model. This talk summarized only results published or made public in the year preceding the Rencontres de La Vallée d'Aoste conference. For that reason, the searches described fall into three main categories: "new" ideas, generally interpretations of older analyses in the context of models which arose only recently; final results of very complicated searches; and combinations of final results from several collaborations.

2 New Ideas for Old Data

While most of the results presented in this talk are the final results of searches which have been ongoing since at least the beginning of LEP 2, there have been a few fresh initiatives in the last two or three years.

2.1 Pentaquarks

All four LEP experiments investigated their sensitivity to pentaquarks in the LEP 1 dataset, following the controversial publication of evidence for their existence. No evidence was found for a signal. The ALEPH collaboration published [1] the null results of their searches for resonances consistent with the decays of pentaquarks (see Table 1).

Table 1: *Upper limits on production rates of exotic states per hadronic Z^0 decay, from* [1].

Pentaquark State	Decay	Number per Z-decay
$\Theta(1535)^+$	$\mathrm{p}K^0_S$	$< 6.2 \times 10^{-4}$
$\Xi(1862)^{--}$	$\Xi^-\pi^-$	$< 4.5 \times 10^{-4}$
$\Xi(1862)^0$	$\Xi^-\pi^+$	$< 8.9 \times 10^{-4}$
$\Theta_C(3100)^0$	$\mathrm{p}D^{*-}$	$< 6.3 \times 10^{-4}$
$\Theta_C(3100)^0$	$\mathrm{p}D^-$	$< 31 \times 10^{-4}$

2.2 Radions and Branons

Models of gravity propagating in additional dimensions may imply the existence of scalars which could be detected at LEP energies or could affect the detection of the Standard Model Higgs at LEP. The OPAL collaboration re-evaluated [2] the limits on the Standard Model Higgs boson and the Higgs limits from flavour-independent searches in the context of the Randall-Sundrum model [3] of gravity propagating in an additional dimension with a special warped geometry which is introduced to solve the "hierarchy problem" associated with the large difference between the electro-weak and gravitational energy scales. This model predicts the existence of a new scalar, the radion, associated with fluctuations in the separation between branes. The radion could be light enough to be produced at LEP, even if all other scalars in the model, including the graviton, are too massive. The radion has the same quantum numbers as the Higgs boson, allowing the two scalars to mix; however, unlike the Higgs, the radion couples directly to gluon pairs. This means that its decays are quite different from those of the Standard Model Higgs. If the Higgs mixed with a radion, it might not have been detected in searches for the expected Standard Model fermionic final states. As a result, the limit on the mass eigenstate which in the absence of mixing would be the Standard Model Higgs decreases to only 58 GeV in the worst case.

The alternative Arkani-Hamed–Dimopoulos–Dvali models [4] of gravity in large extra dimensions predict the existence of another scalar, the branon, associated with the brane tension f. Branons may be produced at lower energies than gravitons if f is much less than the extra dimension scale M_F. They would not interact in the detector, and would be observed as missing energy in the processes:

$$\mathrm{e^+e^-} \rightarrow \tilde{\pi}\tilde{\pi}\mathrm{Z}^0 \rightarrow \tilde{\pi}\tilde{\pi}\mathrm{q\bar{q}} \tag{1}$$

$$\mathrm{e^+e^-} \rightarrow \tilde{\pi}\tilde{\pi}\gamma \tag{2}$$

The L3 collaboration has reinterpreted [5] their searches for photons and missing energy in the context of this model. No excess of these events is observed with respect to Standard Model predictions, so limits are set on the cross-section as a function of f and M_F. The 95% confidence level lower limits constrain the branon mass to be greater than 103 GeV in the extreme case of small brane tension ($f = 0$), and the branon tension to be greater than 180 GeV in the extreme case of light branons ($M_F = 0$).

2.3 Anomalous Higgs Couplings

If the couplings of the Higgs boson to fermions or gauge bosons are larger than the Standard Model or MSSM predictions, its production cross-section could be anomalously large at LEP energies. L3 derived limits [6] on the couplings d, d_B, Δg_1^Z, $\Delta\kappa_\gamma$ and ξ^2, and on the $H \rightarrow \gamma\gamma$ and $H \rightarrow \gamma Z$ decay rates. All were consistent with Standard Model predictions.

3 Final Results from Long-term Efforts

3.1 Photons with Missing Energy

The results of a topological search by the OPAL collaboration [7] for final states containing only photons with missing transverse momentum are interpreted as electron-positron annihilation into pairs of weakly interacting neutral particles ("$e^+e^- \to XX$") with prompt radiative decays into other weakly interacting neutrals ("$X \to \gamma Y$") which escape undetected. In the more general case where both X and Y are massive (*e.g.* $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_2$, $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\gamma$) the 95% cross-section limits on this process are set between 10 and 60 fb as long as $M_X - M_Y > 5$ GeV. In the special case of nearly massless Y (*e.g.* GMSB models where $X = \tilde{\chi}^0_1$ and $Y = \tilde{G}$ or composite models where X is an excited neutrino), the limits are between 20 and 40 fb.

3.2 Excited Leptons

The DELPHI collaboration has performed dedicated searches [8] for charged and neutral excited leptons decaying to ordinary leptons and gauge bosons. If it is assumed that the weight factors f and f', associated with the SU(2) and U(1) gauge groups respectively, are either equal (no photon decays for the excited neutrino) or equal and opposite (no photon decays for the exicted charged lepton), then the results of all of these searches can be interpreted very simply as limits in the f/Λ versus m^*_l plane, where Λ is the compositeness scale.

3.3 Exotic Higgs Searches

The three following searches were made in the context of rather general two Higgs doublet models (2HDM). Most of the papers summarized here provide many plots showing regions of parameter space excluded at specific benchmark points; however, the most important and durable results from these searches are model-independent cross-section limits. These stand as the final results of LEP, and can be re-interpreted in the context of new models, as we saw in Section 2.

3.3.1 Fermiophobic Higgs

If the lightest neutral Higgs boson had a much larger branching ratio for decays to photon pairs than it does in the MSSM, anomalously large cross-sections would be observed for final states containing two photons and two jets, two photons and a lepton pair, or two photons and missing energy from neutrinos. The DELPHI collaboration searched for these final states [9] and interpreted them either as h^0Z^0, in which case the invariant mass of the jet or lepton pair or the missing momentum was required to correspond to the Z^0 mass, or as h^0A^0, in which case only the $b\bar{b}\gamma\gamma$ topology was considered, as the A^0 would still decay to fermions. The numbers of events selected in both analyses matched the Standard Model background predictions very closely.

3.3.2 Invisible Higgs

The L3 collaboration performed a search [10] for $e^+e^- \rightarrow HZ^0$ in the case where the Z^0 decays to jets, electrons or muons and the Higgs to weakly interacting neutral particles (LSP, fourth generation neutrinos, scalars associated with extra dimensions, majorons, ...). The results were interpreted as a limit on the ratio of the cross-section for h^0Z^0 with invisibly decaying Higgs to the Standard Model HZ^0 cross-section, as a function of the Higgs mass. For masses up to just over 112 GeV, this ratio is less than unity, meaning that the Standard Model cross-section is excluded.

3.3.3 Neutral Higgs Searches in Two-Higgs-Doublet Models

The OPAL collaboration combined many searches for neutral Higgs bosons and interpreted them very generally [11] in the context of 2HDM. Limits were given at many benchmark points, including ones where the usual assumption of CP-conservation in the Higgs sector was dropped, and the CP-even and CP-odd eigenstates were allowed to mix. In such a general scenario, LEP data can by no means exclude the whole of the kinematically allowed region. In addition to the benchmark scenario limits, there were model-independent cross-section limits on the ratio of the excluded cross-section for a given final state to σ_{HZ^0} in the Standard Model or $\sigma_{h^0Z^0}$ in the MSSM with $\cos^2(\beta - \alpha) = 1$.

4 Final LEP Combinations

4.1 Lightest Supersymmetric Particle Mass Limit in the MSSM

The combination of MSSM LSP limits performed by the ALEPH collaboration [12] was updated with the combined results of the four LEP collaborations for scalar lepton and Higgs searches [13]. The lower mass limits on the LSP depend slightly on the top mass limit, but are generally around 42 GeV if stau mixing is allowed, and about 5 GeV higher if it is assumed that there is no mixing in the stau sector. In the special case of minimal SUGRA, the limit is set at lower values of $\tan\beta$ at around 50 GeV, and depends rather more strongly on the top mass limit.

4.2 Neutral Higgs Searches in the MSSM

The results of the four LEP collaborations' searches for neutral Higgs bosons were combined [14], as discussed in the OPAL search of Section 3.3.3. Many of the CP-conserving MSSM benchmark scenarios considered are excluded over most of their parameter space.

4.3 Large Extra Dimensions

A sufficiently light graviton would be produced directly in the process $e^+e^- \rightarrow G\gamma$. Events from the four LEP experiments containing a single photon and nothing else were analyzed together [15]. LEP can exclude a fundamental gravity scale M_D of up to about 1.6 TeV for two extra dimensions and about 650 GeV for six.

5 Conclusions and Summary

Most of the final LEP 2 search results have now been finalized and are either published or in the last stages of approval by the collaborations. As we can see from the pentaquark searches, new initiatives are still possible; however, big surprises seem unlikely at this stage.

The results of searches for physics beyond the Standard Model at LEP can be summarized briefly by the words "no significant excess found". While this may be disappointing, the LEP results have also excluded many of the original LHC benchmark scenarios, and are helping to point the way to where the new physics will be found in the near future.

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