THE LEP TESTIMONY: EXOTIC SEARCHES AND STUDIES

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A selection of recent results on searches for phenomena beyond the Standard Model is presented from the LEP Collaborations, based on the data collected up to the highest centre-of-mass energies of 209 GeV.

1 Introduction

The Standard Model (SM) accurately describes the observed phenomena, but it leaves several fundamental questions unanswered. Many extensions of the SM have been developed to solve these puzzles, of which the supergravity inspired Constrained Minimal Supersymmetric Standard Model (CMSSM) is the most widely studied.

In this paper, recent results of the LEP experiments, ALEPH, DELPHI, L3 and OPAL, on the searches for phenomena beyond the SM and the "standard" CMSSM are reviewed. These include the study of the CMSSM Higgs sector with CP-violation, flavour independent searches for Higgs bosons, Type II Two Higgs Doublet Model (2HDM II) interpretation of neutral Higgs boson searches, searches for Higgs boson decays to gauge boson pairs, signatures of Gauge Mediated Supersymmetry Breaking, new scalar particles (branons and radions) predicted by scenarios with extra spatial dimensions, 4th generation b' quarks and single top quark production.

The results are based on the data collected at LEP2 up to the highest energies of 209 GeV, corresponding to an integrated luminosity of around 700 pb^{-1} per experiment.

None of the searches show evidence for new phenomena. In most cases, cross-section times branching ratio limits are computed at the 95% confidence level (CL) with minimal model assumptions, providing the most general, almost model independent results. These are then

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interpreted in the framework of specific theoretical models to constrain the accessible parameter space and the properties of the new particles, such as their masses.

2 Higgs bosons

In the SM, the electroweak (EW) symmetry is broken via the Higgs mechanism generating the masses of elementary particles. This requires the introduction of a Higgs field doublet and implies the existence of a single neutral scalar particle, the Higgs boson. The minimal extension of the SM Higgs sector, required for example by supersymmetric models, contains two Higgs field doublets leading to five Higgs bosons: three neutral and two charged.

2.1 CP-violation in the Higgs sector

In the MSSM, the Higgs potential is assumed to be invariant under CP transformation at tree level. It is possible, however, to break CP symmetry in the Higgs sector by radiative corrections. Such a scenario could provide a possible solution to the cosmic baryon asymmetry.

Both CP-conserving (CPC) and CP-violating (CPV) scenarios are studied at LEP. In the CPC case, the three neutral Higgs bosons are CP eigenstates: h and H are CP even, A is CP odd. They are dominantly produced in the Higgs-strahlung processes $e^+e^- \to hZ$, HZ and the pair-production processes $e^+e^- \to hA$, HA. In the CPV case, however, the three neutral Higgs bosons, H_i, are mixtures of CP-even and CP-odd Higgs fields and the processes $e^+e^- \to H_iZ$ and $e^+e^- \to H_iH_j$ $(i,j = 1,2,3,\ i \neq j)$ may all occur. The decay properties of the Higgs bosons maintain a certain similarity in the two scenarios: the largest branching ratios are those to $b\bar{b}$ and $\tau^+\tau^-$, but Higgs-to-Higgs cascade decays occur and can be dominant when kinematically allowed.

A large number of search channels are used in the MSSM Higgs hunt: SM Higgs-strahlung searches are reinterpreted, searches for pair-production H_iH_j, Yukawa production bbH_i, flavour independent H_iZ and H_iH_j and decay mode independent H_iZ searches are developed. Higgs-to-Higgs decays $H_j \to H_iH_i$ and $H_j \to H_iZ$ are considered. The search for invisible decay of Higgs bosons is used to explore specific parameter regions. In general, searches designed to detect CPC Higgs production can be reinterpreted in the CPV scenario. However, modified or newly developed searches are also necessary to cover new dominating final state topologies, such as $H_2Z \to H_1H_1Z \to b\bar{b}b\bar{b}Z$ with $m_{H_2} \approx 100 - 110$ GeV.

The CMSSM has seven parameters. At tree level two parameters are sufficient to describe the Higgs sector: the ratio of the vacuum expectation values ($\tan\beta$) and a Higgs mass. Additional parameters appear after radiative corrections. Instead of varying all the parameters, only a certain number of representative benchmark sets [1] are considered.

In the CPC benchmark scenarios, the h and A masses are excluded at least up to 87.3 and 93.1 GeV, respectively, except for a tiny region with $\tan\beta < 0.7$ in the no-mixing scenario.

The picture dramatically changes, as illustrated on Figure 1, in the CPV scenario, called CPX [2], which was designed to maximize the CPV effects while fulfilling the experimental constraints from electron and neutron electric dipole moment (EDM) measurements [b]. In this scenario H_1 decouples from Z in the range $4 < \tan\beta < 10$. H_2 couples to the Z, but it is heavier than around 100 GeV. Where kinematically open, $H_2 \to H_1H_1$ is dominant. The excluded areas [5], by the combined results of the LEP experiments, are shown in Figure 1(b-d) for different values of the top quark mass. It is important to note that while in the CPC case the effect of the top quark mass is moderate (see the different contours of the theoretically inaccessible area for large m_h values on Figure 1(a)), the experimental exclusion in the CPV case changes

[b] During the conference the question was raised whether the recent neutron EDM measurement [3] help to close the holes in the LEP exclusion. According to Ref. [4], these results do not constrain further the CPX scenario.

significantly due to the change in the predicted cross-sections and the ratios of the Higgs masses with the top quark mass for a given $[m_{H_1} - \tan\beta]$ point.

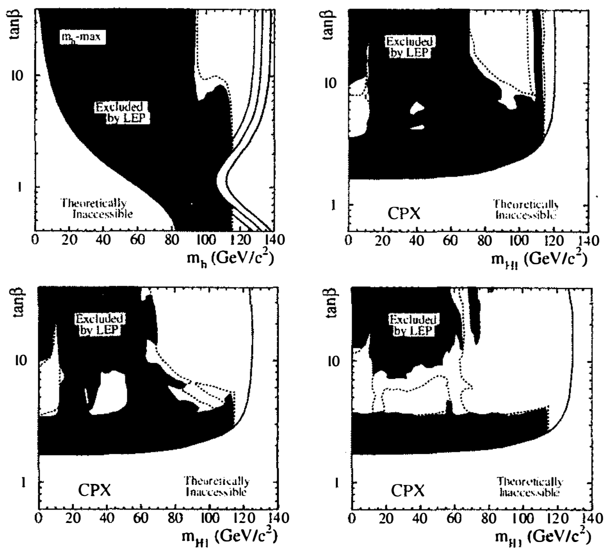

Figure 1: Search for the CMSSM neutral Higgs bosons: Exclusion in the $[m_{H_1} - \tan\beta]$ plane in the (a) CPC m_h−max scenario, (b-d) in the CPX scenario for a top quark mass of 169.3, 174.3 and 179.3 GeV, respectively. The yellow (light gray) area is theoretically inaccessible, the dark green (dark gray) region is excluded at the 99% CL, the green (gray) region at the 95% CL, and the dashed line shows the expected exclusion at the 95% CL.

2.2 Flavour Independent Searches and Type II Two Higgs Doublet Models

In certain models, for example in the large-μ CMSSM benchmark or in general 2HDM II, the Higgs coupling to $b\bar{b}$ is suppressed for large regions of the parameter space. To cover such possibilities, the LEP Collaborations developed flavour independent selections for H_iZ and H_iH_j productions, followed by the decay $H_i \rightarrow q\bar{q}$, gg. These analyses are experimentally challenging as it is rather difficult to separate the signal from the overwhelming WW, ZZ and $q\bar{q}(g)$ backgrounds without the use of the highly discriminating b- and τ-tagging algorithms.

The pair-production process was sought by the DELPHI[6] and OPAL[7] Collaborations. The results are expressed as limits on the cross-section scaling parameter C^2, which is defined to be 1 for the maximal production cross-section allowed by EW symmetry breaking and for 100% decay into hadrons. Figure 2(a) shows such a model-independent presentation from DELPHI.

The OPAL Collaboration interpreted the results of neutral Higgs boson searches in the framework of a general 2HDM II model, assuming CP-conservation in the Higgs sector and no additional non-SM particles other than the Higgs bosons[7]. The parameters m_h, m_A, $\tan\beta$ and α (the mixing angle in the neutral CP-even Higgs sector) were scanned and the other two free parameters m_H and $m_{H^\pm}$ were set above the kinematically accessible region. The excluded areas are shown in Figure 2(b).

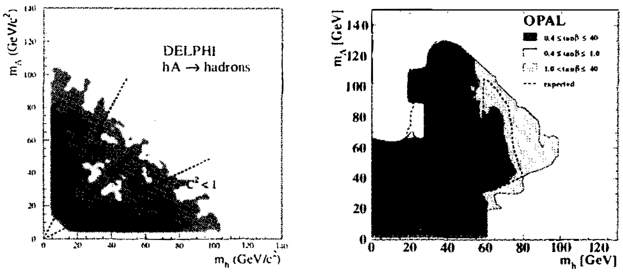

Figure 2: (a) Flavour independent search for the pair-production of neutral Higgs bosons: Upper bounds on the parameter C^2 in the $[m_h - m_A]$ (or equivalently $[m_{H_2} - m_{H_1}]$) plane. (b) Interpretation of neutral Higgs boson searches in 2HDM II: Excluded areas in the $[m_h - m_A]$ plane, independent of α.

2.3 Fermiophobic Higgs bosons

In the SM the Higgs branching ratio to heavy gauge bosons increases with mass, but even at the LEP2 kinematic limit, it accounts for less than 10% of the decays. In certain extensions (for example in Type I Two Higgs Doublet Models), the Higgs boson may become fermiophobic and its decay to gauge bosons may become dominant.

The ALEPH and L3 Collaborations performed searches for H $\rightarrow$ WW* (ZZ*) decays [8]. The resulting numerous six fermion final states are grouped into different topological classes depending on the number of hard and soft leptons, jets and the amount of missing energy. The L3 results are given on Figure 3(a). These can be combined with the searches for H $\rightarrow \gamma\gamma$, see the example from ALEPH on Figure 3(b), to improve the sensitivity to the fermiophobic benchmark scenario, which assumes SM-like Higgs couplings to bosons and no coupling to fermions.

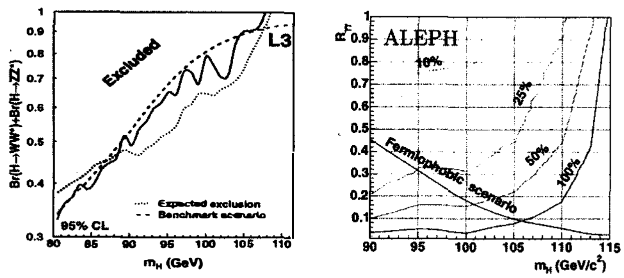

Figure 3: Search for fermiophobic Higgs bosons: (a) Excluded region in the $[m_H - Br(\mathrm{H}\rightarrow \mathrm{WW}^*, \mathrm{ZZ}^*)]$ plane. (b) Upper bounds on the total decay rate to electroweak gauge bosons (Br_{boson}) as a function of m_H and the ratio of the H$\rightarrow \gamma\gamma$ decay rate to the total bosonic decay rate ($R_{\gamma\gamma} = Br_{\gamma\gamma}/Br_{boson}$).

3 Signatures of Gauge Mediated Supersymmetry Breaking

Supersymmetry (SUSY), the best proposed solution to the problems of the SM, postulates the existence of a partner for each SM particle chirality state. The discovery of these superpartners would be the most direct evidence for SUSY. Since SUSY particles are not observed with the same mass as their SM partners, SUSY must be broken. In the most widely investigated scenarios, it is assumed that SUSY is broken in some *hidden* sector of new particles and is *communicated* to the *visible* sector of SM and SUSY particles by gravity or gauge interactions.

We review here a study of gauge-mediated SUSY breaking (GMSB) topologies [9] using the data collected by the OPAL detector.

In models with GMSB, the lightest SUSY particle (LSP) is a light gravitino $\tilde{G}$. The phenomenology is driven by the nature of the next-to-LSP (NLSP), which is either the lightest neutralino $\tilde{\chi}_1^0$, scalar tau $\tilde{\tau}_1$ or mass-degenerate scalar leptons $\tilde{\ell}$. As the gravitino couples very weakly to heavier SUSY particles, those will decay typically to the NLSP which then decays via $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ or $\tilde{\ell} \rightarrow \ell\tilde{G}$. All relevant final states are considered: direct NLSP production and its appearance in the decay chain of heavier SUSY particles, like charginos, neutralinos and scalar leptons.

The minimal GMSB model introduces five new parameters and a sign: the SUSY breaking scale ($\sqrt{F}$), the SUSY particle mass scale (Λ), the messenger mass (M), the number of messenger sets (N), $\tan\beta$ and the sign of the SUSY Higgs mass parameter (sign(μ)). As the decay length of the NLSP depends on $\sqrt{F}$ and is effectively unconstrained, NLSP decays inside and outside of the detector are searched for. With increasing decay length, the event signatures include: energetic leptons or photons and missing energy due to the undetected gravitino, tracks with large impact parameters, kinked tracks, or heavy long-lived charged particles. In total more than 14 different selections are developed to cover the GMSB topologies. The results are combined (with special attention to treat the overlaps among the many channels properly) to get lifetime independent results, eliminating the dependence on $\sqrt{F}$.

None of the searches shows evidence for SUSY particle production. To interpret the results, a detailed scan of the minimal GMSB parameter space is performed.

"Model independent" cross-section limits are derived for each topology as a function of the NLSP lifetime, both for direct NLSP production and, for the first time, also for cascade decays. For direct NLSP production, this is done by taking the worst limit for a given NLSP mass from the generated GMSB parameter scan points. For cascade channels, the cross-section evolution is assumed to be β/s for spin-1/2 and β^3/s for scalar SUSY particles, and the highest bound for all intermediate particle masses is retained. The maximum limit valid for all lifetimes is then quoted as the "lifetime independent" cross-section limit. In the neutralino NLSP scenario this is typically better than 0.04 pb for direct NLSP production, 0.1 pb for scalar electron and scalar muon production, 0.2 pb for scalar tau production and 0.3 pb for chargino production. In the scalar tau and scalar lepton co-NLSP scenarios, the limit on direct NLSP production cross-section is smaller than about 0.05 pb for scalar muons, 0.1 pb for scalar electrons and scalar taus. For the cascade decays the bounds are typically better than 0.1 pb for neutralino, 0.2 for chargino and, in the scalar tau NLSP scenario, 0.4 for scalar electron and scalar muon production.

The cross-section limits can be turned into constraints on the NLSP mass. For scalar leptons, the lowest mass limits are found for very short lifetimes, except for scalar electrons, shown in Figure 4(a), where searches using $\mathrm{d}E/\mathrm{d}x$ measurements loose efficiency for particles with momenta around 65 GeV. The lifetime independent limits are $m_{\tilde{e}_R} > 60.1$ GeV, $m_{\tilde{\mu}_R} > 93.7$ GeV and $m_{\tilde{\tau}_1} > 87.4$ GeV. The limit on $m_{\tilde{\tau}_1}$ is the same in the scalar tau and the scalar lepton co-NLSP scenarios. In the scalar lepton co-NLSP scenario, where by definition the mass differences between the different scalar lepton flavors are smaller than the lepton masses, the best limit can be used to derive a universal limit on $m_{\tilde{\ell}} = m_{\tilde{\mu}_R} - m_{\tau} > 91.9$ GeV. For neutralino NLSP, no lifetime independent NLSP mass limit can be set directly. For short lifetimes ($\tau < 10^{-9}$ s), a mass limit of $m_{\tilde{\chi}_1^0} > 96.8$ GeV is derived.

The GMSB parameter space can also be constrained by these results as illustrated in Figure 4(b) for $N = 1$, $M = 1.01 \cdot \Lambda$ and sign(μ) > 0. The universal SUSY mass scale is $\Lambda > 40, 27, 21, 17, 15$ TeV for messenger indices $N = 1, 2, 3, 4, 5$, independent of the other model parameters. The constraints on Λ imply a lifetime independent lower limit on the neutralino mass in the neutralino NLSP scenario: $m_{\tilde{\chi}_1^0} > 53.5$ (94.0) GeV for $N = 1$ (5).

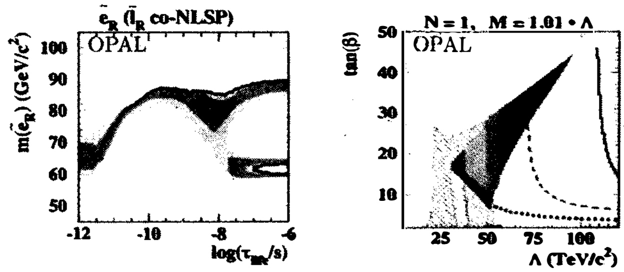

Figure 4: Search for GMSB signatures: (a) Observed (thick red/dark gray) and expected (thin black) lower mass limits for pair-produced scalar electrons in the scalar lepton co-NLSP scenario as a function of the NLSP lifetime. The 68% and 95% probability intervals are shown by orange/grey shades. (b) Regions in the [Λ – tanβ] plane excluded by the different searches in the scalar tau and scalar lepton co-NLSP scenarios (direct NLSP production - black, chargino - dark gray, neutralino - gray, scalar electron and scalar muon production with scalar tau NLSP - light gray) and in the neutralino NLSP scenario (neutralino production - dense hatched, chargino - hatched). The LEP1 search region is cross-hatched and the theoretically not allowed area is sparse hatched gray. The constraint from the LEP combined Higgs limit of $m_H > 114.4$ GeV is also shown (full line) together with the indication of the large effect from theoretical (dashed) plus top quark mass (dotted) uncertainties, weakening this constraint.

4 Extra Dimensions

Models with extra spatial dimensions (EDs) have been introduced to solve the hierarchy problem of the SM through geometrical considerations. Most LEP results are derived in the original Arkani-Hamed – Dimopoulos – Dvali (ADD) framework, which assumes n compact EDs, with the Planck scale M_D in $D = 4 + n$ dimensions set close to the EW scale. SM particles propagate in a four dimensional (4D) subspace (brane), while gravity in the full D dimensional space. The 4D Planck scale M_{Planck} satisfies $M^2_{Planck} = V_n M_D^{n+2}$, where V_n is the volume of the EDs.

An other interesting scenario was suggested by Randall and Sundrum. They assume only one ED and generate the hierarchy by a specifically chosen "warped" geometry. Gravity is then located close to a second brane and its propagation in the ED is exponentially damped.

A general prediction of these scenarios is the existence of massive Kaluza-Klein excitations of the graviton in the 4D effective theory.

4.1 Branons

In a general ADD like geometry, where SM particles live on a 3-brane, the presence of brane fluctuations of a typical size $1/f$ manifests themselves as new scalar weakly interacting particles, the branons, which also serve as possible dark matter candidates. If the branes are flexible, i.e. the brane tension f is much smaller than the D dimensional Planck scale, the graviton KK modes decouple from SM particles and the first signal from the EDs could be the discovery of branons.

Branons ($\tilde{\pi}$) couple in pairs to SM particles, and they would appear in e^+e^- collisions in $Z/\gamma\ \tilde{\pi}\tilde{\pi}$ final states, giving a single Z or γ plus missing energy. The limits on branon production from the L3 Collaboration [10] are shown on Figure 5(a).

4.2 Radions in the Randall-Sundrum Model

In the Randall-Sundrum (RS) scenario, the radion corresponds to local fluctuations of the inter-brane distance. The radion has the same quantum numbers as the Higgs boson and mixes with it, resulting in a radion-like (r) and a Higgs-like (h) state. The radion couplings are similar to the Higgs couplings but suppressed by a factor of $v/(\sqrt{6}\Lambda_W)$, where v is the vacuum expectation

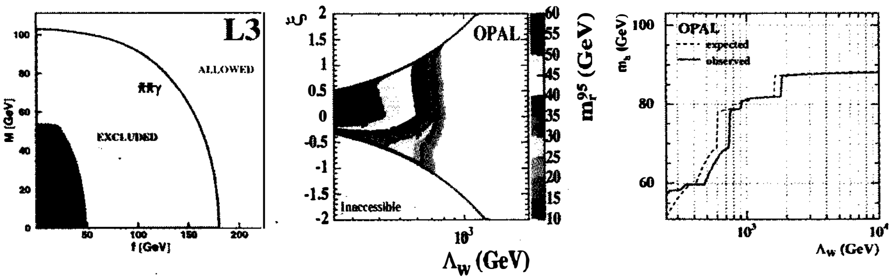

Figure 5: (a) Search for branons: Excluded region in the [brane tension - branon mass] plane, assuming only one branon of mass M. Search for radions: (b) Lower limit on the mass of the radion-like state as a function of Λ_W and ξ. (c) Absolute lower limit on the mass of the Higgs-like state as a function of Λ_W.

value of the Higgs field and Λ_W is the energy scale on the SM brane. The radion, however, also couples to gluon pairs, and the r $\rightarrow$ gg decay is dominant.

The OPAL Collaboration re-interpreted its SM, flavour and decay-mode independent Higgs boson searches in the RS model and derived limits on the r and h masses as a function of Λ_W and the mixing parameter, ξ, as shown for the radion-like state on Figure 5(b). As opposed to the Higgs-like state, searches for the radion-like state loose sensitivity for larger values of Λ_W and for large negative values of ξ close to the theoretically inaccessible region, therefore, no absolute limit on the mass can be derived. The absolute lower limit on the mass of the Higgs-like state is given on Figure 5(c).

5 Fourth Generation b' Quarks

In the SM, the number of fermion generations and their mass spectrum are not predicted. Precision EW measurements allow for the existence of an extra, heavy fermion generation, if $|m_{t'} - m_{b'}| < 60$ GeV is fulfilled. For $m_Z < m_{b'} < m_H$, the b' quark decays predominantly into bZ and cW.

The DELPHI Collaboration performed a search for b'b' production in the bZbZ and cWcW final states for $m_{b'} = 96 - 103$ GeV, and derived upper limits on the b' $\rightarrow$ bZ and b' $\rightarrow$ cW branching ratios of 51 and 43% for $m_{b'} = 96$ GeV, degrading to 74 and 55% for $m_{b'} = 101$ GeV, respectively [12]. The branching ratio limits can be used to constrain the extended CKM matrix within a four-generation sequential model, as shown on Figure 6.

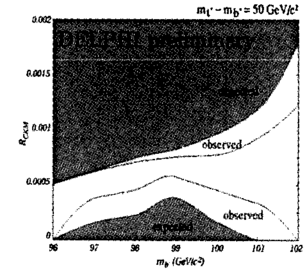

Figure 6: Search for b' quarks: Excluded regions in the $[m_{b'} - R_{\mathrm{CKM}}]$ plane for $m_{t'} - m_{b'} = 50$ GeV . The constraints on $R_{\mathrm{CKM}} = |V_{cb'}/(V_{tb'}V_{tb})|$ weaken as the mass difference $m_{t'} - m_{b'}$ decreases.

6 Single Top Quark Production via Contact Interactions

As flavour changing neutral currents (FCNCs) are forbidden at tree level in the SM, in good agreement with the experimental data, rare FCNC processes are ideal to look for new physics. The LEP Collaborations conducted searches for single top quark production via FCNC, described in terms of vector-like anomalous couplings (κ_γ, κ_Z) associated with the photon and the Z boson.

A more general approach is to consider possible new 4-fermion contact interactions, including scalar-, vector- and tensor-like couplings, through an effective Lagrangian with FCNC operators. The eetc vertex is then characterized by the couplings S_{RR}, V_{ij} and T_{RR}, where i, j = L,R. To account for the 'traditional' FCNC Ztc vertex, the couplings a_j^Z are also introduced.

The DELPHI Collaboration considered several scenarios in this framework defined by the couplings that are different from zero: S, V, T, SVT, a, V−a, V+a, where the −/+ signs refer to destructive or constructive interference between the vector like 4-fermion and the Ztc couplings. From the search for the $e^+e^- \to t\bar{c} \to b\bar{c}q\bar{q}'$ and $b\bar{c}\ell\nu_\ell$ processes, they placed bounds on the physics scale $\Lambda >$ 0.69, 1.07, 1.20, 1.40, 0.50, 1.09, 1.06 TeV, in the six scenarios listed above[13]. These results are consistent with earlier results of the L3 Collaboration in the S, V, T scenarios[14]. When only one coupling is different from zero, it can also be constrained from the data: $S/\Lambda^2 < 2.14 \cdot 10^{-6}$ and $T/\Lambda^2 < 6.90 \cdot 10^{-7}$ GeV^{-2}.

7 Conclusion

The LEP machine was an ideal tool to search for physics beyond the SM, and a huge number of such scenarios were studied and constrained. The LEP results, both on precision EW measurements and direct searches, give us hints how to continue the quest to uncover a more fundamental theory of particle physics at the LHC and beyond.

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