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SEARCHES AT LEP

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This contribution reviews the results of searches at LEP, which were obtained during the last years. As a model for new physics, searches for Supersymmetric particles and searches for effects of extra dimensions are shown. Despite the growing motivation for physics beyond the standard model obtained from cosmology, no sign of new phenomena has been found at LEP. An overview of the large number of different signatures for which LEP is setting competitive limits is shown, including sfermion, chargino and neutralino searches and R-parity violating models. Additionally, searches for radions in the Randall-Sundrum-model are presented.

1 Introduction

The Standard Model (SM) describes the fundamental interactions of matter with impressive precision [1]. However, some experimental and theoretical problems of the SM persist. These are for example the dark matter and dark energy content in the universe, which is unexplained in the context of the SM, and the theoretical problems of the unification of the forces and the explanation of the mass hierarchies (see e. g. [2]). Therefore extensions of the SM are sought at LEP.

The four LEP experiments ALEPH, DELPHI, L3 and OPAL took data of e^+e^- collisions at centre-of-mass energies of $\sqrt{s} = 91 - 209$ GeV from 1989 to 2000. All four LEP experiments have pursued a long list of signatures of different possible extensions of the SM. This paper concentrates on the two models connected with extra dimensions: Supersymmetry (SUSY) [3] as an extra fermionic dimension, and the Randall-Sundrum (RS) model [4] as an example for extra space dimensions. In many search channel LEP continues to update its searches and to set the strongest limits four years after the end of data taking.

2 Searches for Supersymmetry

Basically all searches for SUSY at LEP are pursued in context of the Minimal Supersymmetric Standard Model (MSSM), which is the SUSY extension of the SM with minimal particle content. In SUSY, an additional fermionic degree of freedom is introduced, generating for each SM boson a SUSY fermion, and vice versa, with the same mass and couplings as the SM particles. Thus the particle content of the SM is doubled. Since these SUSY partners of the SM particles are not observed, they must be heavier than the SM, meaning that SUSY must be a broken symmetry. The MSSM models under study at LEP are characterised by the SUSY breaking mechanism from which they are motivated. Additionally, an extended Higgs sector with two doublets exists.

At LEP, searches for all SUSY particles are pursued. These are searches for sleptons and squarks, the bosonic partners of the SM fermions, and gauginos, the partners of the SM bosons. The mass eigenstates of the gauginos are separated in charged spin-1/2 particles, the charginos, and neutral spin-1/2 particles plus the gluino, the partner of the gluon. Additionally, the extended Higgs sector is studied, which is reported in [5].

Topological selections independent of the model parameters and just depending on the particle masses and couplings are used to search the particles. Since for most of the searches, such as chargino χ_1^+ production, the expected signal rate or even the signal topology (as in case of interference between s and t channel) depends not only on the particle searched for, but also on other particles, the observed mass limits however usually depend on assumptions on other SUSY particles, such as the masses of sneutrinos exchanged in the t channel of the chargino production.

The results of the topological searches are then combined and used to derive limits on the parameters of the SUSY models, such as minimal Supergravity (mSUGRA). For the results shown here, R-parity violation is assumed, assuring that the lightest supersymmetric particle (LSP) is stable.

2.1 Sfermion Searches

The partners of the SM fermions, the sleptons and squarks, are produced at LEP in the s-channel Z/γ exchange. The cross-section of selectrons is increased by the additional t channel exchange of a neutralino. For the left-handed and the right-handed degree of freedom of the SM fermions one spin-0 bosonic partner exists. In most models, the partners of the righthanded fermions are predicted to be lighter, therefore the searches concentrate on them. For the third generation only the mixing of the right- and the left-sfermions into general mass eigenstates must be taken into account.

In large regions of the MSSM parameter space, the dominant decay of the sfermions $\tilde{f}$ proceeds into the corresponding fermion f and the neutralino χ^0, which is the LSP: $\tilde{f} \to f\chi^0$. The signature in the detector therefore depends on the missing energy carried away by the neutralino, i. e. on the mass difference $\Delta m = m_{\tilde{f}} - m_{\chi_1^0}$.

Table 1 shows the mass limits on various SUSY particles from combined LEP analyses. In case of the slepton searches, the mass limits for the righthanded partners are shown. They depend on the missing energy carried away by the neutralino.

For the mixing of the $\tilde{\tau}_R$ and $\tilde{\tau}_L$ states into mass eigenstates adjusted such that the minimal coupling to Z/γ is achieved, the lowest mass limit is only very slightly reduced for large $m_{\chi_1^0}$ and otherwise stays constant.

The lightest squarks are expected to be the partners of the third generation. Here, the mass limit is given for the mass eigenstate with the smallest coupling to Z/γ and for different decays, depending on the mass difference of the squark to the neutralino.

In all cases, limits close to the kinematic limit of around 100 GeV for the largest part of the LEP 2 data are achieved. Also if R-parity violation is allowed in the SUSY models under study, the mass limits from sfermion [10] searches are close to

Particle	Assumptions	Obs. Limit (GeV)
	Sleptons [6]	
$m_{\tilde{e}}$	RR coupling, $m_{\chi_1^0} = 0 - 40$ GeV	99.9
$m_{\tilde{\mu}}$	RR coupling, $m_{\chi_1^0} = 0 - 40$ GeV	94.9
$m_{\tilde{\tau}}$	RR coupling, $m_{\chi_1^0} = 0 - 40$ GeV	86.6
	Stops and Sbottoms [7]	
$m_{\tilde{t}}$	$\to \mathrm{c}\chi_1^0$, $m_{\tilde{t}} - m_{\chi_1^0} = 20 - 60$ GeV	95
$m_{\tilde{t}}$	$\to \mathrm{b}\ell\tilde{\nu}_\ell$, $m_{\tilde{t}} - m_{\tilde{\nu}} = 20 - 40$ GeV	96
$m_{\tilde{b}}$	$\to \mathrm{b}\chi_1^0$, $m_{\tilde{b}} - m_{\chi_1^0} = 20 - 60$ GeV	94
	Charginos [8]	
$m_{\chi_1^\pm}$	any value of $m_{\chi_1^\pm} - m_{\chi_1^0}$	91.9
	Neutralinos [9]	
$m_{\chi_1^0}$	mSUGRA	50.0
$m_{\chi_1^0}$	$X_\tau = 0$ GeV, GUT constraint	43.1
$m_{\chi_1^0}$	any X_τ, GUT constraint	29.7
$m_{\chi_1^0}$	any X_τ, no GUT constraint	0

Table 1. Limits on the masses of SUSY particles from searches at LEP. RR coupling means that the production of the sfermions is studied which are the partners of the righthanded fermions. Most of the limits are preliminary.

the kinematic limit from LEP 2.

2.2 Chargino and Neutralino Searches

Charginos $\chi_i^\pm$ and neutralinos χ_i^0 are produced in s channel Z/γ exchange or in t-channel sneutrino or selectron exchange. The charginos decay via a W into fermions and the LSP (here χ_1^0). Since the lightest neutralino escapes the detector, it can only be searched indirectly [11].

The chargino and neutralino mass limits for different assumptions are given in Table 1. The chargino can be effectively excluded for all model assumptions. In case of the lightest neutralino, the situation is different. Limits can only be set in the presence of model assumptions. In the framework of the mSUGRA scenario, for example, the indirect limit on $m_{\chi_1^0}$ from searches on Higgs bosons, charginos and sleptons is 50 GeV. If any mixing in the $\tilde{\tau}$ sector is allowed, but unification of the gaugino mass parameters at the unification scale is still assumed, the limit shrinks to $m_{\chi_1^0} > 29.7$ GeV. Finally, for no model assumptions, no mass limit can be set [11].

2.3 Combination of the topological searches

The combination of the results of all topological searches for sfermions, gauginos and Higgs bosons for different model assumptions (i. e. different masses and couplings) can be used to exclude regions in the theoretical parameter space of the model. In Figure 1 this is shown for the mSUGRA scenario, which has the ratio of the Higgs

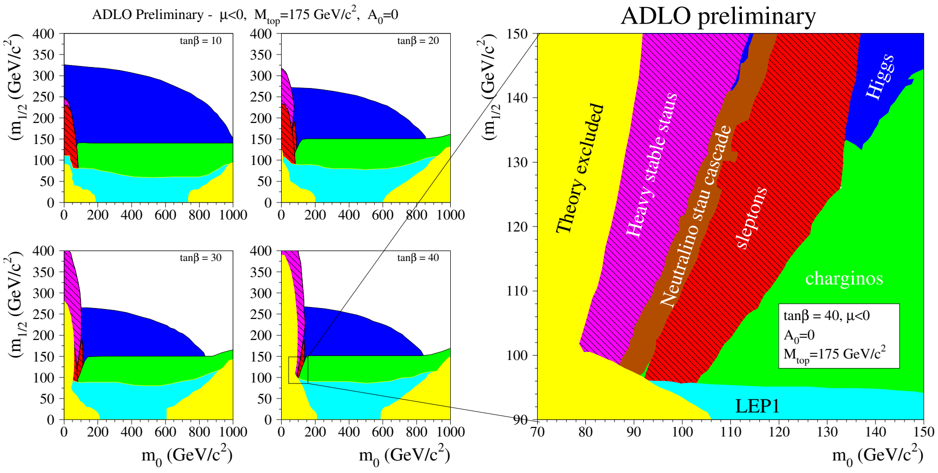

Figure 1. The interplay between different searches for the parameter limits on the mSUGRA scenario [12].

vacuum expectation values tanβ, the common trilinear coupling A_0, the common sfermion mass scale m_0 and the common gaugino mass scale $m_{1/2}$ as parameters. The absence of a signal in any of the searches is then turned into an exclusion in the parameter space.

3 Extra Dimensions

As an example for a different approach to solve the hierarchy problem of the SM, the Randall-Sundrum model is shown. It assumes the existence of an non-compactified extra dimension. The SM forces are bound on one four-dimensional brane, whereas gravity is located on another plane. A warped space-time between the two weakens gravity when it penetrates the additional dimension, leading to the large apparent Planck mass on the SM brane. The excitations of the distance between the two branes manifest themselves as a spin-0 particle called radion with the quantum numbers of the SM Higgs boson, therefore it mixes with the Higgs boson. Due to the large coupling of the radion to gluons (see Fig. 2 (a)) it diminishes the mass limit on a spin-0 particle with Higgs boson quantum numbers down to $m_{\mathrm{spin0}} > 58$ GeV [13], to be compared with the SM Higgs mass limit of $m_{\mathrm{h}} > 114.4$ GeV [14].

4 Conclusions

The LEP collaborations performed extensive searches for signatures of physics beyond the SM. No evidence for a signal exists. Due to the large number of different phenomena in the extensively tested SUSY framework, very few loopholes for new physics at LEP energies exist. For most of the SUSY particles both in R-parity conserving and violating models, mass limits in the region of 80 to 100 GeV can be

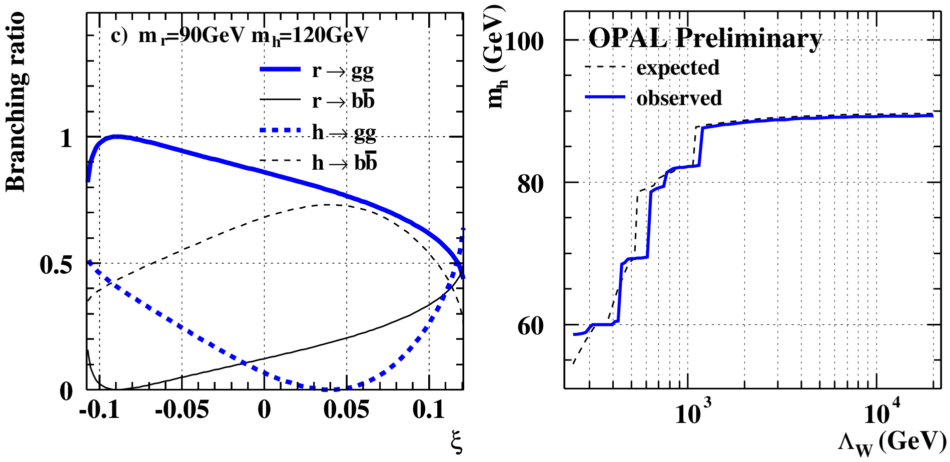

Figure 2. On the lefthand side, the branching ratio of the Higgs-like and the radion-like states in the RS-model [4] into b$\bar{b}$ and gluons is shown. The right plot shows the lowest mass limit on a spin-0 particle in this model, depending on the RS parameter choice [13].

set by LEP. However, for some of the SUSY particles such as neutralinos, limits can only be set in the context of model assumptions, such as gaugino mass unification at the unification scale. If these assumptions are dropped, no limit on $m_{\chi_1^0}$ can be set.

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