SEARCHES FOR SUSY AND EXTRA DIMENSIONS AT LEP

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Many searches for physics beyond the Standard Model have been performed at LEP. In this paper searches for topologies expected from the Gauge Mediated Supersymmetry Breaking model and from various models with extra spatial dimensions, based on typically 600 pb$^{-1}$ of data at $\sqrt{s} = 189 - 209$ GeV, are presented.

Keywords: GMSB; LEP; Extra Dimensions; SUSY.

1. Introduction

The Standard Model (SM) of particle physics is remarkably successful. However, many open questions remain, and thus various models for physics beyond the SM have been proposed. Currently the two most popular classes of models are those assuming supersymmetry (SUSY) and extra dimensions (ED). In this paper, searches for the Gauge Mediated Supersymmetry Breaking (GMSB) model and for various models with extra spatial dimensions are presented.

2. Searches for Gauge Mediated SUSY Breaking Topologies

That supersymmetry must be broken follows from the experimental fact that no SUSY particles have been discovered yet. Various mechanisms for SUSY breaking have been proposed. Typically SUSY breaking takes place in a hidden sector, and is mediated to the visible sector of SM and SUSY particles via a messenger sector. In the GMSB model, the messenger sector interacts with the visible sector via the usual gauge interactions and the SUSY breaking scale $\sqrt{F}$ is typically low. Consequently the gravitino $\tilde{G}$ is light and actually the Lightest Supersymmetric Particle (LSP). The GMSB model is described by six free parameters: the messenger mass scale $M$, the number of generations of messenger particles $N$, the SUSY breaking scale $\sqrt{F}$, the SUSY particle mass scale $\Lambda$, the ratio of the vacuum expectation values of the Higgs doublets, $\tan \beta$, and the sign of the Higgs sector mixing parameter $\mu$.

The next-to-lightest SUSY particle (NLSP) can either be the stau $\tilde{\tau}$ (stau NLSP scenario), all (mass-degenerate) sleptons $\tilde{l}$ (slepton co-NLSP scenario) or the lightest neutralino $\tilde{\chi}_1^0$ (neutralino NLSP scenario). The NLSP decays like $\tilde{\tau} \rightarrow \tau \tilde{G}$, $\tilde{l} \rightarrow l \tilde{G}$ and $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$, respectively. The most distinct feature of GMSB is the fact that the lifetime of the NLSP, which depends on the fourth power of $\sqrt{F}$, is arbitrary, such that all possible lifetimes of the NLSP must be considered in the searches.

2.1. Slepion NLSP Scenario

Sleptons can be pair-produced directly, but also indirectly via e.g. neutralino or chargino pair-production, followed by the decays $\tilde{\chi}_1^0 \rightarrow \tilde{l}_i^\pm l^\mp$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{l}_i^\mp \nu$. The experimental topology depends on the slepton lifetime. For prompt decays, two tracks from the decay leptons will be present. For medium lifetimes, when the decay length of the sleptons is macroscopic, tracks with large impact parameters or kinks are expected. Finally, if the sleptons decay outside the detector, they
will produce tracks with an anomalously high ionization energy loss, \(dE/dx\), in the tracking chambers. In any case there will be missing energy from the invisible gravitinos. Additional tracks will be present for indirect slepton production.

Searches for all possible topologies have been performed by the OPAL collaboration\(^1\)\(^2\). No significant excess was found in any of the search channels. To derive limits on cross sections, masses and model parameters, a scan of the GMSB parameter space was performed, based on the framework of Dimopoulos et al.\(^3\). For \(M\) the values 1.01 \(\cdot \Lambda\), 250 TeV/c\(^2\) and 10\(^6\) TeV/c\(^2\) were considered, \(N\) was varied from 1 to 5, \(\Lambda\) was scanned between 5 and 150 TeV/c\(^2\) and tan \(\beta\) between 1 and 50. All search channels were combined to derive lifetime independent limits on the production cross sections. Overlaps between channels were taken into account, and systematic and statistical uncertainties were included\(^4\). In Fig. 1 the 95% CL cross section limits for stau pair-production in the stau NLSP scenario are shown. In most regions of the stau mass \(-\log\) (lifetime) plane, cross sections above 0.1 pb are excluded. Similar limits are obtained for slepton pair-production in the slepton co-NLSP scenario. Cross sections above 0.1 pb and 0.2 pb are excluded for neutralino and chargino pair-production, respectively.

For direct slepton pair-production, the cross section limits were compared with the expected \(\sigma \cdot BR\), to derive lifetime-independent limits on the slepton masses. The stau mass limit in the stau NLSP scenario amounts to 87.4 GeV/c\(^2\), the slepton mass limit in the slepton co-NLSP scenario is derived from the smuon mass limit and amounts to 91.9 GeV/c\(^2\).

\[\text{OPAL, } e^+ e^- \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0\] \[\text{NLSP}^\text{95} \text{(pb)}\]

**Fig. 1.** Limits on the stau pair-production cross section in the stau NLSP scenario in the stau mass \(-\log\) (lifetime) plane, at 95% CL.

For prompt neutralino decays, the experimental signature are photons plus missing energy. For intermediate neutralino lifetimes the photons will be non-pointing. In both cases additional leptons or jets will be present in the case of indirect production. Finally if the neutralino decay happens outside the detector, only the indirect production channels are visible at all.

Searches for almost all existing channels were performed by the OPAL collaboration. In the indirect production channels, searches were combined to derive lifetime-independent limits on \(\sigma \cdot BR\) in the plane of the neutralino mass and the mass of the primary particle. Typically cross sections above 0.2 pb are excluded for all lifetimes.

### 2.3. Interpretation

All cross section limits were used to exclude regions in the GMSB parameter space, based on the scan described in Sec. 2.1. The lifetime independent limits on the SUSY particle mass scale \(A\) are 40, 27, 21, 17, 15 TeV/c\(^2\) for \(N = 1, 2, 3, 4, 5\), respectively.

\[\text{2.2. Neutralino NLSP Scenario}\]

In the neutralino NLSP scenario neutralinos are either pair-produced directly or indirectly via chargino pair-production, followed by the decay \(\tilde{\chi}_1^\pm \rightarrow W^{\pm} \tilde{\chi}_1^0\), or slepton pair-production, followed by decays \(l^+_i \rightarrow l^+_1 \tilde{\chi}_1^0\).
3. Searches for Extra Dimensions

Models with extra dimensions provide a motivation for the large hierarchy between the electro-weak and the Planck scale, which cannot be explained within the SM. The two most popular classes of models are the ADD type models\(^5\) and the Randall Sundrum type models. In the ADD model, \( n \) large compact extra spatial dimensions are proposed. While the SM particles live on the 4-dimensional brane, gravity can propagate in the \( D = 4 + n \) dimensional bulk. The gravitational mass scale \( M_D \) in \( D \) dimensions is of the order of the weak scale. The effective gravitational mass scale in four dimensions \( M_P \) is large only because it depends on the large hidden volume of the extra dimensions: \( M_P^2 \approx M_D^{2+n}R^n \).

One phenomenological consequence of EDs is the existence of massive excitations of the graviton, the Kaluza Klein tower of states. In the ADD model, those states interact only gravitationally with the SM particles, but the weakness of the interaction is compensated for by the large multiplicity of states.

In all analyses presented here the results are interpreted in the framework of the ADD model or variations of it.

3.1. Searches for Gravitons

In the framework of EDs, single gravitons could be produced at LEP in association with a photon, resulting in a photon plus missing energy signature. The differential cross section for this process is strongly enhanced for low photon energies and polar angles\(^6\). The main backgrounds are the processes \( e^+e^- \rightarrow e^+e^-\gamma(\gamma) \) and \( e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma) \).

All LEP collaborations have searched for this signature, typically considering photons with a \( p_T > 0.02 \sqrt{s} \). The L3 collaboration has increased the phase space by searching for photons with a \( p_T \) as low as 0.008 \( \sqrt{s} \). No significant excess over the background expectation was observed. The number of expected events is calculated as a function of \( (1/M_D)^{n+2} \) and compared with the number of observed events in the \( x_\gamma = |\cos \theta_\gamma| \) grid (where \( x_\gamma = E_\gamma/E_{\text{beam}} \)). For the LEP combination, results are based on a data sample of 1.9 fb\(^{-1}\) at \( \sqrt{s} = 183 - 209 \) GeV. The individual log likelihood functions were added for each value of \( n \) and used to fit the parameter \( (1/M_D)^{n+2} \). Limits were calculated using the Bayesian likelihood method. In Fig. 2 the LEP-combined limits on \( M_D \) are shown.

3.2. Search for one Large ED

In the classical ADD model, the case of one large ED is excluded by astronomical and astrophysical constraints. For a slightly warped geometry, however, the case of \( n = 1 \) is allowed\(^9\). The differential cross section is expected to peak at high \( x_\gamma \).

The DELPHI collaboration has analyzed their data for this special case\(^10\). The resulting \( x_\gamma \) distribution is shown in Fig. 3, together with the signal expectation for \( M_D = 1.25 \) TeV/\( c^2 \), after a correction for efficiency and the energy resolution in the calorimeter. No significant excess over the background, which is predominantly from neutrino pair-production with photons from initial state radiation, is observed. A limit on \( M_D \) of 1.69 TeV/\( c^2 \) is obtained.
3.3. Search for Branons

For ADD type geometries brane oscillations lead to new massive scalar fields, so-called branons\textsuperscript{11}. These particles can be regarded as the Goldstone bosons associated with the spontaneous symmetry breaking of the (non-exact) translational invariance produced by the presence of the brane. At LEP these particles would be pair-produced in association with a Z boson or a photon. If the brane tension, described by the parameter \( f \), is much smaller than the mass scale \( M_D \), gravitons are expected to decouple from SM particles and the first experimental hint for EDs could come from the discovery of branons.

The L3 collaboration has performed a search for branons both in the Z and the photon channel, assuming one light branon with mass \( M \)\textsuperscript{12}. Since no hint for an excess over the background from \( \nu \bar{\nu} Z \) and \( \nu \bar{\nu} \gamma \) events was observed, limits on the brane tension \( f \) and the branon mass \( M \) have been derived from a bin-wise comparison between the number of observed and expected events in the two-dimensional \( x - \cos \theta \) distribution. The excluded regions in the \( f - M \) plane are shown in Fig. 4.

4. Summary

Searches for signals expected from the GMSB model and models with EDs have been performed at LEP. No significant excesses over the background expectations have been observed. The limits on the SUSY particle mass scale \( \Lambda \) amount to 40 and 15 TeV/c\(^2\) for \( N = 1 \) and \( 5 \), and the bounds on the gravitational mass scale \( M_D \) are 1.69, 1.60 and 0.66 TeV/c\(^2\) for 1, 2 and 6 EDs, respectively.

References