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SEARCH FOR SUPERSYMMETRY AT LEP*

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Search for supersymmetric particles are performed with the data collected by the four LEP detectors, ALEPH, DELPHI, L3 and OPAL, at centre-of-mass energies up to 209 GeV, between 1995 and 2000. No evidence for a signal related to the production of sfermions, charginos and neutralinos in the framework of the Minimal Supersymmetric Standard Model (MSSM) is observed. The number of candidate events observed is in agreement with that expected from Standard Model (SM) background sources, for each signal topology. The absence of any excess is turned into exclusions domains in the space of the relevant MSSM parameters and lower limits on the mass of the supersymmetric particles are derived at 95% Confidence Level (C.L.).

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1. Introduction

Supersymmetric models [1] are possible extensions of the SM [2], based on the assumption that a symmetry transformation turns bosons into fermions. For each fermion and gauge boson of the SM, a supersymmetric partner with spin different by 1/2 unit is expected.

The theoretical framework used in this paper is the MSSM [3] that is the extension of the SM with the minimal particle content. Unlike SM, two doublets of complex scalar Higgs are necessary to give masses to up and down-type quarks and charged leptons. The R-parity conservation[1] hypothesis is made to prevent from the proton decay and the lightest neutralino

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[1] R-parity is a multiplicative quantum number defined as $R = (-1)^{3(B-L)+2S}$ where B, L and S are the baryon number, the lepton number and the spin of the particle, respectively. SM particle have $R = +1$ while their SUSY partners have $R = -1$.

is assumed to be the Lightest Supersymmetric Particle (LSP). The MSSM parameters that are considered for the interpretation the results are the ratio of the vacuum expectations values of the two Higgs doublets, $\tan\beta$, the mixing mass parameter in the sector of Higgs, μ, the U(1)$\times$ SU(2)$\times$ SU(3) gaugino masses M_1, M_2, M_3 at the electroweak scale and the slepton and squark masses. The gaugino masses are assumed to be unified to a common value at Grand Unification Theory (GUT) scale, $m_{\rm GUT} \simeq 10^{16}$GeV and the same is believed for all the sfermion masses (m_0 being the unified common value).

After the electroweak symmetry breaking (EWSB), the spectrum of the MSSM particles includes four neutralinos and two charginos which are combinations of the supersymmetric partners of the neutral and charged gauge and Higgs bosons, respectively. The lightest neutralino and chargino are usually labeled with χ and χ_1^+ respectively. In the MSSM are also expected three generations of squarks and sleptons, as supersymmetric partners of SM fermions, and five Higgs bosons whose two charged, two neutral with CP $= +1$ and one neutral with CP $= -1$.

The production mechanisms of the supersymmetric particles, the decay modes and the final state topologies addressed by the searches described in this paper are simulated using a Monte Carlo generator SUSYGEN [4]. The decay properties depend mainly on the mass difference between the decaying particle and the LSP, Δm, and on the leptonic branching ratio. The main signatures of the decay are the missing energy due to the neutralino LSP and a acoplanar pair of leptons or hadrons. As much as Δm becomes large, the signal and the four fermions background topologies look like the same one. Instead, if Δm is smaller than few GeV$/c^2$, the signal is overwhelmed by the two photons events. All the background events expected from SM processes are generated with statistics corresponding to at least 20 times the integrated luminosity of the data.

2. Sleptons and squarks

Two different supersymmetric scalars are predicted to be the partners of the left and the right-handed chiral states of each SM fermion. If the unification of the sfermion masses at GUT scale is assumed, lower masses and cross sections are typically expected for the partners of right-handed fermions. The right handed charged sleptons of the first two families are called selectrons and smuons and are labeled with $\tilde{e}_{\rm R}$, $\tilde{\mu}_{\rm R}$. For charged sleptons and squarks of the third family, the large Yukawa couplings cause a relevant mixing between the left and the right states.

Both the left and the right-handed sleptons and squarks are pair produced at LEP via Z$/\gamma$ exchange in the s channel and also through the

t-channel neutralino exchange which increases the cross section especially for selectrons. In large regions of the MSSM parameter space the dominant decay of the sfermions, $\tilde{f}$, is to the corresponding fermion and the lightest neutralino, $\tilde{f} \to f\chi$. Therefore the final state topologies are a pair of leptons or jets and missing energy for sleptons and squarks respectively. With regard to the $\tilde{l} \to l\chi$ decay, in figure 1(a) is shown the 95% C.L. excluded region in the plane ($M_{\tilde{l}}$, M_χ) obtained by the combination of the results of the four LEP collaborations at centre-of-mass energies between 183 and 208 GeV [5]. The exclusion domain for the stau, labeled with $\tilde{\tau}$, is derived in the most conservative condition looking for the minimal cross section which depends on the mixing angle θ (due to the variation in strength of the coupling to Z component of the weak current) and has a minimum close to $\theta \simeq 45°$. The selectron, the smuon and the stau masses are excluded at 95% C.L. up to 99.4, 95.4, 80 GeV/c^2, respectively. In the case of the stop, $\tilde{t}$, the decay to the top quark and the neutralino LSP is not kinematically allowed at LEP and the dominant two body decay channel is $\tilde{t} \to c\chi$. In figure 1(b) is shown the 95% exclusion domain in the plane ($M_{\tilde{t}}$, M_χ) under the assumption of minimal ($\theta \simeq 0°$) and maximal ($\theta \simeq 56°$) cross section [6]. Stop masses up to 96 GeV/c^2 are excluded at 95% C.L.

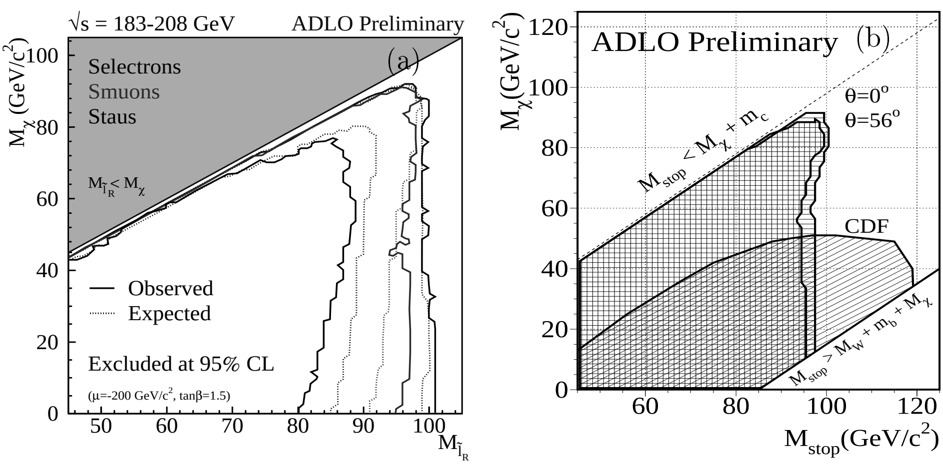

Fig. 1. (a) 95% C.L. exclusion domain in the plane ($M_{\tilde{l}}$, M_χ) for the right selectron, the right smuon and the stau in the vanishing coupling to Z condition, using all data collected by the 4 LEP experiments at centre-of-mass energies between 183 and 208 GeV [5]. The observed and the expected limits are given by the full and the dotted lines respectively. The gray region is not kinematically allowed; (b) Excluded region at 95% C.L. in the plane ($M_{\tilde{t}}$, M_χ) for two values of mixing angle corresponding to the minimal ($\theta = 56°$) and the maximal ($\theta = 0°$) coupling to Z [6]. The region denoted CDF is excluded by the CDF Collaboration [7].

3. Charginos and neutralinos

Charginos (neutralinos) are pair produced at LEP via s-channel $Z/\gamma(Z)$ exchange or t-channel exchange of a sneutrino (selectron). The t-channel contribution becomes relevant if the slepton is light. The interference with the s-channel is destructive in the case of charginos but constructive in the case of neutralinos. The decay of the lightest charginos (neutralinos) proceeds into the LSP and a pair of fermions via $W(Z)$ emission depending on the value of the scalar masses.

In the large scalar masses scenario and in the case of chargino pair production, the final state is expected to be four jets if both charginos decay hadronically, two jets and one lepton if one chargino decays into $l\nu\chi$ and with acoplanar leptons if both charginos decay into leptons and χ. In figure 2(a) is shown the 95% C.L. lower limit on the chargino mass as a function of the sneutrino mass ($M_{\tilde{\nu}}$) obtained combining the results from the four LEP collaborations at centre-of-mass energies up to 208 GeV [8]. Chargino masses up to 103.5 GeV/c^2 are excluded at 95% C.L. for sneutrino masses larger than 300 GeV/c^2. In the small sneutrino mass scenario the reduction of the chargino cross section and the enhancement of the leptonic decays lower the sensitivity of the direct search. The sensitivity is recovered from the direct production of neutralinos and sleptons, translating the lower limit on their production into constraints on the MSSM parameters.

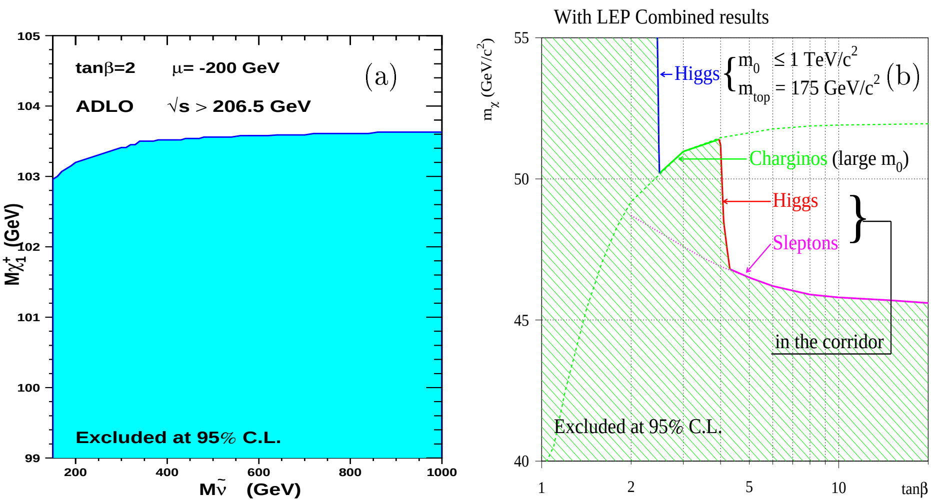

Fig. 2. (a) 95% C.L. exclusion domain in the plane $(M_{\chi_1^+}, M_{\tilde{\nu}})$ at centre-of-mass energies up to 208 GeV ($\tan\beta = 2$ and $\mu = -200$ GeV/c^2) [8]; (b) Lower limit at 95% C.L. on the neutralino LSP mass as a function of $\tan\beta$ obtained combining the results from the charginos, sleptons and Higgs searches at centre-of-mass energies up to 208 GeV [12]. The lines are used to distinguish the contributions of each analysis.

All the results quoted before are derived assuming a large value of the mass difference between the chargino and the LSP (typically $\Delta m > 5\,\mathrm{GeV}/c^2$). If Δm is smaller than few GeV/c^2 the final decay products are not efficiently detected due to the small visible energy; in this case the detection of isolated and energetic initial state radiation (ISR) photons produced in association with chargino pairs ensure the trigger of data acquisition and an efficient signal to two photons background discrimination [9]. No Δm independent limit on the chargino mass can be set in the light sfermion scenario and chargino masses up to $m_Z/2$ are excluded indirectly from the measurement of the Z total width at LEP 1 [10].

In the case of neutralinos production the most important signatures are expected to be acoplanar pairs of jets or leptons with missing energy and momentum. Heavier neutralinos give also rise to cascade decays with multiple jets or leptons in the final state also accompanied by photons. From the direct searches for charginos and neutralinos a lower limit on the mass of the lightest neutralino is derived as a function of $\tan\beta$ [11]. The lowest value is about 40 GeV/c^2 at 95% C.L. and holds for any value of m_0 if the combinations with slepton searches results is performed. Moreover, with the assumption that the mixing in the stau sector is negligible, constraints from neutral Higgs bosons searches are used to derive a lower limit on M_2 as a functions of $\tan\beta$ for a given m_0; this is easily translated into a lower limit on the neutralino LSP mass [12]. In the range $\tan\beta < 2.5$ the lower limit on χ is set at large m_0 by Higgs bosons searches while for $2.5 < \tan\beta < 4$ it is provided by the chargino searches as shown in figure 2(b). As much as $\tan\beta$ increases, constraints from the Higgs sector becomes less powerful and the limit on the LSP mass is set at small m_0 by the slepton searches. A lower limit on the neutralino mass of $45\,\mathrm{GeV}/c^2$ at 95% C.L. is set by the combination of the searches for charginos, sleptons and neutral Higgs bosons at centre-of-mass energies up to 208 GeV.

4. Conclusions

Search for sfermions, charginos and neutralinos are performed with the data collected at LEP, at centre-of-mass energies up to 209 GeV. No evidence for a signal is observed and the results are interpreted in the framework of MSSM. In the hypotheses of gaugino and sfermion masses unification, lower limits on the mass of the supersymmetric particles are derived. The selectrons, smuons, staus and stop masses are excluded up to 99.4, 95.4, 80 and 96 GeV/c^2 at 95% C.L, respectively. In the large scalar masses scenario, charginos masses are excluded up to 103.5 GeV/c^2. The searches for sleptons, charginos and neutral Higgs bosons are combined and a 95% C.L. lower limit on the neutralino LSP mass of about 45 GeV/c^2 is set.

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