Search for MSSM Sfermions and Gauginos

K. Nagai[a]

[a]Queen Mary, University of London, London E1 4NS, UK

Searches for sfermions and gauginos, predicted by super-symmetric theories have been performed using data with an integrated luminosity of 220 pb^{-1}. These were collected by each LEP experiment at the highest centre-mass-of-energies at LEP in 2000. No evidence was found. Results are translated into model parameter space together with data from previous years.

1. Introduction

The LEP collider was operated at centre of mass energies, $\sqrt{s}$, around 206 GeV in 2000, where each of four LEP experiments (ALEPH, DELPHI, L3 and OPAL) collected data with an integrated luminosity of approximately 220 pb^{-1}, including 9 pb^{-1} at the highest centre of mass energy greater than 207.5 GeV. These high statistics samples at high energies provide an opportunity to extend the region to search for new particles predicted by super-symmetric theories (SUSY), such as minimal super-symmetric extension of the standard model (MSSM).

Since the super symmetry is a generalisation of time-space symmetries of quantum field theory, this symmetry cannot be an exact symmetry, *ie* it must be broken. In the standard SUSY model at LEP, it is considered that super-symmetry breaking is mediated by gravity. In this model the super partner of graviton, gravitino, is heavy and has no role in the phenomenology in the LEP energy region. R-parity conservation is also assumed in the model. This implies that the lightest SUSY particle (LSP) must be stable. In cosmology the LSP is expected as a cold dark matter candidate. Under the R-parity conservation, SUSY particles must be pair-produced and the LSP has to exist in the final decay chain.

Scalar fermions (sfermions) are the bosonic partners of quarks and leptons, called squarks ($\tilde{\mathrm{q}}$) and sleptons ($\tilde{\ell}$), respectively. Mass eigenstates of squarks and charged sleptons are formed by a mixing between right-handed and left-handed sfermions.

Charginos, $\tilde{\chi}^{\pm}_j$, are mass eigenstates formed by mixing of the fields of the fermionic partners of the W boson (winos) and those of the charged Higgs bosons (charged Higgsinos). Fermionic partners of the γ (photino), Z (zino) and neutral Higgs bosons mix to form mass eigenstates called neutralinos, $\tilde{\chi}^0_i$. In each case, the index j or i is ordered by increasing mass. The LSP is usually considered to be the lightest neutralino, $\tilde{\chi}^0_1$, although it could be the scalar neutrino (sneutrino), $\tilde{\nu}$, if it is sufficiently light.

MSSM is used to translate experimental results into theoretical frameworks. Motivated by Grand Unification (GUT) and to simplify the physics interpretation, a constrained MSSM (CMSSM) is used, but more general cases are also studied. In the CMSSM, introducing unification of masses and couplings at the GUT scale, the number of parameters is reduced to six: the SU(2) gaugino mass parameter at electroweak-scale M_2, common scalar mass at GUT-scale m_0, ratio of VEV's of two Higgs doublets v_2/v_1, mixing parameter of two Higgs doublet field μ, common trilinear coupling A_0, and mass of the CP odd Higgs boson, m_A.

2. Production and decay of SUSY particles

Assuming R-parity conservation, sleptons and squarks are expected to be pair-produced through the s-channel. In addition, selectron can be produced in the t-channel by exchanging $\tilde{\chi}^0_1$, which usually cause constructive interference with the s-channel. The mixing between left-handed and right-handed sfermions affects the production cross section, especially for the third generation of sfermions, which is decreased due to decoupling to the Z boson with a given parameter. For squarks, stop mixing is usually expected due to large mass of top quark and sbottom may have a mixing if $\tan\beta$ is large. For sleptons, selectrons and smuons are almost mass eigenstates but staus may have a large mixing at large $\tan\beta$. These mixings can make large mass splitting between two mass eigenstates of sfermions so that $\tilde{\tau}_1$, $\tilde{\mathrm{t}}_1$ and $\tilde{\mathrm{b}}_1$ can be light.

If charginos exist and are sufficiently light, they will be produced mainly via s-channel through a γ or Z exchange. For the wino component of chargino there is a production process via t-channel $\tilde{\nu}$ exchange. The production cross section for charginos is large unless the sneutrino ($\tilde{\nu}$) is light, in which case the cross section is reduced by destructive interference between the s-channel and the t-channel. Neutralino pairs ($\tilde{\chi}^0_2\tilde{\chi}^0_1$) can be produced through an s-channel with virtual Z, or by t-channel with selectron exchange, which makes constructive interference. The MSSM prediction for the $\tilde{\chi}^0_2\tilde{\chi}^0_1$ production cross section can vary significantly depending on the choice of MSSM parameters. It is typically a fraction of a picobarn and usually much lower than the cross section for $\tilde{\chi}^+\tilde{\chi}^-$ production.

Charged sleptons decay with a diagram $\tilde{\ell}^\pm \rightarrow \ell^\pm\tilde{\chi}^0_1$, where $\tilde{\ell}$ is $\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$, and ℓ is the corresponding ordinary leptons. Slepton events are characterised by two acoplanar leptons and missing energy due to LSP's. Event topologies also depend on mass difference ΔM between the LSP and a produced SUSY particle. For example, at small ΔM region, produced leptons are soft. Searches are therefore divided into several regions depending on ranges of mass of sleptons and the LSP. Contents of background events depend on search regions. Irreducible backgrounds are coming from W^+W^- production and two photon processes at large and small ΔM, respectively.

Stop and sbottom decay with diagrams $\tilde{\mathrm{t}} \rightarrow \mathrm{c}\tilde{\chi}^0_1$ and $\tilde{\mathrm{b}} \rightarrow \mathrm{b}\tilde{\chi}^0_1$, respectively. If it is kinematically allowed, decay mode, $\tilde{\mathrm{t}} \rightarrow \mathrm{b}\ell^+\tilde{\nu}$ can be dominant for stop decay. Event topologies for stop and sbottom production are characterised by acoplanar two jets with missing energy, or two leptons and two jets with missing energy for latter case of stop. Topologies also depend on ΔM. Background is coming from W^+W^- production, $We\nu$ and $q\bar{q}(\gamma)$ processes for large ΔM and two photon processes for small ΔM.

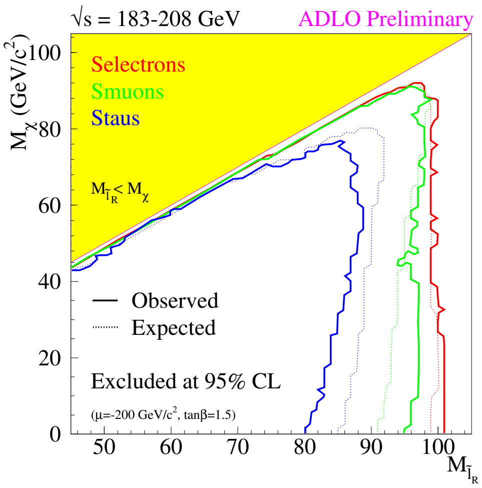

Figure 1. Exclusion region at 208 GeV at 95% C.L. in mass plane of the LSP and sleptons. The solid (dashed) dark, light and darkest curves are observed (expected) limits for $\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$, respectively.

The details of chargino decay depend on the parameters of the mixing and the masses of the scalar partners of the ordinary fermions. The lightest chargino $\tilde{\chi}^+_1$ can decay into $\tilde{\chi}^0_1\ell^+\nu$, or $\tilde{\chi}^0_1\mathrm{q}\bar{\mathrm{q}}'$, via a $\mathrm{W}^{(*)}$ boson, slepton or squark. In much of the MSSM parameter space, $\tilde{\chi}^+_1$ decays via a $\mathrm{W}^{(*)}$ boson are dominant. For small slepton masses decays to leptons become important. Due to the energy and momentum carried away by the LSP (and possibly by neutrinos), the experimental signature for $\tilde{\chi}^+_1\tilde{\chi}^-_1$ events is large missing energy and large missing momentum transverse to the beam axis. If the sneutrino is lighter than the chargino, the two-body decay $\tilde{\chi}^+_1 \rightarrow \tilde{\nu}\ell^+$ dominates. The $\tilde{\chi}^0_2$ will decay into $\tilde{\chi}^0_1\nu\bar{\nu}$, $\tilde{\chi}^0_1\ell\ell$ or $\tilde{\chi}^0_1\mathrm{q}\bar{\mathrm{q}}$, through a $\mathrm{Z}^{(*)}$ boson, sneutrino, slepton,

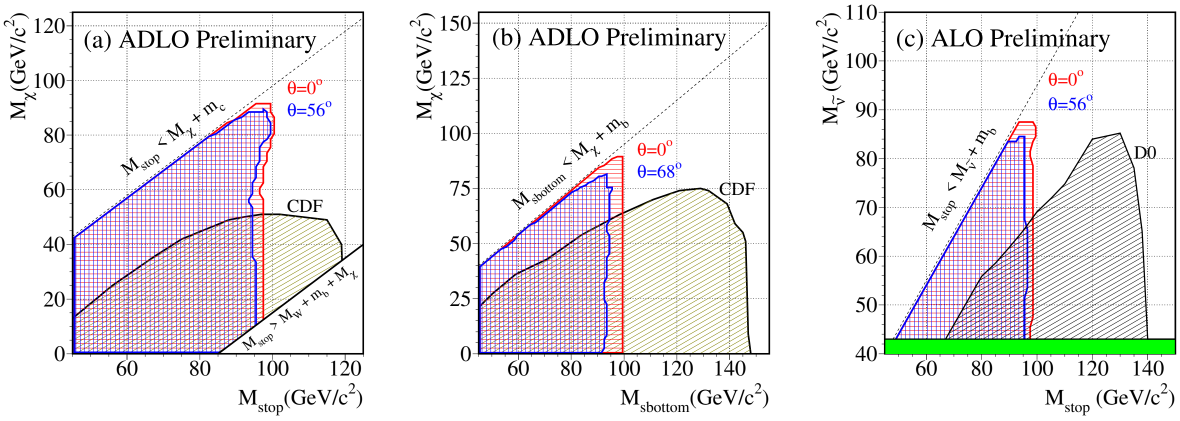

Figure 2. Exclusion limit at 95% C.L. for search processes $\tilde{\mathrm{t}} \to \mathrm{c}\tilde{\chi}_1^0$ (a), $\tilde{\mathrm{b}} \to \mathrm{b}\tilde{\chi}_1^0$ (b) and $\tilde{\mathrm{t}} \to \mathrm{b}\ell^+\tilde{\nu}$ (c) in mass plane of the daughter sparticle and the squark. Areas hatched horizontally and vertically show limit with no squark mixing and with a minimal cross section due to the mixing, respectively. Results from CDF/D0 are shown by area with tilted hatches.

squark or a neutral SUSY Higgs boson (h^0 or A^0). The decay via $\mathrm{Z}^{(*)}$ is the dominant mode in most of the parameter space. For small slepton masses decays to a lepton pair are important. For the cases of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$ or $\tilde{\chi}_1^0\mathrm{q}\bar{\mathrm{q}}$, this leads to an experimental signature consisting either of an acoplanar pair of particles or jets, or a mono-jet if the two jets in the final state have merged. The radiative decay process $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ is also possible and can dominate for some regions of the parameter space. For each case, topologies of signal tend to be low multiplicity in small ΔM region and to form hadron jets in large ΔM region. The contribution from each background process also depends on the ΔM region. In the small ΔM region, two photon processes are dominant. Increasing ΔM results in four fermion processes becoming dominant.

3. Results

Analyses to search for SUSY particles at LEP have been performed [1–9], and these are usually categorised into several regions by using event topologies and ΔM. No evidence of such particles has been found in data at LEP. Limits on production cross section for the particles were calculated and translated into MSSM parameter space.

3.1. Sleptons

Results for slepton searches from all LEP experiments at $\sqrt{s}$ = 183-208 GeV have been combined by LEPSUSY working group [10]. Although the results from $\tilde{\tau}$ searches in 1999 showed an excess around a mass point of $(m_{\tilde{\chi}_1^0}, m_{\tilde{\tau}}) = (20, 85)$, results in 2000 show no significant excess and agree with SM expectation. Fig. 1 shows exclusion area for LEP results of slepton searches in mass plane of the LSP and sleptons together with each expected limit. Observed (expected) limits are obtained with ΔM > 10 GeV to be 99.(99.), 95.(91.) and 80.(85.) GeV for selectron, smuon and stau, respectively. If stau mixing exists, the mass limit for stau becomes worse by about 2 GeV with a given mixing angle where $\tilde{\tau}$ production cross section is minimised.

3.2. Squarks

Fig. 2 shows LEP exclusion limit at 95% C.L. as derived for each channel of squark search [11]. Each limit is plotted in mass plane of the LSP or sneutrino, and the squark together with results from CDF [12] and D0 [13]. The area with horizontal hatch is showing the limit with no squark

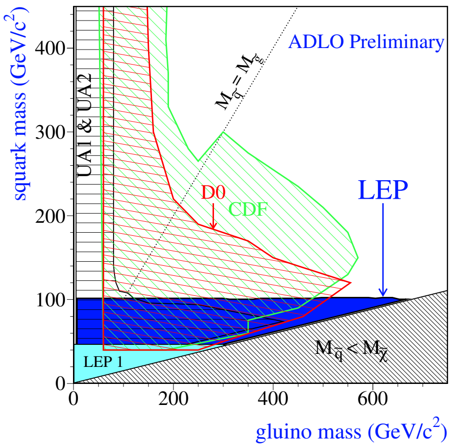

Figure 3. Exclusion limit at 95% C.L. in mass plane of squark and gluino. The dark and light negative hatches show D0 and CDF results, respectively. Horizontally hatched area is excluded by UA1 and UA2. Results from LEP1 and LEP2 are shown by light and dark shaded regions.

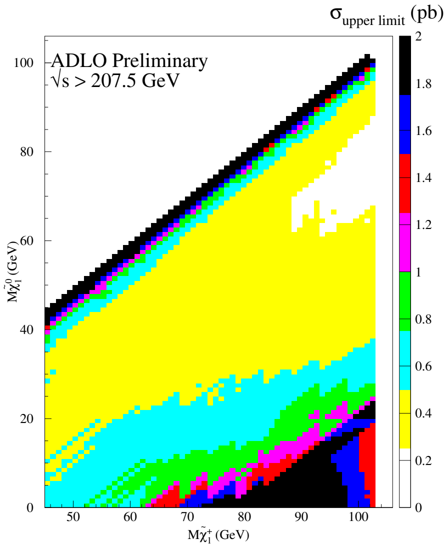

Figure 4. Upper limits on $\tilde{\chi}^+\tilde{\chi}^-$ production cross section at $\sqrt{s} = 208$ GeV at 95% C.L., assuming $\mathrm{BR}(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \mathrm{W}^{+(*)}) = 100\%$.

mixing and region with vertical hatch with a minimal cross section due to the mixing.

The TEVATRON has good sensitivity for $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{g}$ production as well as for $\tilde{q}\tilde{q}$. In order to compare LEP limit with those from TEVATRON, LEP results are translated into an exclusion limit in $\tilde{q}$ and $\tilde{g}$ mass plane under some assumption [4] as shown in Fig. 3. Hatched areas indicate exclusion region from CDF [14] and D0 [15], respectively. The regions with low $\tilde{q}$ and with low $\tilde{g}$ mass have been excluded by LEP1 and by UA1 and UA2, respectively. Results from LEP2, shown with dark shaded area, exclude a gap between the TEVATRON limit and the theoretical limit.

3.3. Neutralinos and charginos

Fig. 4 shows a LEP combined limit at 95% C.L. on the chargino pair-production cross section in a mass plane of $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^+$ [16]. Limits have been set close to the kinematic limit. The space left in small ΔM region shows that the standard searches do not have good sensitivity due to large background from two photon processes. To obtain sensitivity an analysis for charginos mass-degenerate with $\tilde{\chi}_1^0$ has been introduced [1,7–9], which reduces the contribution from two photon processes by tagging a photon from initial state radiation. A cross section limit at 95% C.L. from OPAL [9] on neutralino pair production is shown in Fig. 5.

The obtained cross section limits are interpreted into CMSSM parameter space, using results from acoplanar lepton searches. In the CMSSM analyses reported here possible cascade decay processes are taken into account. However, the number of considered cascade decays are different among experiments. Fig. 6 from ALEPH [2] shows the exclusion region at 95% C.L. in M_2-μ space for large m_0 case. The dark shaded area beyond the kinematic limit of chargino pair-production is extended from direct neutralino searches.

The results are also translated into mass limits as a function of several parameters in MSSM.

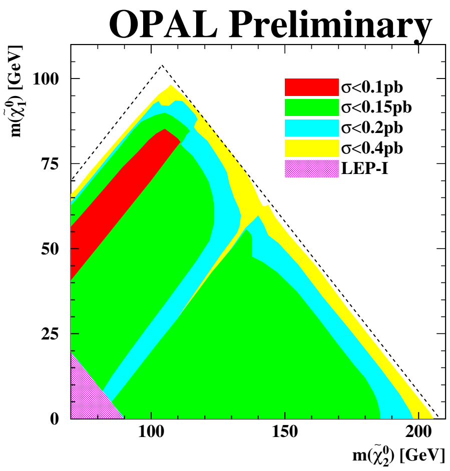

Figure 5. Upper limits on $\tilde{\chi}^0_2\tilde{\chi}^0_1$ production cross section at $\sqrt{s} = 208$ GeV at 95% C.L., assuming $\mathrm{BR}(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \mathrm{Z}^{(*)}) = 100\%$.

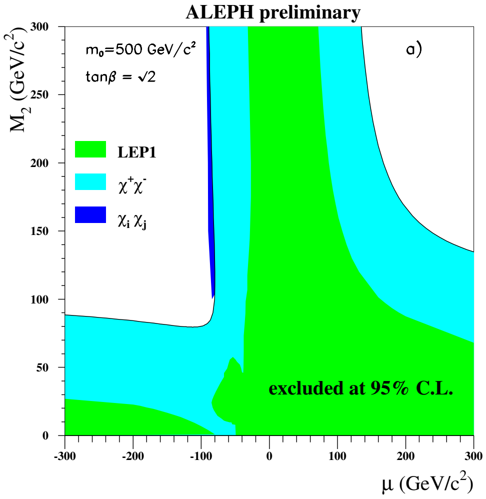

Figure 6. Exclusion region at 95% C.L. in the $(M_2,\ \mu)$ plane with $\tan\beta = \sqrt{2}$ and $m_0 = 500$ GeV. The lightest shaded area shows region excluded by chargino search, which reaches at the kinematical boundary of $\tilde{\chi}^+\tilde{\chi}^-$ production at $\sqrt{s} = 208$ GeV. The darkest shaded region extending beyond the kinematical boundary is obtained by results from the direct neutralino searches.

Fig. 7 shows the chargino mass limit 95% C.L. from L3 [8]. In the region of large sneutrino mass the limit is defined by chargino searches. When the sneutrino mass becomes smaller than the chargino mass, slepton searches become important and define the limit. Fig. 8 shows a mass limit for neutralino from LEP combined results as a function of $\tan\beta$. In large m_0 case shown with the dashed curve, almost the complete limiting curve is determined by chargino results, except for near $\tan\beta = 1$, where results from direct neutralino search provide constraint on neutralino mass. In small m_0 case, the shape of curve is changed dramatically in high $\tan\beta$ region due to two body decays of chargino and neutralino with the slepton and sneutrino, where results from the slepton search determine limits. The mass limit from direct searches is set at $\tan\beta = 1$ to be about 40 GeV.

LEP Higgs searches [17] have excluded the region of low $\tan\beta$ between 0.5 and 2.4 in a given MSSM parameters. These results have been interpreted with the results from direct SUSY particle searches. The impact of the MSSM Higgs searches on the lightest neutralino mass limit is also shown in Fig. 8. The area excluded by the constraint from Higgs searches is shown by the dark solid curve. The limit is obtained at high $\tan\beta$ to be about 45 GeV.

The mixing of $\tilde{\tau}$ also affects the mass limit, which becomes weak at high $\tan\beta$ region. As results in a study from DELPHI [7] show, the mass limit is reduced to be 36.7 GeV. Studies of cascade decays of chargino through stau and those of the second lightest neutralino [7,6] show that the limit will be improved by detail analyses for stau-cascade decays.

4. Summary

Each of the four LEP experiments collected data with an integrated luminosity of about 220 pb^{-1} in 2000, including 9 pb^{-1} at the highest energy region, greater than 207.5 GeV. Searches

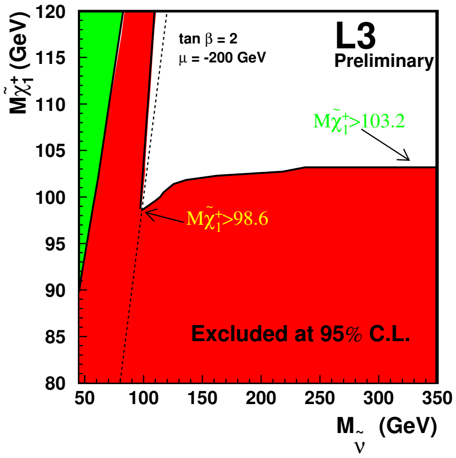

Figure 7. The lower limit at 95% C.L. on the lightest chargino mass as a function of $\tilde{\nu}$ mass.

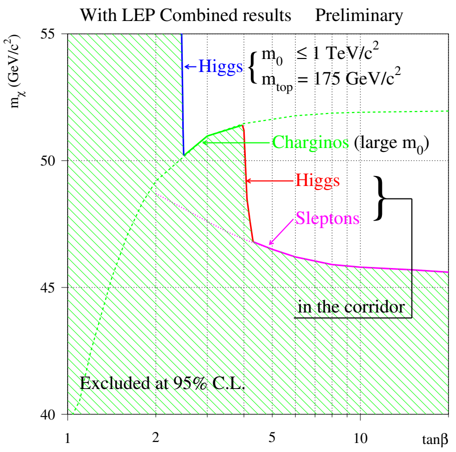

Figure 8. The lower limit at 95% C.L. on the lightest neutralino mass as a function of $\tan\beta$. The dashed and dotted curves show the limit obtained from LEP combined results from chargino with large m_0 and slepton searches. The solid curve shows the effect of the results from the maximal M_{h^0} scenario in Higgs boson searches.

for gauginos and sfermions have been performed, covering a variety of final states expected from SUSY particle production. No evidence of signals for these particles was found. The results are translated into upper limit of production cross sections as well as limits in the MSSM parameter space. The constraint on $\tan\beta$ from the MSSM Higgs boson searches in a given parameter space has been taken into account in the MSSM interpretation.

REFERENCES

1. ALEPH collab., ALEPH 2001-004, see http://alephwww.cern.ch/ALPUB/oldconf/summer01/summer.html.
2. ALEPH collab., ALEPH 2001-009.
3. ALEPH collab., ALEPH 2001-018.
4. ALEPH collab., ALEPH 2001-065.
5. ALEPH collab., ALEPH 2001-067.
6. ALEPH collab., ALEPH 2001-068.
7. DELPHI collab., DELPHI 2001-085 CONF 513, see http://delphiwww.cern.ch/~pubxx/delsec/conferences/summer01/Physics/searches.html.
8. L3 collab., L3 Note 2707 (2001), see http://l3www.cern.ch/conferences/Budapest2001/.
9. OPAL collab., OPAL Physics Note PN470 (2001), see http://opal.web.cern.ch/Opal/pubs/physnote/html/pn470.html.
10. LEP SUSY working group, ALEPH, DELPHI, L3 and OPAL experiments, LEPSUSYWG/01-01.1 (2001). See http://lepsusy.web.cern.ch/lepsusy/.
11. LEP SUSY working group, ALEPH, DELPHI, L3 and OPAL experiments, LEPSUSYWG/01-02.1 (2001).
12. CDF collab., Phys. Rev. Lett. **84**,5704 (2000).
13. D0 collab., submitted to Phys. Rev. Lett., hep-ex/0108018.
14. CDF collab., submitted to Phys. Rev. Lett., hep-ex/0106001.
15. D0 collab., Phys. Rev. Lett. **75**, 618 (1995).
16. LEP SUSY working group, ALEPH, DELPHI, L3 and OPAL experiments, LEPSUSYWG/01-03.1 (2001).
17. The ALEPH, DELPHI, L3 and OPAL collab., and the LEP Higgs working group, LHWG Note/2001-04 (hep-ex/0107030).