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Searches for supersymmetry at high-energy colliders: the past, the present and the future

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Abstract. The present status of the experimental searches for supersymmetry at LEP and Tevatron is reviewed. Prospects at future machines, i.e. the Large Hadron Collider and lepton colliders, are also discussed. The phenomenology of several scenarios, the experimental strategies and the analysis methods are described, and the sensitivities and reaches of the various machines are compared.

1. Introduction

There are numerous indications that the standard model (SM) is not the ultimate theory of elementary particles and their interactions. They include, among others, the recent evidence for atmospheric [1] and solar [2] neutrino oscillations, and the incapacity of the SM to give satisfactory answers to many fundamental questions like how to include gravity, the origin of the matter–antimatter asymmetry in the universe, the flavour and mass problems etc.

The most urgent issue is probably to explain the origin of the particle masses. The SM Higgs mechanism has received no experimental confirmation as yet, and the lower limit on the mass of the Higgs boson ($m_H > 114.4$ GeV from direct searches at LEP [3]) has become close to the indirect upper bound derived from a fit to the electroweak data ($m_H < 193$ GeV at the 95% CL [4]), which starts to raise questions about the internal consistency of the theory. In addition, in the SM the Higgs mass increases with the energy scale Λ up to which the SM is valid, and therefore requires a large amount of 'fine tuning' to be kept at the electroweak scale (the so-called 'naturalness' problem), and the fermion mass generation spoils the simplicity of the theory with a proliferation of unknown parameters.

Supersymmetry (SUSY) [5] is probably the best motivated scenario today for physics beyond the SM. It does not contradict the precise, and therefore very constraining, electroweak data, it predicts a light Higgs boson, as favoured by these data, it allows the unification of the gauge couplings at the grand unification scale and a natural incorporation of gravity, it is an essential

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element of string theories, that many consider as the best candidate for the 'theory of everything', and it can provide an explanation for the cold dark matter in the universe. Furthermore, it is able to stabilize the Higgs boson mass, through radiative corrections, provided that the SUSY particles (sparticles) have masses at the TeV scale or below.

For these and other reasons, SUSY has been the object of intense searches at high-energy colliders. A large number of topologies have been studied and an impressive number of experimental results have been produced by past and present machines, like LEP and Tevatron. No evidence for sparticles has been found so far, which has provided numerous constraints on many models.

SUSY is also one of the main physics motivations for the upgrades of present machines and for the construction of future accelerators, since it gives compelling arguments for the investigation of the TeV scale. In the coming years, the upgraded Tevatron and HERA colliders should pursue SUSY searches in the few hundred GeV range more effectively than before for several scenarios. At the end of the decade, the CERN Large Hadron Collider (LHC [6]) will explore directly for the first time the TeV energy range, so that this machine should be able to discover low-energy (i.e. TeV-scale) SUSY or to rule it out definitively.

Despite its huge physics potential, the LHC will most likely not be able to answer all questions. For instance, assuming that SUSY is discovered at the LHC, observation of the whole SUSY spectrum and full understanding of the new theory will probably require operation in a cleaner and more constrained environment. Projects for e^+e^- linear colliders operating at $\sqrt{s} \leq 1$ TeV [7], and for linear colliders [8] and muon colliders [9] in the multi-TeV energy range, are actively discussed in the high-energy physics community, and should address SUSY searches and precision SUSY measurements in a way complementary to the LHC.

The present status of experimental searches for SUSY at LEP and Tevatron is summarized in this paper. Particular emphasis is given to the LEP results, because they are the most recent ones. Prospects at future high-energy colliders are also reviewed. The phenomenology of several scenarios, the experimental strategies and the analysis methods are discussed, and the sensitivities and reaches of the various machines are compared. It would be impossible to cover the large amount of experimental work in this field, and only a few examples are given here. The reader is therefore referred to the bibliography for a more complete picture.

This paper is organized as follows. Section 2 summarizes the energies and luminosities of high-energy colliders addressing SUSY searches. Section 3 introduces briefly the main SUSY models and their parameters. Sections 4–6 discuss the results of and prospects for searches for the Higgs bosons and sparticles at past, present and future machines. Finally section 7 is devoted to the conclusions.

2. The machines

The energies and luminosities of past, present and future high-energy colliders are summarized below.

- Since 1996, i.e. since the beginning of its phase two, the CERN LEP e^+e^- collider has delivered an integrated luminosity of about 700 pb^{-1} to each of the four experiments (ALEPH, DELHPI, L3 and OPAL) at centre-of-mass energies above the W-pair production threshold. The machine performance in terms of both energy and luminosity was beyond any optimistic expectation. Most relevant to searches are the data recorded in the year

2000 (the last year of operation) at centre-of-mass energies above 206 GeV, about 130 pb^{-1} per experiment, of which about 8 pb^{-1} per experiment are at the highest useful energy of $\sqrt{s} \simeq 208$ GeV.

- The CDF and D0 experiments at the Fermilab Tevatron $\mathrm{p\bar{p}}$ collider have collected about $110\ \mathrm{pb}^{-1}$ each at $\sqrt{s} = 1.8$ TeV during run 1. Run 2 started in Spring 2001 at a centre-of-mass energy of 2 TeV and with a luminosity goal of up to $5 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. Only physics results from run 1 are available as of today.
- At the DESY HERA ep collider, the H1 and ZEUS experiments have both collected about $135\ \mathrm{pb}^{-1}$ as of September 2000, at centre-of-mass energies of up to 318 GeV. SUSY searches performed so far [10] are competitive with those at LEP and Tevatron only in a few cases, and are not discussed here. Data taking started again in Autumn 2001 with an upgraded machine and a luminosity goal of $7 \times 10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. Increased sensitivity to SUSY is expected.
- The LHC should start to take data in the year 2007, at a pp centre-of-mass energy of $\sqrt{s} = 14$ TeV and at an initial luminosity of $\sim 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, which should increase after two or three years of operation to the design luminosity of $\sim 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ [6]. The two general-purpose experiments ATLAS and CMS should each collect 10 $\mathrm{fb}^{-1}/\mathrm{year}$ in the initial phase at low luminosity and 100 $\mathrm{fb}^{-1}/\mathrm{year}$ in the high-luminosity phase.
- An $\mathrm{e^+e^-}$ linear collider [7] with $\sqrt{s} = 0.5$–1 TeV should operate at a luminosity of $\sim 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The CLIC [8] $\mathrm{e^+e^-}$ linear collider should achieve $\sqrt{s} = 3$–5 TeV and an instantaneous luminosity of $\sim 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. A high-energy muon collider [9] could reach $\sqrt{s} = 3$–4 TeV and a luminosity of $\sim 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

A pp machine with $\sqrt{s} = 100$–200 TeV (Very Large Hadron Collider, VLHC [11]) is also being considered in the scientific community. However, the potential for SUSY studies of such a machine is difficult to predict today in the absence of experimental indications about the features of the SUSY spectrum and the scale associated with SUSY breaking. Therefore the VLHC case is not discussed here.

3. The models and the parameters

Because the masses of the SM particles and of their supersymmetric partners are not equal, SUSY cannot be an exact symmetry of nature. The mechanism responsible for SUSY breaking is not known today. Therefore it is assumed that SUSY is broken in a hidden sector, i.e. at some unknown scale and in an unknown way, and that SUSY breaking is then communicated to the visible sector through some messenger interactions which couple to both sectors. The sparticle mass scale $\tilde{m}$ is related to the SUSY-breaking scale $\sqrt{F}$ and to the messenger scale M by the relation

$$\tilde{m} \sim \frac{F}{M}. \tag{1}$$

Several SUSY models have been proposed, which differ mainly in the nature of the messenger interactions and therefore predict different phenomenologies and experimental signatures. Since most experimental results have been obtained so far in the context of supergravity (SUGRA) models and gauge-mediated SUSY-breaking (GMSB) models, only these two scenarios are discussed here.

In SUSY theories there is a multiplicative quantum number, R-parity, which takes the value $+1$ for SM particles and -1 for sparticles. If R-parity is conserved, sparticles must be produced in pairs, and the lightest supersymmetric particle (LSP), to which all sparticles eventually decay, must be stable. In most models the LSP interacts (very) weakly with matter, and therefore escapes experimental detection, leading to the celebrated missing energy signature for SUSY. The results presented in this paper have been obtained under the assumption of R-parity conservation, which is the preferred scenario for cosmology because the (stable) LSP is a candidate for the universe cold dark matter. Reviews of R-parity violating phenomenology and searches can be found in [12].

The next two sections summarize briefly the frameworks in which experimental SUSY searches are performed and the various assumptions.

3.1. Supergravity models

In SUGRA models [13] the messenger interaction is gravity and M is the Planck scale. Therefore, setting $\tilde{m} \sim 1$ TeV, equation (1) gives a SUSY-breaking scale $\sqrt{F} \sim 10^{11}$ GeV.

In minimal models, such as the minimal supersymmetric extension of the standard model (MSSM [5]), the physical SUSY spectrum includes squarks ($\tilde{\mathrm{q}}$) and sleptons ($\tilde{\ell}$), which are the scalar partners of quarks and leptons, the gluino ($\tilde{\mathrm{g}}$), which is the fermionic partner of the gluon, two charginos ($\chi^{\pm}_{1,2}$) and four neutralinos ($\chi^{0}_{1,2,3,4}$), which are mixtures of the fermionic partners of the electroweak and Higgs fields. There are two doublets of Higgs fields, which give rise to five Higgs bosons: $\mathrm{h}, \mathrm{H}, \mathrm{A}, \mathrm{H}^{\pm}$. In most SUGRA models the LSP is the lightest neutralino χ^0_1, which is a massive, neutral and weakly interacting particle, and therefore is an excellent candidate for cold dark matter.

Experimental searches are performed and interpreted in more constrained frameworks with fewer parameters than the general MSSM. In the constrained MSSM (CMSSM), all sfermions ($\tilde{\mathrm{q}}$ and $\tilde{\ell}$) have a common mass m_0 at the grand unification scale, and all gauginos ($\tilde{\mathrm{g}}$, $\chi^{\pm}_{1,2}$, $\chi^{0}_{1,2,3,4}$) have a common mass $m_{1/2}$ at the grand unification scale. There is in addition a common trilinear mixing parameter (A_0) and a Higgsino mass parameter (μ). At the tree level the Higgs sector depends on the mass of one of the Higgs bosons (e.g. m_A) and on $\tan\beta$, which is the ratio of the vacuum expectation values of the two Higgs doublets. In more constrained models than the CMSSM, like minimal SUGRA [13], the parameters m_0 and m_A are not independent and only the sign of μ is free.

3.2. Gauge-mediated SUSY-breaking models

In GMSB models [14] SUSY breaking is communicated to the visible sector by the SM gauge interactions. Since these interactions are stronger than gravity, the messenger scale in these models is lower than the Planck scale, and the SUSY-breaking scale is also lower than in SUGRA (typically $\sqrt{F} \leq 10^6$ GeV).

Distinctive features of GMSB theories which have important phenomenological consequences (see section 6) are the following. Due to the low SUSY-breaking scale, the gravitino $\tilde{\mathrm{G}}$, which is the supersymmetric partner of the graviton, has a mass in the range 10^{-4}–10^{-2} eV (to be compared to $\sim$1 TeV in SUGRA), and is therefore the LSP. Since it interacts very weakly with matter, it gives rise to missing energy in the final state. The next-to-lightest supersymmetric particle (NLSP) is in general either the lightest neutralino χ^0_1, which decays according to $\chi_1^0 \rightarrow \gamma\tilde{\mathrm{G}}$, or a slepton (usually the stau), which decays according to $\tilde{\ell} \rightarrow \ell\tilde{\mathrm{G}}$; since the coupling between the gravitino and the NLSP decreases with increasing values of the SUSY-breaking scale, in GMSB models the NLSP lifetime depends on $\sqrt{F}$:

$$c\tau \sim 100\ \mu\mathrm{m} \left(\frac{100\ \mathrm{GeV}}{m}\right)^5 \left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4 \quad (2)$$

where $c\tau$ and m are the NLSP lifetime and mass, respectively. Given the loose bounds on $\sqrt{F}$, the NLSP decay length is essentially unconstrained and can be as short as 1 μm and as large as several kilometres.

In minimal models the fundamental parameters of the theory are the SUSY-breaking scale $\sqrt{F}$, the messenger scale M, the number of messenger fields N_{mess}, a universal mass Λ and the same parameters related to the Higgs sector as in the MSSM. The sparticle masses depend on Λ, M, N_{mess} and the relevant gauge couplings (e.g. the masses of the strongly interacting sparticles depend on α_s). The sparticle content is similar to that of the MSSM, and the Higgs sector is essentially the same in both models.

4. Searches for SUSY Higgs bosons

A distinctive feature of SUSY is that the lightest of the five Higgs bosons, h, is predicted to be light, because its mass is specified by the gauge couplings. Indeed, irrespective of the model, i.e. irrespective of the details of the SUSY-breaking mechanism, the h mass is expected to be smaller than ∼135 GeV, except in very general models with additional fields [15] where (still) $m_h \leq 190$ GeV. Hence, a light Higgs boson, as favoured by the electroweak data, is natural in SUSY.

Over a large part of the SUSY parameter space the h boson couples to fermions and bosons in the same way as a SM Higgs boson, and therefore searches for a SM Higgs address also the h case. These searches are discussed in section 4.1. Present experimental constraints on the parameter space of the SUSY Higgs sector are presented in section 4.2, while future prospects are summarized in section 4.3.

4.1. Searches for a SM-like Higgs boson at LEP

As of today, the only relevant results from the searches for a SM-like Higgs boson come from LEP, where this particle is expected to be produced mainly in association with a Z boson through the Higgsstrahlung process $\mathrm{e^+e^-} \rightarrow \mathrm{Z^*} \rightarrow \mathrm{ZH}$. In the mass range accessible to LEP, the dominant Higgs decay modes are $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ (branching ratio ∼75%) and $\mathrm{H} \rightarrow \tau\tau$ (branching ratio ∼7%). Therefore Higgs production at LEP should give rise to four main final states, addressed by as many dedicated searches: four-jet final states, if $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ and $\mathrm{Z} \rightarrow \mathrm{q\bar{q}}$, which is the channel with the highest sensitivity; two-jet and missing energy final states, if $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ and $\mathrm{Z} \rightarrow \nu\bar{\nu}$; two-jet and two-lepton final states, if $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ and $\mathrm{Z} \rightarrow \mathrm{ee}, \mu\mu$, and two-jet and two-tau final states, if either $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ and $\mathrm{Z} \rightarrow \tau\tau$ or $\mathrm{H} \rightarrow \tau\tau$ and $\mathrm{Z} \rightarrow \mathrm{q\bar{q}}$. It should be noticed that LEP is sensitive to most topologies arising from Higgs production and decay, unlike hadron colliders where fully hadronic final states are difficult to extract from the background. At LEP, the main backgrounds are ZZ, WW and $\mathrm{q\bar{q}}(\gamma)$ production, which give rise to events containing jets, jets and leptons, and jets and missing energy. The cross-sections for these processes, as measured by

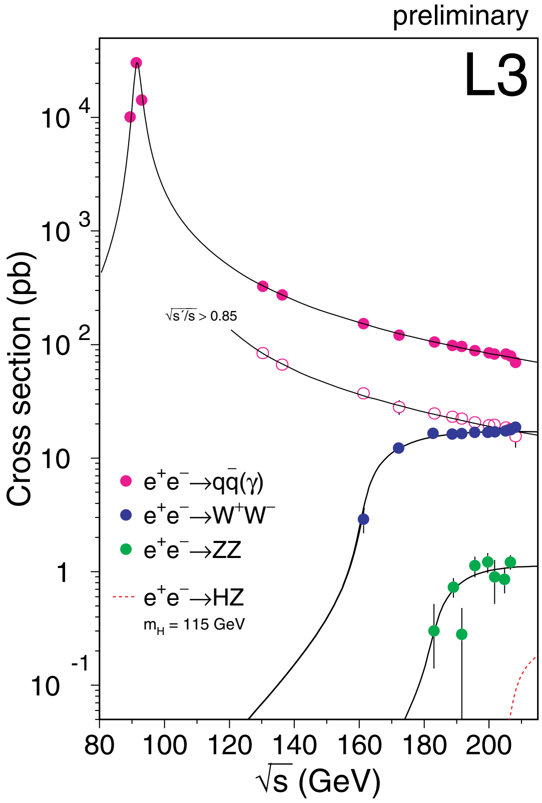

Figure 1. Cross-sections of several SM processes, as a function of the centre-of-mass energy, as measured by the L3 experiment at LEP (dots). The full curves show the theoretical prediction. The dotted curve indicates the expected cross-section for a Higgs boson of mass 115 GeV.

the L3 experiment, are displayed in figure 1 as a function of the centre-of-mass energy, together with the cross-section expected for a Higgs boson of mass 115 GeV. It can be seen that the main backgrounds are globally well understood, and that the needed rejection is at most a factor of 10^3, unlike at hadron colliders where rejections of up to 10^7 must be achieved. Such a rejection is obtained at LEP by using several handles, such as the presence of b jets and of a Z boson in the final state and the event kinematics.

In the year 2000, when LEP was running at centre-of-mass energies above 205 GeV, an excess of events at the level of $\sim 3\sigma$ was observed, consistent with the production of a SM-like Higgs boson of mass $\sim$ 115 GeV [16]. Since then, the four experiments have produced their final results [17]–[20]. These are based on more refined and complete studies, including e.g. the use of definitive detector calibration constants and of larger-statistics Monte Carlo samples, and the revision of the analysis procedure in some cases. As a result, the significance of the excess has decreased to $\sim 1.7\sigma$ [3].

To distinguish a possible Higgs signal from the background processes, the LEP experiments use a statistical estimator, the likelihood ratio $-2\ln Q$ [3], which allows all the relevant features of the observed candidates in the data (e.g. the b-quark content, the event kinematics) to be compared with two hypotheses: that these candidates come from background only, or that they come from a mixture of signal and background.

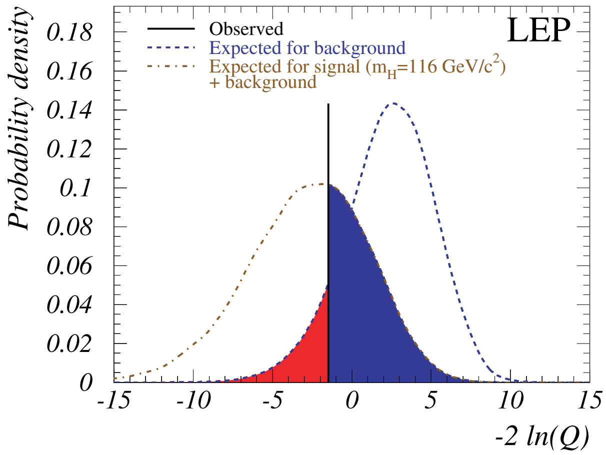

Figure 2. Probability distributions for the statistical estimator $-2\ln Q$, as expected at LEP from simulated background-only experiments (dashed) and from simulated $\text{signal} + \text{background}$ experiments with $m_H = 116$ GeV (dash–dotted). The vertical line is the value of $-2\ln Q$ observed in the data. The light-shaded area and the dark-shaded area define $1 - \text{CL}_b$ and CL_{s+b} respectively (see text). From [3].

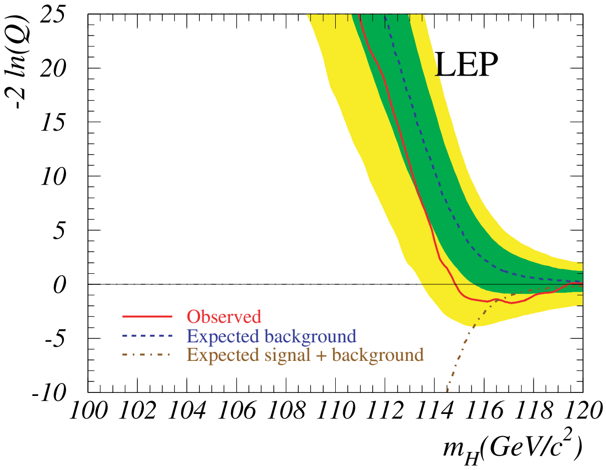

Figure 3. Distribution of the statistical estimator $-2\ln Q$ as a function of the Higgs mass hypothesis, as obtained by combining the four LEP experiments. The dashed curve is the background-only expectation, the dash–dotted curve is the $\text{signal} + \text{background}$ expectation and the full curve is the observation. The dark- and light-shaded regions show the 68 and 95% probability bands for the background expectation respectively. From [3].

Figure 2 shows the expected distributions of the variable $-2\ln Q$ for two classes of simulated LEP experiments: experiments observing only background, and experiments observing a signal on top of the background. The value of $-2\ln Q$ obtained from the 2000 data is also shown. It can be seen that the data slightly favour the $\text{signal} + \text{background}$ hypothesis to the background-only hypothesis. The distribution of $-2\ln Q$ as a function of the Higgs mass is plotted in figure 3.

Table 1. The values of $1 - \mathrm{CL}_b$ and CL_{s+b}, as obtained for a test mass $m_H \sim 116$ GeV by the four experiments individually and from their combination. From [3].

	$1 - \mathrm{CL}_b$	CL_{s+b}
LEP	0.099	0.369
ALEPH	2.4×10^{-3}	0.956
DELPHI	0.874	0.033
L3	0.348	0.408
OPAL	0.543	0.208

The observed curve shows a broad minimum over the mass range 115–118 GeV extending into the $\mathrm{signal + background}$ region. The expectation for the $\mathrm{signal + background}$ case is consistent with the observation for $m_H \sim$116 GeV.

To better quantify the compatibility of the observation with the background-only and the $\mathrm{signal + background}$ hypotheses, two numbers are defined. The background-only confidence level $(1-\mathrm{CL}_b)$ is the integral of the $-2\ln Q$ distribution for an ensemble of simulated background-only experiments from $-\infty$ to the observed value in the data (light-shaded area in figure 2), and gives the probability that such experiments are more signal-like than the observation. The $\mathrm{signal + background}$ confidence level (CL_{s+b}) is the integral of the $-2\ln Q$ distribution for an ensemble of simulated $\mathrm{signal + background}$ experiments from the observed value in the data to $+\infty$ (dark-shaded area in figure 2), and gives the probability that such experiments are more background-like than the observation. A small $1 - \mathrm{CL}_b$ and a large CL_{s+b} indicate a signal-like observation.

Table 1 shows the values of $1 - \mathrm{CL}_b$ and CL_{s+b} obtained for $m_H \sim 116$ GeV from the LEP 2000 data. Combining the four experiments together, the confidence level of the background-only hypothesis, i.e. the probability of a background fluctuation, is $\sim 10\%$, which corresponds to an excess of $\sim 1.7\sigma$. This excess comes mainly from ALEPH, which observes a deviation from the background-only expectation of about 3σ [17], and is mostly due to four-jet final states.

A graphical display of the most signal-like event is shown in figure 4. It was collected by ALEPH at a centre-of-mass energy of 206.7 GeV and contains four jets, two of which are well b tagged (two well reconstructed displaced vertices can be seen in figure 4). The reconstructed mass of the two b jets, which come from the Higgs boson candidate, is 114.3 ± 3.0 GeV, whereas the reconstructed mass of the two other jets, 92.1 GeV, is very close to the nominal Z mass. The event energy flow is well measured, as demonstrated also by the fact that the missing momentum vector points in the direction of one of the b jets, where also a muon is observed, thereby indicating a semileptonic b decay. The best background explanation for this event would be $\mathrm{e^+e^-} \to \mathrm{b\bar{b}} \to \mathrm{b\bar{b}gg}$ production, where both gluons are radiated by the b quarks in the final state. However, the two jets which are not b tagged have energies ($\sim$45 GeV) and invariant mass (92.1 GeV) compatible with coming from a Z decay.

The four LEP experiments have also been combined to derive a lower limit on the Higgs mass. The result is $m_H > 114.4$ GeV at the 95% CL. It should be noted that in 1989, when LEP started to collect data, there was essentially no bound on the mass of a SM-like Higgs boson.

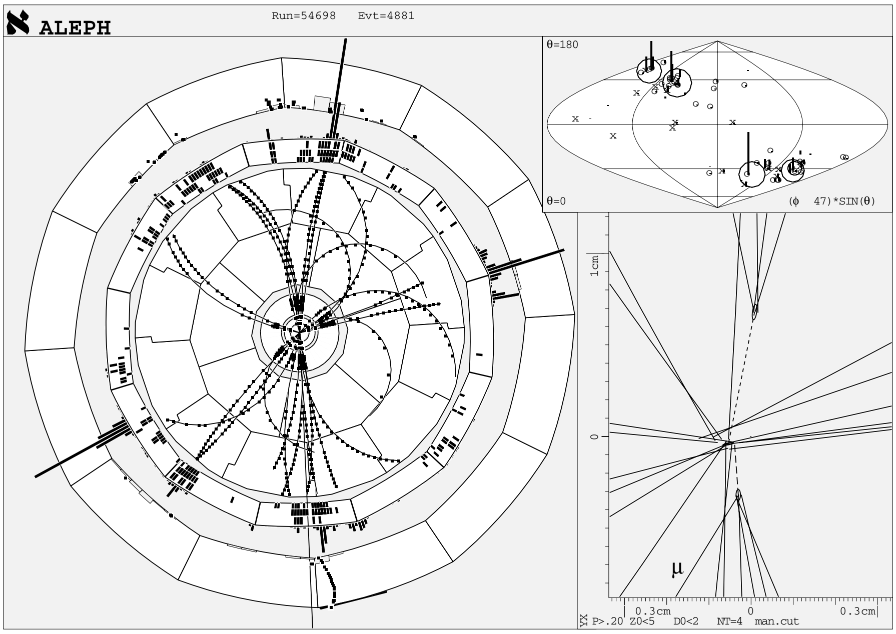

Figure 4. Display of the most significant LEP Higgs boson candidate, collected by ALEPH [21]. The event is shown in the view transverse to the beam direction, in the $\theta - \phi \sin\theta$ view, and in a zoom of the vertex region.

4.2. Constraints on the SUSY Higgs sector from LEP and Tevatron

At LEP only two SUSY Higgs channels are *a priori* accessible, i.e. hZ production and hA production, because the other SUSY Higgs bosons are in most cases predicted to be too heavy.

Searches at LEP have excluded a good part of the allowed h mass range. More precisely, since the h mass increases (through radiative corrections) with increasing mixing between the SUSY partners of the left-handed and right-handed top quarks ($\tilde{t}_L$, $\tilde{t}_R$), the scenario where there is no mixing between $\tilde{t}_L$ and $\tilde{t}_R$ has been almost fully ruled out by LEP since $m_h < 115$ GeV in this case. On the other hand, the SUSY parameters can be chosen in such a way as to maximize the value of the h mass, thereby leading to the more conservative '$m_h - \max$' scenario. This case is presented in figure 5.

The hZ process is relevant mainly in the region $m_A > 100$ GeV, and gives rise to similar final states as HZ production in the SM. The hA process is relevant in the region $m_A < 100$ GeV, and gives rise mainly to final states with four b jets (when both Higgs bosons decay to $b\bar{b}$ pairs) or with two b jets and two taus. As shown in figure 5, searches for hA production at LEP have excluded the region $m_A < 91.9$ GeV at 95% CL. In the region at large m_A, the lower limit on the h mass obtained from hZ searches is around 114 GeV as in the SM case. This limit can be translated into a lower limit on $\tan\beta$, as shown in the figure, since the h mass increases with increasing tanβ. In the '$m_h - \max$' scenario and for the central value of the measured top mass (174.3 GeV) the region $0.5 < \tan\beta < 2.4$ is excluded at 95% CL. In the same scenario, this exclusion reduces to $0.6 < \tan\beta < 1.9$ in the more conservative case $m_{\text{top}} = 179$ GeV (corresponding to $+1\sigma$ from the central measured value). The experimental exclusion of the low-$\tan\beta$ region of the constrained MSSM, which is very much motivated in some grand unification theories [24], is an important legacy from LEP.

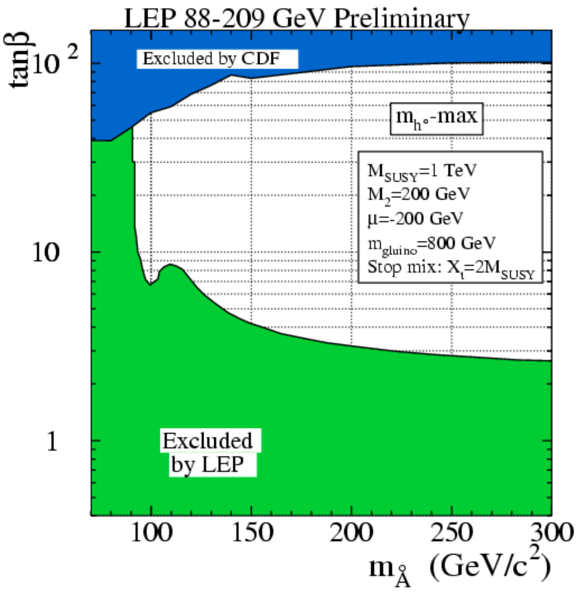

Figure 5. The regions of the CMSSM plane m_A–tanβ excluded (at the 95% CL) in the '$m_h - \max$' scenario by Higgs searches at LEP [22] (light shaded) and in the CDF experiment [23] (dark shaded).

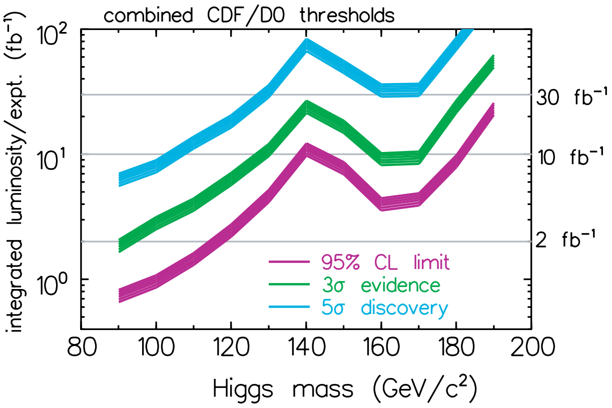

Figure 6. The integrated luminosities per experiment needed at Tevatron run 2 to exclude a SM-like Higgs boson at 95% CL (lower band), to observe it at the 3σ level (middle band) and to discover it at the 5σ level (upper band), as a function of mass [25]. These results were obtained by combining CDF and D0 together. The width of each band indicates the systematic uncertainty.

As shown in figure 5, the CDF results from run 1 [23] are complementary to those from LEP. Indeed, Tevatron has enough centre-of-mass energy to produce any neutral SUSY Higgs boson in association with a $\mathrm{b\bar{b}}$ pair ($\mathrm{hb\bar{b}}$, $\mathrm{Hb\bar{b}}$ and $\mathrm{Ab\bar{b}}$) up to masses of about 300 GeV. These processes have rates which are strongly enhanced at large $\tan\beta$, and could therefore have been observed with the data sample collected in run 1. Since the Higgs bosons decay mainly into $\mathrm{b\bar{b}}$ pairs, the expected final states contain four b jets, to which only the CDF experiment was sensitive in run 1 because a very efficient b tagging is required. No signal has been found, which

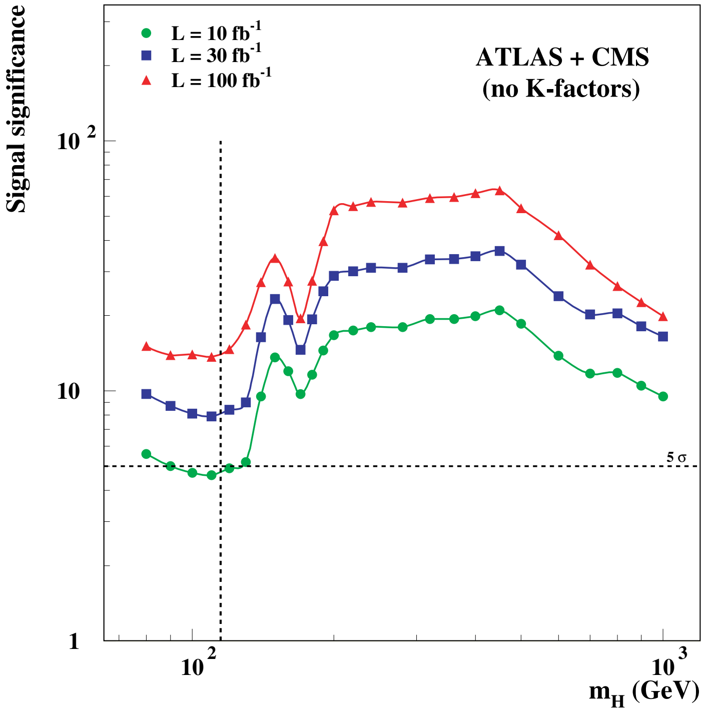

Figure 7. Expected signal significance for a SM-like Higgs boson as a function of mass at the LHC [26], for integrated luminosities of 10 fb^{-1} (dots), 30 fb^{-1} (squares) and 100 fb^{-1} (triangles) per experiment, as obtained by combining ATLAS and CMS together. The vertical line indicates the mass lower limit from LEP.

has allowed the exclusion of the large tanβ region as shown in figure 5. The area between the CDF and the LEP contours in figure 5 has not been explored so far because LEP had not enough centre-of-mass energy and Tevatron not enough luminosity.

4.3. Future prospects

The Tevatron experiments CDF and D0 had little sensitivity to a potential SM-like Higgs signal in run 1. In run 2 the integrated luminosity is expected to be larger by a factor of up to 100, which opens interesting prospects [25]. These are summarized in figure 6. In the low-mass region, which is most relevant for h searches in the SUSY framework, Higgs masses around 115 GeV can be excluded at the 95% CL with an integrated luminosity of 2 fb^{-1} per experiment, which should be collected by the end of 2003. After a luminosity upgrade, the machine could deliver, by the end of 2004, the 5 fb^{-1} needed for a 3σ observation for $m_H \sim 115$ GeV, and, by the end of 2007, the 15 fb^{-1} required for a 5σ discovery up to masses of ~120 GeV or for a 95% CL exclusion up to masses of ~185 GeV. Discovery for masses larger than 120 GeV would require much more luminosity than 15 fb^{-1} and therefore looks difficult. The most sensitive search channel at the Tevatron is $\mathrm{Wh} \to \ell\nu\mathrm{b}\bar{\mathrm{b}}$. By combining these searches for the lightest Higgs boson h with searches for four-b-jet final states similar to those described in section 4.2, the Tevatron experiments should be able in run 2 to fully explore the CMSSM Higgs plane shown in figure 5 at least at the 95% CL [25].

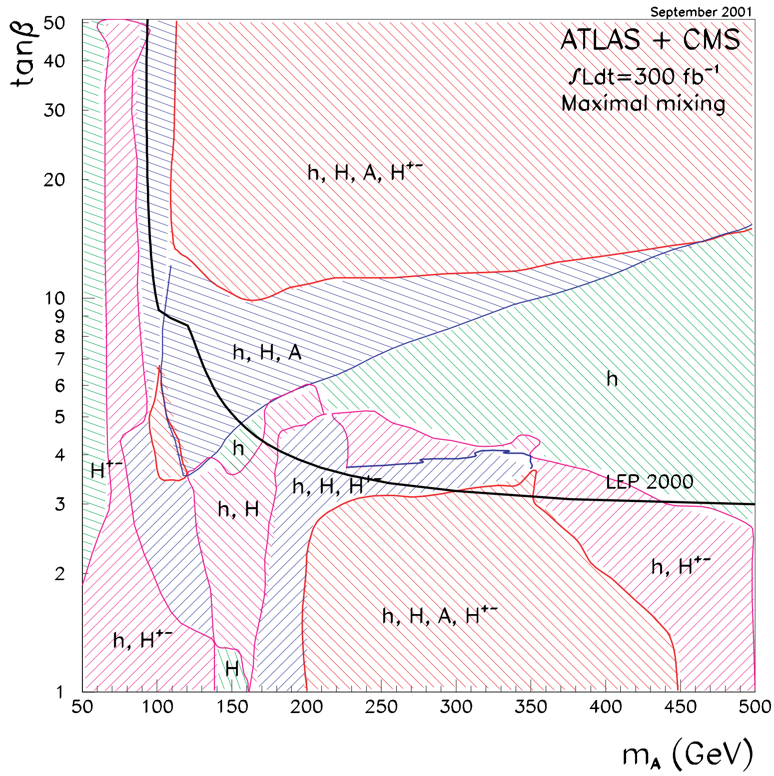

Figure 8. The regions of the CMSSM plane m_A–tanβ where the various SUSY Higgs bosons can be discovered at $\geq 5\sigma$ at the LHC through their decays into SM particles, in the '$m_h - \max$' scenario [26].

The LHC should start to take data in 2007. As shown in figure 7, with an integrated luminosity of 10 fb^{-1} per experiment ATLAS and CMS could obtain a combined 5σ significance for m_H values close to the LEP limit. In this mass region, which is the most difficult one at the LHC, the sensitivity is provided by two complementary channels: $\mathrm{H} \rightarrow \gamma\gamma$ and $\mathrm{t\bar{t}H}$ production with $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$. As already mentioned, for masses larger than 120 GeV the LHC has no competition from the Tevatron and should also be able to perform precise measurements of some of the Higgs properties [26]. However, a detailed investigation of the Higgs sector, including the measurements of the various branching ratios and couplings to the per cent level, of the Higgs self-couplings to the $\sim$10–20% level and of the spin, requires a cleaner machine such as an $\mathrm{e^+e^-}$ linear collider [7].

The LHC potential for the exploration of the SUSY Higgs parameter space is summarized in figure 8. Over a good part of this space, several Higgs bosons should be discovered even with little integrated luminosity (10 fb^{-1} per experiment). The exception is the region at large m_A and moderate $\tan\beta$, just above the LEP limit, where only h is accessible at the LHC unless the heavier Higgs bosons have observable decay modes into sparticles (e.g. charginos or neutralinos). The LHC may therefore miss the heavy part of the SUSY Higgs spectrum. Complete and model-independent observation of this part of the spectrum may require a very high-energy lepton collider ($\sqrt{s} \geq 2$ TeV).

5. Searches for SUSY particles in SUGRA models

The physics environment and the expected SUSY phenomenology, and therefore the search strategies and the physics potential, are quite different at LEP (or, more generally, at lepton colliders) as compared to the Tevatron (or, more generally, to hadron colliders):

- At LEP, all kinematically accessible sparticles (except gluinos) are expected to be pair produced more or less democratically through the s channel with γ/Z exchange. At the Tevatron, on the other hand, the production of $\tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$, which is mediated by strong interactions, is expected to dominate by far over other (electroweak) processes.
- At the LEP energies, direct decays to the LSP should dominate, e.g. $\tilde{\ell} \to \ell\chi_1^0, \tilde{q} \to q\chi_1^0$. Therefore the main topology arising from the pair production of sparticles should be quite simple: two acoplanar objects (e.g. leptons, jets) plus missing energy produced by the escaping neutralinos. At hadron colliders, on the other hand, squarks and gluinos, which are quite heavy given the present experimental limits (see below), are expected to decay through multi-step cascades, e.g. $\tilde{g} \to q\tilde{q} \to qq\chi_2^0 \to qqZ\chi_1^0$. These decays give rise to very crowded final states with many high-p_T jets and leptons and large missing transverse energy (E_T^{miss}).
- At LEP, SM backgrounds (e.g. WW and ZZ production, $\gamma\gamma$ interactions) are not a big concern. As a consequence, the experiments are sensitive to almost all kinematically accessible sparticles, to almost all decay modes (including fully hadronic decays), and even to very modest ($\sim$GeV) energy depositions in the detector, such as those expected if the mass difference Δm between the produced sparticle and the LSP is small. The Tevatron experiments, on the other hand, are mainly sensitive to squarks and gluinos, which have a large cross-section and give rise to spectacular signatures used to reject the huge backgrounds (QCD multijet production, $W/Z+$jets etc). Furthermore, the low-Δm region is not accessible, because a large amount of visible energy ($\gg$10 GeV) is needed to trigger the experiments and reject the backgrounds.
- As a consequence of the above points, at LEP the mass reach is limited mainly by the available centre-of-mass energy and luminosity rather than by the physics environment. In addition, by combining several searches it is possible to cover almost all corners of the kinematically accessible parameter space, and therefore to derive absolute mass limits (i.e. valid for any choice of the parameters) within constrained models. Tevatron, on the other hand, has a huge mass reach for squarks and gluinos (up to $\sim$300 GeV in run 1), but the kinematically accessible parameter space cannot be fully covered (e.g. there is no sensitivity to the small Δm values), and therefore absolute mass limits cannot be set.

A few examples which illustrate the above considerations are discussed below. More details can be found in [27]–[29].

5.1. Sleptons

Despite the simple topology expected in the final state, i.e. two acoplanar leptons accompanied by missing energy, slepton-pair production is not observable at the Tevatron because of the small signal-to-background ratio. Therefore the present experimental limits come mainly from LEP. Searches for acoplanar leptons in the data collected by the four experiments up to $\sqrt{s} \simeq 208$ GeV have found no deviations from the SM expectation (the dominant background is $WW \to \ell\nu\ell\nu$

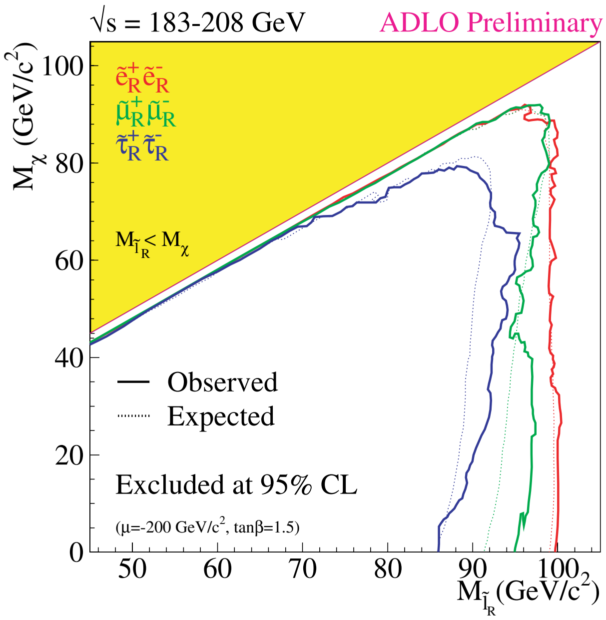

Figure 9. Regions of the plane slepton mass versus LSP mass excluded at the 95% CL by LEP [27]. The full lines show the experimental lower limits on (from left to right) the stau mass, the smuon mass and the selectron mass. The dashed lines indicate the corresponding expected limits. The shaded region is theoretically forbidden.

production). The derived mass limits, shown in figure 9, range from about 80 GeV for staus to about 100 GeV for selectrons (which benefit from a larger production cross-section). Many of these limits will remain valid until the LHC era.

5.2. Squarks and gluinos

In contrast to the slepton case, Tevatron has the largest discovery potential for generic squarks and for gluinos. The signature expected from the pair production of these sparticles consists of large missing transverse energy (from the escaping neutralinos) plus several jets and/or leptons coming from the more-or-less long cascade decays. One of the main experimental difficulties in these searches is to understand the E_T^{miss} distribution in the data, which can receive large contributions from instrumental effects such as badly measured jets in QCD multijet events. The most stringent limits on the $\tilde{q}$ and $\tilde{g}$ masses, shown in figure 10, come from a recent CDF search for events with multijet plus missing transverse energy [30]. The highest mass reach, up to $\sim$300 GeV, is obtained if squarks and gluinos are mass degenerate. The lower limit on the gluino mass valid for any value of the squark mass is 195 GeV.

Figure 10 shows that the LEP experiments have no sensitivity to gluinos and a modest impact on generic $\tilde{q}$ searches. This is however not the case for the stop squarks. Since the mixing between the SUSY partners of the left-handed and right-handed quarks (e.g. the mixing between $\tilde{t}_L$ and $\tilde{t}_R$) is proportional to the quark mass, mixing could be significant in the stop sector. As a consequence of this large mixing, the lighter of the two resulting states may be light and therefore may be accessible at LEP.

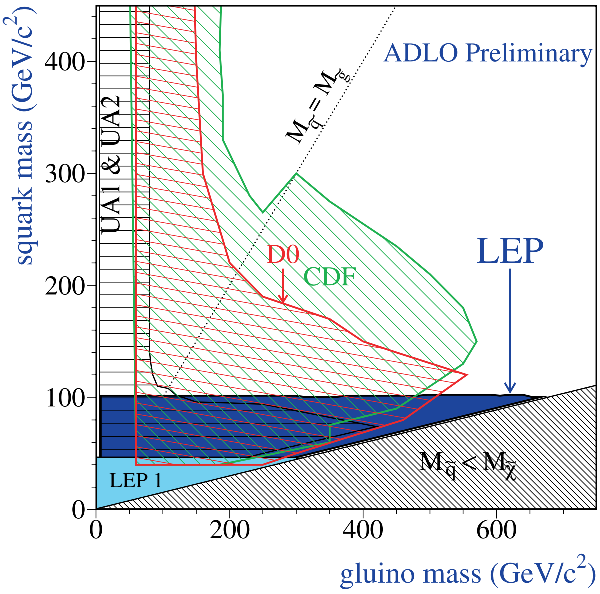

Figure 10. Regions of the plane squark mass versus gluino mass excluded at the 95% CL by CDF [30], D0 [31] and LEP [27], assuming five mass-degenerate squark flavours. The hatched region at the bottom right corner is theoretically forbidden.

Searches for pairs of stops have been performed at both LEP and Tevatron. The LEP potential depends on the mixing angle θ between $\tilde{\mathrm{t}}_L$ and $\tilde{\mathrm{t}}_R$, which determines the strength of the stop coupling to the Z. No signal has been found. The mass limits obtained by assuming that both stops decay according to $\tilde{\mathrm{t}} \to \mathrm{c}\chi_1^0$, giving rise to two acoplanar jets in the final state plus missing (transverse) energy, are shown in figure 11. They nicely illustrate the complementarity between the two machines. The CDF reach [32], which is more limited than that for generic squarks mainly because of the smaller $\tilde{\mathrm{t}}\bar{\tilde{\mathrm{t}}}$ production cross-section, extends to higher masses than the LEP reach, as expected. However LEP, unlike the Tevatron, is sensitive to mass differences between the stop and the LSP down to a few GeV. In addition, by combining the above searches with searches for long-lived stop hadrons, the ALEPH experiment was able to set an absolute lower limit of $\sim$65 GeV on the stop mass, irrespective of the stop–LSP mass difference, of the stop lifetime and of the stop decay branching ratios [33].

5.3. Charginos

The most stringent and model-independent results on chargino production come from LEP. The process $\mathrm{e}^+\mathrm{e}^- \to \chi^+\chi^-$, followed by $\chi^\pm \to \mathrm{W}^*\chi_1^0$ or $\chi^\pm \to \ell\tilde{\nu} \to \ell\nu\chi_1^0$, is expected to give rise to final states containing jets plus missing energy, or jets plus one lepton plus missing energy, or acoplanar leptons. By looking for these topologies, the LEP experiments have been able to rule out charginos with masses smaller than 103.6 GeV [27], a bound which is only a few hundred MeV below the kinematic limit for chargino pair production at $\sqrt{s} \simeq 208$ GeV. This bound, which is valid over a large region of the parameter space, is deteriorated by a few GeV in two cases. First, if the common sfermion mass m_0 is small, sneutrinos are light, and the chargino production cross-section is reduced by the negative interference between the t channel with sneutrino exchange and the s channel with γ/Z exchange.

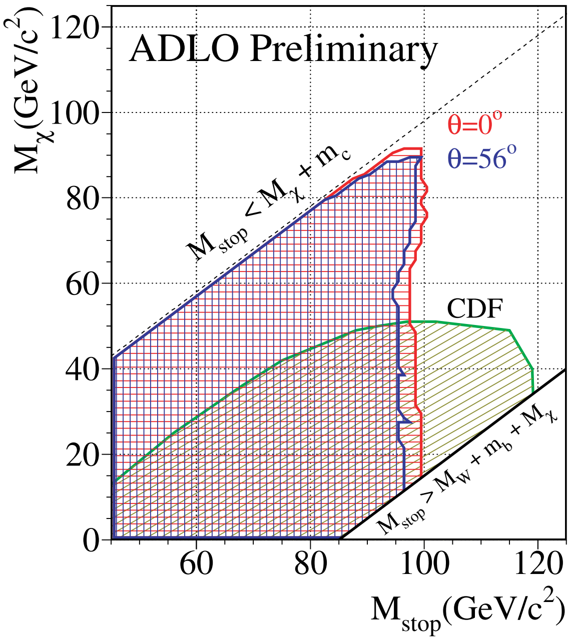

Figure 11. Regions of the plane stop mass versus LSP mass excluded at the 95% CL by searches for $\tilde{t} \to c\chi_1^0$ at LEP [27] for two values of the stop mixing angle: $\theta = 0°$ (horizontal hatching) and $\theta = 56°$ (vertical hatching). The region excluded by CDF [32] for the same decay mode is also shown. Above the dashed line and below the full line this decay is forbidden or suppressed.

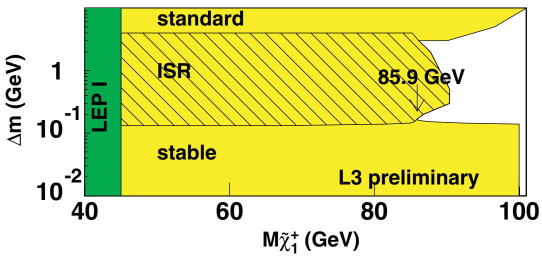

Figure 12. The 95% CL lower limit on the chargino mass obtained by the L3 experiment [35], as a function of the difference Δm between the chargino and the LSP masses, in the most difficult low-Δm region (see text).

The second case (illustrated in figure 12) is when the mass difference Δm between the chargino and the LSP is small (<5 GeV). This configuration is possible only in limited (and unusual) regions of the MSSM parameter space if gaugino mass unification is assumed, but is common in SUSY models with anomaly-mediated SUSY breaking (AMSB [34]). For $\Delta m > 4$–5 GeV the standard searches mentioned above are used. For $\Delta m < 100$ MeV charginos are stable, and therefore can be discovered or excluded by looking for anomalous ionization (as expected from heavy stable charged particles) in the tracking detectors of the LEP experiments. For intermediate values of Δm charginos decay into very soft

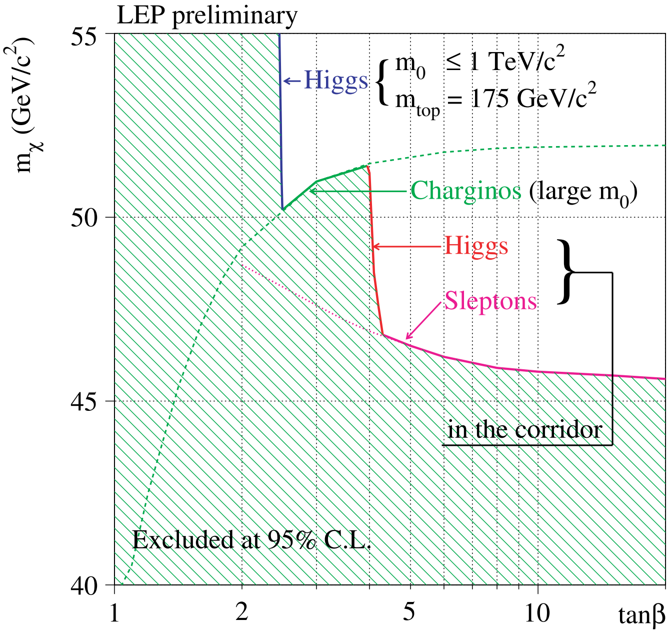

Figure 13. The 95% CL lower limit on the mass of the lightest neutralino, as a function of $\tan\beta$, as obtained in the constrained MSSM by combining the four LEP experiments [27]. The searches used to set the limit in the various $\tan\beta$ regions are indicated.

hadrons, and a dedicated search has been developed which requires a hard initial-state radiation (ISR) photon, to trigger the experiment and reject the background, accompanied by a small amount of additional visible energy. Figure 12 shows that the lower limit on the chargino mass obtained for any Δm value (85.9 GeV in the case of the L3 experiment [35], 92.4 GeV combining the four experiments together [27]), is only a few GeV below the kinematic limit, thus demonstrating that LEP is able to address the most difficult topologies.

The LEP bounds on the chargino mass will likely remain the most stringent ones over a large part of the CMSSM parameter space until the advent of LHC. The Tevatron experiments in run 2 have sensitivity to heavier chargino masses than LEP (up to ∼200 GeV), however limited to those regions of the parameter space where the clean $\mathrm{p\bar{p}} \to \chi^\pm\chi^2_0 \to 3\ell$ channel is open and observable [36].

5.4. Limit on the LSP mass

A very important legacy from LEP is the absolute limit on the mass of the lightest neutralino, which has important cosmological implications because this sparticle is considered today the best candidate for the cold dark matter in the universe.

Since the direct production of χ^0_1 pairs is not observable, an indirect limit is obtained from the interplay of the exclusion domains in the parameter space provided by other searches. This is possible because within constrained models, such as the CMSSM discussed here, the masses

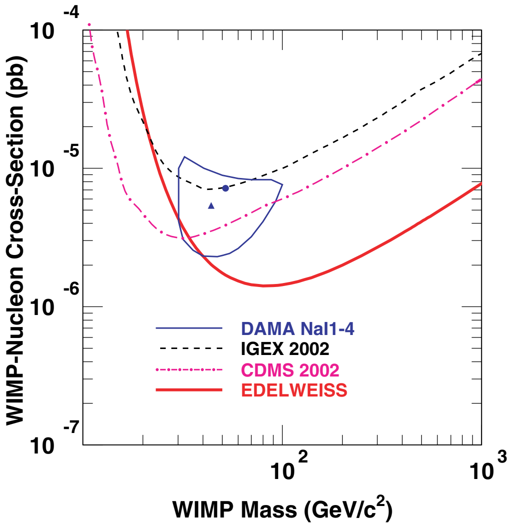

Figure 14. The regions of the plane WIMP mass versus WIMP–nucleon spin-independent cross-section favoured at the 3σ level by the DAMA experiment (closed contour, [38]), or excluded at the 90% CL by the EDELWEISS experiment (solid curve, [39]), by the CDMS experiment (dash–dotted curve, [40]) and by the IGEX experiment (dashed curve, [41]). From [39].

of the various sparticles are related. The result is presented in figure 13, which shows the lower limit on the neutralino mass as a function of the parameter tan β. As previously mentioned, h searches at LEP rule out the low-$\tan\beta$ region. At larger tanβ bounds from chargino and slepton searches also contribute. The absolute limit, $m(\chi_1^0) > 45.6$ GeV at 95% CL, is found asymptotically for tan$\beta \geq 20$ and small m_0, in the region (named 'corridor') where charginos decay into $\ell\tilde{\nu}$ pairs, and charginos and sneutrinos are almost mass degenerate. In this case $\chi^+\chi^-$ searches become ineffective because the two leptons in the final state are too soft to be efficiently detected. However, for small m_0 values sleptons should be accessible at LEP, and the negative results from slepton searches exclude part of the 'corridor' and hence provide the above-mentioned limit on the LSP mass. In the more constrained minimal SUGRA model this limit improves to about 60 GeV for $m_{\rm top} = 175$ GeV. More details on the method used to derive the LSP limit, as well as discussions of the impact of mixing in the stau sector, can be found in [37].

The LEP bound on the LSP mass can be compared to the results of direct searches for cold dark matter in our galaxy. These are performed by experiments looking for neutralinos or, more generally, for weakly interacting massive particles (WIMPs) coming from the galactic halo and interacting with the detectors via WIMP–nucleus scattering. Figure 14 shows the region of the plane WIMP mass versus WIMP cross-section favoured by the DAMA Collaboration if the annual modulation in the rate of nuclear recoils they observe [38] is attributed to galactic neutralinos. Also shown are the regions excluded by other experiments of similar scope, in particular a very recent result from the EDELWEISS experiment [39]. It can be seen that the LEP limit $m(\chi_1^0) > 45.6$ GeV is complementary to direct searches for cold dark matter because it does not depend on the neutralino–nucleon cross-section, and therefore is able to exclude regions of the plane where direct searches have no sensitivity.

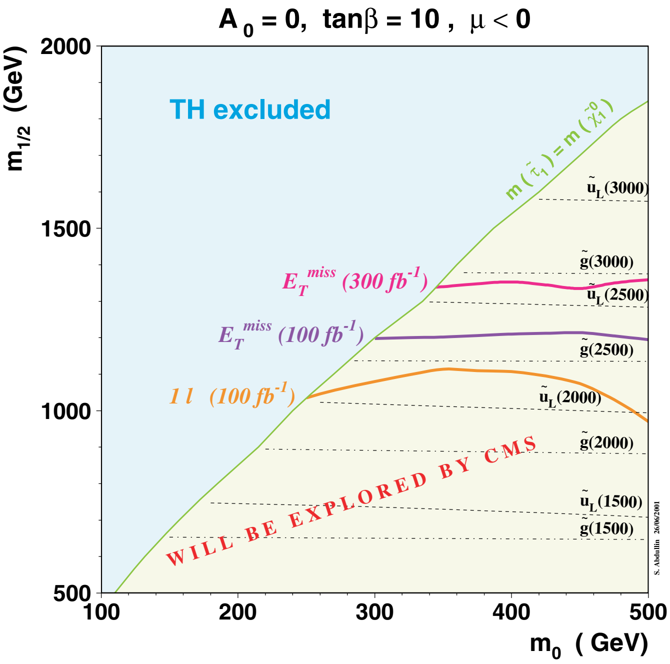

Figure 15. In the minimal SUGRA plane scalar mass versus gaugino mass, the expected 5σ discovery reach of the CMS experiment for integrated luminosities of 100 and 300 fb^{-1} and for two different searches: events with multijet plus E_T^{miss} and events with one lepton. Lines of constant masses for $\tilde{u}$ squarks and gluinos are also indicated. Courtesy of Salavat Abdullin.

5.5. Future prospects

The mass reach of the CDF and D0 experiments in run 2 is, for an integrated luminosity of 15 fb^{-1}, up to about 200 GeV for charginos and for stop squarks and up to 450 GeV for gluinos [36].

At the LHC, a signal from $\sim$1 TeV squarks or gluinos should be easily observed after only a few weeks of data taking, using for instance the rather model-independent multijet-plus-E_T^{miss} signature. For the ultimate integrated luminosity of 300 fb^{-1} per experiment, the discovery potential of this machine extends up to squark and gluino masses of 2.5–3 TeV, as shown in figure 15. As a consequence, if nothing is found at the LHC low-energy SUSY will lose most of its motivation, in particular the possibility of stabilizing the Higgs boson mass without too much fine tuning, and would therefore be ruled out.

On the other hand, if SUSY is found at the Tevatron or at the LHC, then a linear collider of sufficient centre-of-mass energy should be able to perform precise measurements of almost all kinematically accessible sparticles. In particular, chargino and neutralino masses should be measured to 0.1% [7]. These results, combined with a measurement of the gluino mass from the LHC at the per cent level [26], should provide insight into the structure of the theory at high energy, allowing for instance an accurate reconstruction of the common gaugino mass $m_{1/2}$. This should be possible using the values of the gaugino masses measured at the electroweak scale and evolving them up to the grand unification scale by means of the renormalization group equations [42].

Table 2. Final-state topologies expected in different GMSB scenarios ($c\tau$ indicates the NLSP lifetime and $\ell_{detector}$ the detector size).

NLSP	Decay mode	Lifetime	Events with
χ_1^0	$\chi_1^0 \to \gamma\tilde{G}$	$c\tau \ll \ell_{detector}$	Two photons
χ_1^0	$\chi_1^0 \to \gamma\tilde{G}$	$c\tau \sim \ell_{detector}$	Non-pointing photon(s)
χ_1^0	$\chi_1^0 \to \gamma\tilde{G}$	$c\tau \gg \ell_{detector}$	Large missing energy
$\tilde{\ell}$	$\tilde{\ell} \to \ell\tilde{G}$	$c\tau \ll \ell_{detector}$	Two leptons
$\tilde{\ell}$	$\tilde{\ell} \to \ell\tilde{G}$	$c\tau \sim \ell_{detector}$	Kinks in the tracking volume
$\tilde{\ell}$	$\tilde{\ell} \to \ell\tilde{G}$	$c\tau \gg \ell_{detector}$	Heavy stable charged particles

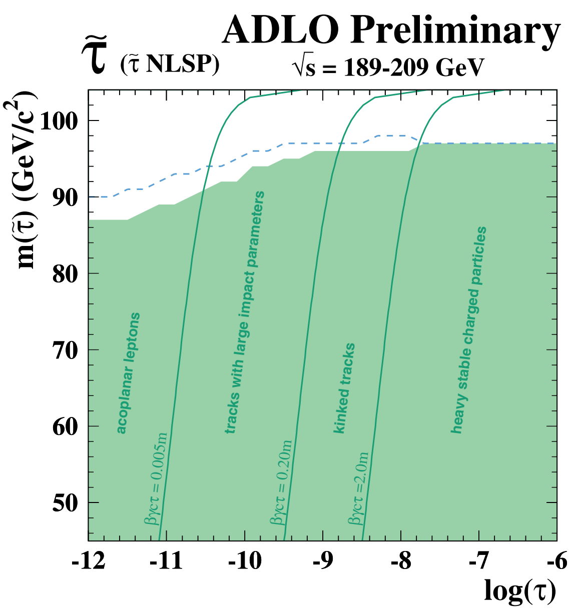

Figure 16. The 95% CL lower limit on the stau mass as a function of the stau lifetime, as obtained at LEP [27] for GMSB scenarios with stau-NLSP. The shaded area shows the region excluded by combining the four experiments, while the dashed curve indicates the expected limit. Lines of constant stau decay lengths are also shown, as well as the regions where the various searches (see text) are most effective.

6. Searches for SUSY particles in GMSB models

Many of the considerations in section 5 about the differences between (and the complementarities of) lepton and hadron colliders are valid also in the GMSB case.

In minimal GMSB scenarios, only pairs of gravitinos and of NLSP are expected to be produced at LEP in most cases, because all other sparticles are in general too heavy.

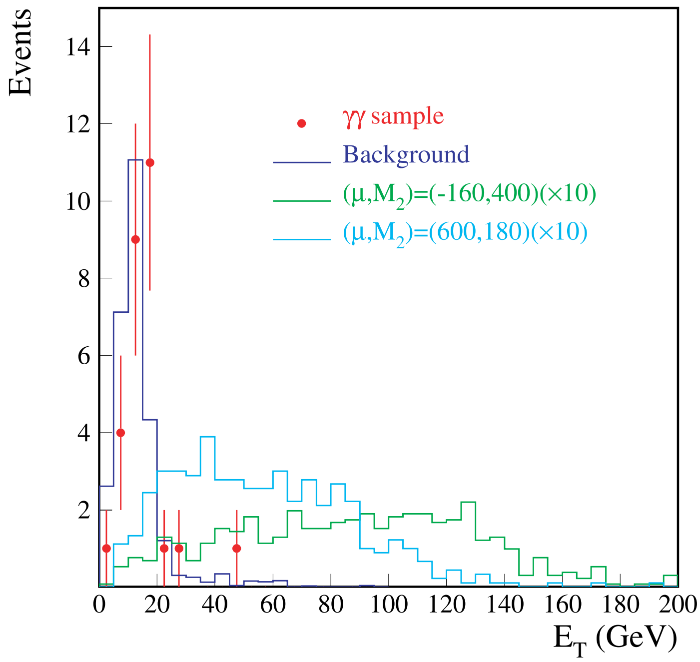

Figure 17. The missing transverse energy spectrum for di-photon events [43] as measured by the D0 experiment (dots) and as expected from SM processes (full line). Also shown are the expected distributions (scaled up by a factor of ten) for two points of the GMSB parameter space (dotted curves).

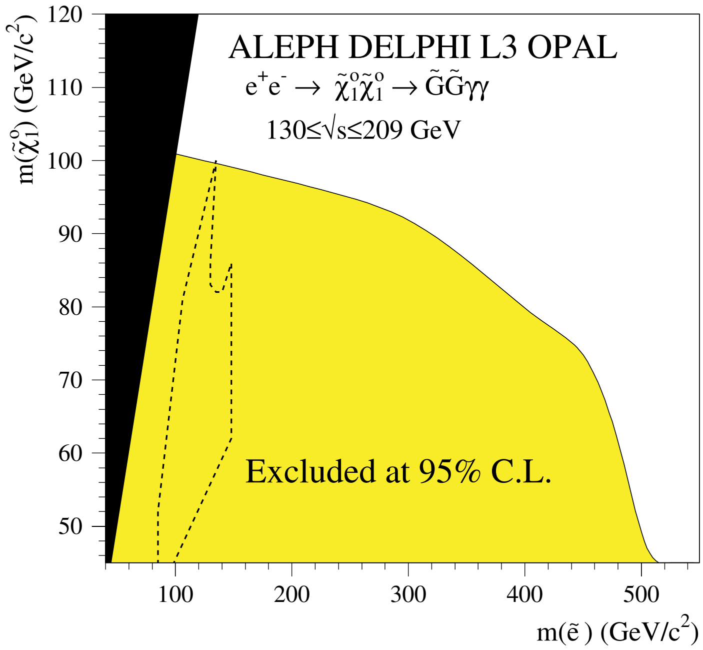

Figure 18. The excluded region (light-shaded area) from di-photon searches at LEP in GMSB scenarios with neutralino-NLSP [27]. The dashed contour shows the region favoured by the CDF event (see text). The dark-shaded area is forbidden in the considered scenario.

At the Tevatron, as already mentioned, the production of pairs of squarks and gluinos should dominate, followed by the cascade decays of these sparticles to the NLSP. The nature and lifetime of the NLSP determine the features of the NLSP $\rightarrow$ LSP decay, and therefore the GMSB phenomenology. The latter can be very different from the SUGRA case.

The main expected topologies are summarized in table 2, under the hypothesis of R-parity conservation. If the NLSP is the lightest neutralino, so that $\chi_1^0 \rightarrow \gamma\tilde{\mathrm{G}}$, then for short neutralino lifetimes all SUSY events contain two photons produced at the interaction vertex, for intermediate neutralino lifetimes they contain one or two photons not coming from the interaction vertex ('non-pointing photons'), whereas for long neutralino lifetimes the topology is similar to that of SUGRA since both neutralinos decay outside the detector giving rise to missing energy and missing mass. If the NLSP is a slepton, so that $\tilde{\ell} \rightarrow \ell\tilde{\mathrm{G}}$, then for short slepton lifetimes all SUSY events contain two leptons produced at the interaction vertex, for intermediate slepton lifetimes they contain kinks in the tracking volume (since $\tilde{\mathrm{G}}$ is invisible and the $\tilde{\ell}$ and ℓ tracks are acollinear) and for long slepton lifetimes they contain two stable sleptons. In all the above cases except the last one, a large amount of missing energy is expected in the final state.

As an example, the LEP experiments have looked for the production of a pair of staus in the stau-NLSP scenario. No signal has been found. The resulting limit on the stau mass is shown in figure 16 as a function of the stau lifetime. For short lifetimes, acoplanar-tau searches similar to those described in section 5.1 have been performed, since the expected topology is similar to stau-pair production in the MSSM. For intermediate lifetimes, analyses looking for tracks with large impact parameters or for kinks in the tracking detectors have been developed. For long lifetimes, events with two stable charged massive particles, therefore giving anomalous signals in the inner detectors of the experiments, have been searched. The lower limit on the stau mass for any stau lifetime is 86.9 GeV (95% CL).

Both the Tevatron and the LEP experiments have looked for events with a pair of photons and missing energy, which could come from the production and decay of two neutralinos with short lifetime in GMSB neutralino-NLSP scenarios. Figure 17 shows the E_T^{miss} spectrum for the sample of D0 events selected by requiring two photons in the final state with transverse energies above 20 and 12 GeV [43]. In the region of large E_T^{miss}, where a possible signal should appear, the data show no excess above the expected SM background, which is dominated by mismeasured QCD multijet events.

Results from unsuccessful LEP searches for the process $\mathrm{e}^+\mathrm{e}^- \rightarrow \chi_1^0\chi_1^0 \rightarrow \gamma\gamma\tilde{\mathrm{G}}\tilde{\mathrm{G}}$, with promptly decaying neutralinos, are shown in figure 18. Since this process receives a contribution also from the t channel with selectron exchange, limits are given in the neutralino–selectron mass plane. Also shown is the region where the features of the famous $\mathrm{ee}\gamma\gamma + E_T^{miss}$ event observed by CDF [44] are consistent with the process $\mathrm{q}\bar{\mathrm{q}} \rightarrow \tilde{\mathrm{e}}_R\tilde{\mathrm{e}}_R \rightarrow \mathrm{ee}\chi_1^0\chi_1^0 \rightarrow \mathrm{ee}\gamma\gamma\tilde{\mathrm{G}}\tilde{\mathrm{G}}$ [45]. It can be seen that LEP is able to exclude at the 95% CL the entire region favoured by the CDF observation.

Future prospects for GMSB searches, both in terms of mass reach and precision measurements, are similar to or better than those discussed in section 5.5 for SUGRA. Indeed the presence of photons and leptons in GMSB events, usually with 'exotic' features, provides additional handles against the background [26]. In addition, a measurement of the NLSP lifetime would give access to the SUSY-breaking scale (through equation (2)) and maybe also to the messenger scale.

7. Conclusions

Over the last ten years, SUSY, probably the best motivated scenario today for physics beyond the SM, has undergone detailed and extensive experimental scrutiny mainly at the LEP and Tevatron colliders. A wealth of different topologies have been studied and the predictions of several models have been explored. No experimental evidence for SUSY has been found, and three main results have been produced. First, a SM-like Higgs boson (as the lightest SUSY Higgs boson h could be) is heavier than 114.4 GeV. However, the electroweak data suggest that the Higgs could be just around the corner, as indeed predicted by SUSY. Second, lower limits on many sparticle masses ranging from ~ 100 up to 300 GeV have been set at various machines. Third, by combining together and interpreting the results of several SUSY and Higgs searches, the LEP experiments have been able to put stringent constraints on the allowed parameter space of minimal SUSY models, and to derive absolute mass limits for several sparticles (e.g. the lightest neutralino).

These and other results, although very challenging, do not yet exclude the existence of TeV-scale SUSY. The next ten years are therefore going to be very exciting for SUSY searches, given the highly motivated energy range which will become accessible to colliders in operation or in construction. Tevatron run 2 will pursue, with increased sensitivity, the exploration of the few hundred GeV region, with a discovery reach of up to ~ 450 GeV for gluinos if an integrated luminosity of ~ 15 fb^{-1} per experiment can be collected. With this luminosity CDF and D0 will have good chances to discover a SM-like Higgs boson up to masses of ~ 120 GeV or to exclude it at 95% CL up to masses of ~ 185 GeV. The upgraded HERA has a mass reach of up to ~ 300 GeV for direct searches, and is complementary to Tevatron for e.g. the sensitivity to R-parity-violating SUSY. Finally, at the end of the decade the LHC will explore in depth the energy range of up to a few TeV, and should therefore be able to discover low-energy SUSY or to rule it out definitively.

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References

[1] Fukuda Y *et al* (Superkamiokande Collaboration) 1998 *Phys. Rev. Lett.* B **81** 1562

[2] Ahmad Q R *et al* (SNO Collaboration) 2001 *Phys. Rev. Lett.* **87** 071301

[3] LEP Higgs Working Group 2002 Search for the standard model Higgs boson at LEP *LHWG Note* 2002 https://lephiggs.web.cern.ch/LEPHIGGS/papers/index.html

[4] LEP Electroweak Working Group 2002 http://lepewwg.web.cern.ch/LEPEWWG

[5] For a phenomenological review see, for instance, Fayet P and Ferrara S 1977 *Phys. Rep.* C **32** 249
Nilles H P 1984 *Phys. Rep.* C **110** 1
Haber H E and Kane G L 1985 *Phys. Rep.* C **117** 75

[6] The LHC Study Group 1995 *The Large Hadron Collider Conceptual Design* CERN/AC/95-05

[7] Heuer T *et al* 2001 TESLA Technical Design Report *Preprint* hep-ph/0106351
Bagger J *et al* (American Linear Collider Working Group) 2000 The case for a 500 GeV e^+e^- linear collider *Preprint* hep-ex/0007022
Matsumoto S *et al* (JLC group) 1992 JLC-1 *KEK Report* 92-16

[8] The CLIC Study Team 2000 *A 3 TeV* e^+e^- *Linear Collider Based on CLIC Technology* CERN 2000-008

CLIC Physics Working Group http://clicphysics.web.cern.ch/CLICphysics
[9] The Muon Collider Collaboration http://www.cap.bnl.gov/mumu/
Autin B *et al* 1999 Prospective study of muon storage rings at CERN *CERN Report* 99-02
[10] http://www-h1.desy.de/h1/www/publications/H1preliminary.short_list.html#BSM
http://www-zeus.desy.de/physics/exo/ZEUS_PUBLIC/exo_public.html
[11] See, for example, http://www-theory.fnal.gov/vlhc/vlhc.html and references therein
Design Study for a staged Very Large Hadron Collider 2001 FERMILAB-TM-2149
Baur U *et al* 2002 Physics at future hadron colliders *Preprint* hep-ph/0201227
[12] For reviews and recent results see, for instance, Allanach B *et al* 1999 Searching for R-parity violation at run 2 of the Tevatron *Preprint* hep-ph/9906224
Pasztor G 2001 *Int. J. Mod. Phys.* **A16S1B** 781
Syrois Y 2002 R_p violating SUSY and exotics at HERA *10th Int. Conf. on Supersymmetry and Unification of Fundamental Interactions SUSY02, DESY (Hamburg, 2002)* http://www.desy.de/susy02/
[13] Chamseddine A H, Arnowitt R and Nath P 1982 *Phys. Rev. Lett.* **49** 970
[14] Giudice G F and Rattazzi R 1999 *Phys. Rep.* **322** 419
Ambrosanio S, Kribs G D and Martin S P 1997 *Phys. Rev.* D **56** 1761
[15] Masip M 1998 *Phys. Lett.* B **444** 352
[16] LEP Higgs Working Group 2000 *Standard Model Higgs Boson at LEP: results with the 2000 data and request for running in 2001* submitted to the LEP Committee and to the CERN Research Board https://lephiggs.web.cern.ch/LEPHIGGS/papers/index.html
[17] Barate R *et al* (ALEPH Collaboration) 2002 *Phys. Lett.* B **256** 191
[18] DELPHI Collaboration 2002 Final result on SM and MSSM neutral Higgs bosons *DELPHI Note* DELPHI-2002-041 CONF-575
[19] Achard P *et al* (L3 Collaboration) 2001 *Phys. Lett.* B **517** 319
[20] OPAL Collaboration 2002 Search for the standard model Higgs boson with the OPAL detector at LEP *OPAL Physics Report* PR367
[21] Barate R *et al* (ALEPH Collaboration) 2000 *Phys. Lett.* B **495** 1
[22] LEP Higgs Working Group 2001 Searches for the neutral Higgs bosons of the MSSM: preliminary combined results using LEP data collected at energies up to 209 GeV *Preprint* hep-ex/0107030
[23] Acosta D *et al* (CDF Collaboration) 2001 *Phys. Rev. Lett.* **86** 4472
[24] Carena M *et al* 1992 *Nucl. Phys.* B **369** 33
[25] Carena M *et al* 2000 Report of the Higgs working group for run 2 of the Tevatron *Preprint* hep-ph/0010338
[26] Airapetian A *et al* (ATLAS Collaboration) 1999 Detector and physics performance *Technical Design Report* CERN/LHCC/99-15
Bayatian G L *et al* (CMS Collaboration) 1994 *The Compact Muon Solenoid Technical Proposal* CERN/LHCC/94-38
[27] LEP SUSY Working Group 2002 http://lepsusy.web.cern.ch/lepsusy/
[28] CDF Exotics Physics Group http://www-cdf.fnal.gov/physics/exotic/exotic.html
[29] D0 Physics Group on Searches for New Phenomena http://www-d0.fnal.gov
[30] Affolder T *et al* (CDF Collaboration) 2002 *Phys. Rev. Lett.* **88** 041801
[31] Abachi S *et al* (D0 Collaboration) 1995 *Phys. Rev. Lett.* **75** 618
[32] Affolder T *et al* (CDF Collaboration) 2000 *Phys. Rev. Lett.* **84** 5704
[33] Heister A *et al* (ALEPH Collaboration) 2002 Search for scalar quarks in e^+e^- collisions at $\sqrt{s}$ up to 209 GeV *Preprint* hep-ex/0204036
[34] Randall L and Sundrum R 1999 *Nucl. Phys.* B **557** 79
Gherghetta T, Giudice G F and Wells J D 1999 *Nucl. Phys.* B **559** 27
[35] Favara A (L3 Collaboration) 2001 Search for Supersymmetry in e^+e^- collisions at $\sqrt{s} = 202$–208 GeV *L3 Note* 2644 http://l3.web.cern.ch/l3/note/notes2001.html

[36] Barger V *et al* 2000 Report of the SUGRA working group for run 2 of the Tevatron *Preprint* hep-ph/0003154
[37] Barate R *et al* (ALEPH Collaboration) 2001 *Phys. Lett.* B **499** 67
ALEPH Collaboration 2002 Absolute mass lower limit for the lightest neutralino in the MSSM from e^+e^- data up to $\sqrt{s} = 209$ GeV *ALEPH note* ALEPH/2002-028 http://alephwww.cern.ch/ALPUB/oldconf/summer02/summer.html
DELPHI Collaboration 2002 Searches for supersymmetric particles in e^+e^- collisions up to 208 GeV, and interpretation of the results within the MSSM *DELPHI Note* DELPHI-2002-027 *CONF-561* http://delphiwww.cern.ch/ pubxx/delsec/conferences/amsterdam02/
[38] Bernabei R *et al* (DAMA Collaboration) 2000 *Phys. Lett.* B **480** 23
[39] Benoit A *et al* (EDELWEISS Collaboration) 2002 Improved exclusion limits from the EDELWEISS WIMP search *Preprint* astro-ph/0206271
[40] Abrams D *et al* (CDMS Collaboration) 2002 Exclusion limits on the WIMP–nucleon cross-section from the Cryogenic Dark Matter Search *Preprint* astro-ph/0203500
[41] Morales A *et al* 2002 *Phys. Lett.* B **532** 8
[42] Blair G A, Porod W and Zerwas P M 2001 *Phys. Rev.* D **63** 017703
[43] Abbot B *et al* (D0 collaboration) 1998 *Phys. Rev. Lett.* **80** 442
[44] Abe F *et al* (CDF collaboration) 1998 *Phys. Rev. Lett.* **81** 1791
[45] Lopez J L and Nanopoulos D V 1997 *Phys. Rev.* D **55** 4450