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SEARCHES FOR NEW PARTICLES AT LEP: A SUMMARY REPORT

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Abstract

We review the progress made at LEP in the quest for new particles.

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1 Introduction

Twelve exciting years of research at the high energy frontier are the legacy of the Large Electron-Positron (LEP) collider at CERN. During its runs at the centre-of-mass (CM) energies of $\sqrt{s} = M_{Z^0}$ (LEP1) and 130–209 GeV (LEP2), this machine has allowed for the collection of an unprecedented amount of data. About 1 fb^{-1} of integrated luminosity has been delivered per experiment. Never before as during the LEP era the Standard Model (SM) of particle physics has undergone such a stringent, yet so successful, scrutiny of its most fine details. LEP has now been turned off, and it is our aim here to provide a comprehensive, yet brief, summary on the subject of searches for new particles at the CERN collider, both within and beyond the SM, and review the prospects at future accelerators.

2 The SM Higgs boson: the LEP excess

Contrary to what hoped for initially, expectations of LEP clarifying the mechanism of Electroweak Symmetry Breaking (EWSB) have faded away. Within the SM of particle physics, EWSB is realised through the so-called Higgs mechanism, whose unmistakable hallmark would be the discovery of a neutral scalar particle, the Higgs boson (hereafter denoted by H). In the year 2000, LEP operations have been optimised towards the SM Higgs boson search [1]. As a result of this, the LEP-combined sensitivity for a 3σ observation reached 115 GeV, assuming Higgs production in association with a Z^0 boson, via $e^+e^- \to HZ^0$. A 115 GeV SM Higgs boson predominantly decays into $b\bar{b}$ (74%) and $\tau^+\tau^-$ (7%). The analyses addressed the following final states: four-jets ($Hq\bar{q}$), missing energy ($H\nu\bar{\nu}$), lepton pairs ($H\ell^+\ell^-$, $\ell = e, \mu$) and τ's ($H\tau^+\tau^-$ plus $H \to \tau^+\tau^-, Z^0 \to q\bar{q}$).

The results of the LEP-combined data presented at the LEPC meeting on November 3rd, 2000, showed an excess of 2.9σ beyond the background expectation. The compatibility of the data with the background-only hypothesis can be parametrised as $1 - \mathrm{CL_b}$, see fig. 1, as a function of the Higgs mass. The distribution exhibits a minimum at 115 GeV. The probability that this minimum arises from a background fluctuation is 0.4%.

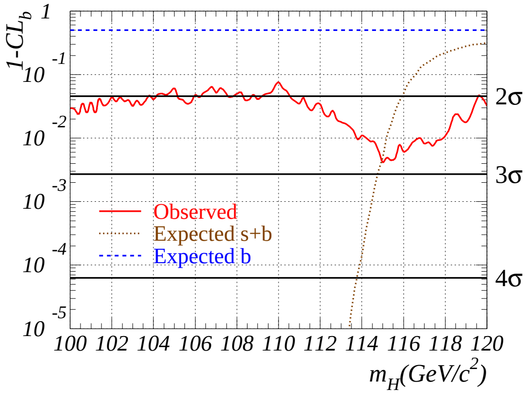

Figure 1: Confidence level 1-$\mathrm{CL_b}$ (full curve) as a function of M_H. The dashed (dotted) curve indicates the expected level in the background only (signal-plus-background) hypothesis. The straight full lines indicate the level 2, 3 and 4σ excesses above the expected background rate.

The log-likelihood ratio (LLR) values at M_H= 115 GeV observed in each experiment are such that the result of ALEPH is a little too signal-like, DELPHI is more background-like whereas L3 and OPAL are close to the most likely value expected for M_H= 115 GeV. The distribution of the four observed values is consistent with the one expected in the signal-plus-background hypothesis.

In the combined results, in each of the four channels, the LLRs observed are close to the most likely value expected for M_H= 115 GeV. The significance of the observed excess is largest in the four-jet channel, followed by the missing energy, the leptonic and the tau one, as expected from the decreasing signal-to-background separation for these final states. Moreover, the observed significance obtained with the data samples analysed shows a progressive and regular increase indicating that the observed effect does not result from an early statistical fluctuation, which would have then been reduced by additional statistics.

The observed excess is compatible with a Higgs boson with mass near 115 GeV. More data, or results from other experiments, will be needed to determine whether the observed excess is real. Unquestionably though, if the 'same' 115 GeV Higgs boson will eventually be detected, at either the Tevatron (Run 2) at FNAL or the Large Hadron Collider (LHC) at CERN, much of the credit for its discovery will have to remain among LEP achievements.

In the meantime, a lower limit of 113.5 GeV at 95% C.L. on the SM Higgs mass has been derived, *i.e.*, about 2 GeV below the median expected 115.3 GeV.

3 Supersymmetry

Despite its innumerable experimental successes, the SM cannot be a fundamental theory valid up to $M_{\mathrm{Planck}} \sim 10^{18}$ GeV (where a description which includes quantum gravity is needed). The SM has to be replaced at an energy higher than the

Particle		Spin	Sparticle		Spin
quark	q	1/2	squarks	$\widetilde{q}_{L,R}$	0
charged lepton	$\ell^{\pm}$	1/2	charged sleptons	$\widetilde{\ell}^{\pm}_{L,R}$	0
neutrino	ν	1/2	sneutrino	$\widetilde{\nu}$	0
gluon	g	1	gluino	$\widetilde{g}$	1/2
photon	γ	1	photino	$\widetilde{\gamma}$	1/2
neutral gauge boson	Z^0	1	zino	$\widetilde{Z}$	1/2
neutral Higgs bosons	h^0, H^0, A^0	0	neutral Higgsinos	$\widetilde{H}^0_{1,2}$	1/2
charged gauge boson	$W^{\pm}$	1	wino	$\widetilde{W}^{\pm}$	1/2
charged Higgs boson	$H^{\pm}$	0	charged Higgsino	$\widetilde{H}^{\pm}$	1/2
graviton	G	2	gravitino/goldstino	$\widetilde{G}$	3/2
$\widetilde{W}^{\pm}, \widetilde{H}^{\pm}$ mix to form 2 chargino mass eigenstates $\chi^{\pm}_1, \chi^{\pm}_2$					
$\widetilde{\gamma}$, $\widetilde{Z}$, $\widetilde{H}^0_{1,2}$ mix to form 4 neutralino mass eigenstates $\chi^0_1, \chi^0_2, \chi^0_3, \chi^0_4$					
$\widetilde{t}_L, \widetilde{t}_R$ (and similarly $\widetilde{b}, \widetilde{\tau}$) mix to form the mass eigenstates $\widetilde{t}_1, \widetilde{t}_2$					

Table 1: Particle content of the MSSM, expressed in terms of its mass eigenstates.

Fermi scale, $G_F^{-1/2} \approx 300$ GeV, by some more fundamental theory. This can be seen from the fact that the one-loop radiative corrections to the SM Higgs mass M_H are quadratically divergent (naturalness or hierarchy problem) [2].

Supersymmetry (SUSY) can solve the hierarchy problem. This is a possible symmetry of nature that relates all the SM fundamental fields (those describing quarks, leptons, gauge and Higgs bosons) to a new set of physical states ('sparticles'), identical to the latter in everything, except for their spins, which differ by half unit. As a consequence of their different statistics, cancellations occur between the bosonic and fermionic loop contributions to the Higgs mass, ensuring that SUSY is free from quadratic divergences. SUSY must be broken though, since we do not observe the 'Superpartners' with the same mass as ordinary matter. However, if SUSY has to remain an (approximate) symmetry above the TeV scale, it must be broken 'softly': *i.e.*, by terms that do not re-introduce quadratic divergences (rather, only logarithmic). These soft parameters are dimensionful and, in order not to contradict naturalness, their mass scale is expected to fall in the TeV region. Are precisely the values of these terms that set the upper scale of the sparticle masses. There are various mechanisms of soft SUSY breaking. These have been reviewed in Ref. [3], with particular emphasis on Minimal-Supergravity (MSUGRA) [4] and Gauge Mediated Symmetry Breaking (GMSB) [5], whose signatures have been of particular concern at LEP [6].

3.1 The MSSM

M-SUGRA and GMSB scenarios can be accommodated within the Minimal Supersymmetric Standard Model (MSSM), wherein the particle content and number of free parameters entering the Lagrangian is kept to the minimum compatible with SUSY. The entire (s)particle spectrum of the MSSM is specified in table 1.

3.1.1 The MSSM Higgs bosons

But let us turn again to the Higgs sector, albeit in the new model. A prerequisite for the realisation of the MSSM is the primordial existence of two Higgs doublets, one coupling to up- and one to down-type (s)fermions (in contrast to the only singlet field of the SM, which is universally coupled), whose non-zero vacuum expectation values (VEVs) induce spontaneous EWSB. Of the initial eight degrees of freedom (in a four-dimensional space) of the two complex Higgs doublet fields of the MSSM, upon EWSB and mass generation in the gauge boson sector, three are absorbed by the standard weak fields (Z^0 and $W^\pm$) in the form of a longitudinal polarisation; five instead survive as physical Higgs states. Of these, three are neutral and two charged. Whereas the latter have a mixed CP-nature, the former comprehend two CP-even (or scalar) states, denoted by h^0 and H^0, and a CP-odd (or pseudoscalar) one, labelled as A^0.

At tree level, all masses and couplings in the Higgs sector can be expressed in terms of only two real parameters, the ratio of VEVs of the two Higgs doublets (denoted by $\tan\beta$) and the mass of one of the bosons (*e.g.*, M_{A^0}). In addition, at lowest order, one has: $M_{h^0} \leq M_{Z^0}$ (see, *e.g.*, [7]). However, this upper value on the lightest Higgs boson mass is significantly modified by virtual effects. At two-loop order [8], it becomes 130 GeV or so, largely within the reach of LEP. Hence, it is not surprising that most of the efforts spared at the CERN e^+e^- collider in detecting physics beyond the SM have actually coincided with the search for this particular Higgs state.

Searches for neutral Higgs bosons. In the MSSM, neutral Higgs bosons are produced via the Higgsstrahlung process $e^+e^- \to h^0 Z^0$ and through pair production $e^+e^- \to h^0 A^0$. The cross section of the former is proportional to $\sin^2(\beta-\alpha)$; the one of the latter to $\cos^2(\beta-\alpha)$. In the mass range of interest for LEP2 searches, the main h^0 and A^0 decay modes are in $b\bar{b}$ and $\tau^+\tau^-$. To search for Higgsstrahlung production the same selections developed for the SM signals were used whereas two more additional signatures arise via $h^0 A^0$ production: the 'four b-jet' and the 'two b-jet plus two tau' final states. Good agreement with the expectations from SM processes has been found for both topologies and upper limits on the $h^0 A^0$ cross section have been set as a function of the A^0 and h^0 masses (see [9] for more details). The results obtained in the searches for $h^0 Z^0$ and $h^0 A^0$ production are interpreted within two scenarios: maximal and minimal mixing in the stop sector. Lower limits on the masses of h^0 and A^0 have been set: $M_{h^0} > 91$ GeV and $M_{A^0} > 92$ GeV for any value of $\tan\beta$. In the conservative maximal mixing scenario, the $\tan\beta$ region [0.48-2.56] is excluded at 95% C.L.

Searches for charged Higgs bosons. Pair production of charged Higgs bosons occurs mainly via s-channel exchange of a photon or a Z^0 boson. The H^+ decays predominantly into $c\bar{s}$ or $\tau^+\nu_\tau$ (and charge conjugates). Three final states have been studied at LEP: $c\bar{s}s\bar{c}$, $c\bar{s}\tau^-\bar{\nu_\tau}/s\bar{c}\tau^+\nu_\tau$ and $\tau^-\bar{\nu_\tau}\tau^+\nu_\tau$. A 3σ deviation with respect to the SM background expectation has been observed by L3 in the $c\bar{s}s\bar{c}$ channel for $M_{H^\pm} \approx 67$ GeV. This effect has not been confirmed by the other experiments (see [10] for more details). A lower limit on $M_{H^\pm}$ has been set at 78 GeV, independently of the branching ratio BR($H^+ \to \tau^+\nu_\tau$). The above numbers are valid within a general Two-Higgs Doublet Model (2HDM) and may also by applied to the MSSM in the mentioned $\tan\beta$ region, where an indirect lower limit on $M_{H^\pm}$ is derived from the one on M_{h^0}: $M^2_{H^\pm} \approx M^2_{W^\pm} + M^2_{h^0} \gtrsim (130\ \mathrm{GeV})^2$.

Production	Decay mode	Topology
$\tilde{\ell}\bar{\tilde{\ell}}$	$\tilde{\ell} \to \ell\chi^0_1$	Acoplanar leptons
$\tilde{e}_{\mathrm{L(R)}}\bar{\tilde{e}}_{\mathrm{R(L)}}$	$\tilde{e} \to e\chi^0_1$	Single electron (small $m_{\tilde{e}_{\mathrm{R}}} - m_{\chi^0_1}$)
$\tilde{q}\bar{\tilde{q}}$	$\tilde{q} \to q\chi^0_1$	Acoplanar jets
$\tilde{t}\bar{\tilde{t}}$	$\tilde{t} \to c\chi^0_1$	Acoplanar jets
$\tilde{b}\bar{\tilde{b}}$	$\tilde{b} \to b\chi^0_1$	Acoplanar b-jets
$\tilde{t}\bar{\tilde{t}}$	$\tilde{t} \to b\ell\tilde{\nu}$	Acoplanar jets plus leptons
$\chi^+\chi^-$	$\chi^\pm \to q\bar{q}'\chi^0_1$	4 jets + $\not{E}$
	$\chi^\pm \to \ell^\pm\nu\chi^0_1$	Acoplanar leptons
	mixed	2 jets + lepton + $\not{E}$
$\chi^0_i\chi^0_j$	$\chi^0_1\chi^0_j \to q\bar{q}\chi^0_1$	Acoplanar jets
	$\chi^0_i\chi^0_j \to \nu\bar{\nu}\chi^0_1 q\bar{q}\chi^0_1, \ldots$	
$j \geq i, j \neq 1$	$\chi^0_1\chi^0_j \to \ell^+\ell^-\chi^0_1$	Acoplanar leptons
	$\chi^0_i\chi^0_j \to \nu\bar{\nu}\chi^0_1\ell^+\ell^-\chi^0_1, \ldots$	

Table 2: Final state topologies studied in MSUGRA.

3.1.2 The MSSM sparticles

Many more physical states are however expected in the SUSY theory, *i.e.*, the Supersymmetric partners of ordinary matter: namely, sleptons, squarks and gauginos/Higgsinos (see table 1). Depending upon the mechanism of SUSY breaking, several signatures involving MSSM sparticles (including the gravitino) were within the reach of LEP. (R-parity is assumed to be conserved throughout.)

Searches for MSUGRA topologies. In the MSUGRA scenario the Lightest Supersymmetric Particle (LSP) is the lightest neutralino (χ^0_1) and the gravitino is heavier than the other SUSY particles. The final states topologies addressed by MSUGRA searches are summarised in table 2 (only the main decay chains contributing to the different topologies are indicated for neutralinos). For a given final state, various selection criteria are applied, which depend mainly on the mass difference ΔM between the produced sparticle and the LSP. The number of events selected by the analyses is in good agreement with the expectation from SM processes. A slight excess was observed in the acoplanar τ-search in the 1998 and 1999 data. It has not been confirmed by the analysis of the 2000 data sample. Lower limits on slepton and squark masses are given in table 3.

Particle	Limit	Conditions of validity	Particle	Limit	Conditions of validity
selectron	99	$\Delta M > 10$	stop	92	$\tilde{t} \to c\chi^0_1$, $6 < \Delta M < 40$
smuon	95	$\Delta M > 10$, $\tilde{\mu} \to \mu\chi^0_1$	stop	93	$\tilde{t} \to b\ell\tilde{\nu}$, $\Delta M > 10$
stau	80	$\Delta M > 10$, $\tilde{\tau} \to \tau\chi^0_1$, $\tilde{\tau}_{\mathrm{R}}$	sbottom	96	$\tilde{b} \to b\chi^0_1$, $\Delta M > 8$, $\tilde{b}_{\mathrm{L}}$

Table 3: Lower limits at 95% C.L. on squark and slepton masses in MSUGRA. For sleptons, $\tan\beta = 2$, $\mu = -200$ GeV. All masses and mass differences are in GeV.

Chargino pair production and neutralino associated production are excluded up to the kinematic limit over a significant fraction of the MSSM parameter space. From the negative outcome of chargino and neutralino searches, a lower limit on the lightest neutralino mass can be derived as a function of $\tan\beta$ for a large scalar mass m_0 (*i.e.*, the mass common to all SUSY scalar states at the unification scale). The loss of sensitivity of chargino and neutralino searches at low m_0 is recovered through slepton searches. A scan performed over the relevant parameter space shows that a lower limit on the LSP mass of 38 GeV holds for all values of m_0.

Constraints from Higgs boson searches are also used to improve the lower limit on the LSP mass. As expected, the limit is strongest for low values of $\tan\beta$ and m_0. The lower limit on the LSP is 45 GeV for a top mass of 175 GeV. These results are however quite sensitive to m_t: *e.g.*, the limit becomes 40 GeV for a top mass of 180 GeV. Besides, the interplay among the searches for sleptons, charginos, Higgs bosons and the Z^0 width measurement at LEP1 can also be exploited in the framework of MSUGRA. This way, the lower limit on the LSP mass is close to $\sqrt{s}/4$, half the lower limit on the chargino mass.

Searches for GMSB topologies. In GMSB scenarios the LSP is the weakly-coupled gravitino ($\tilde{G}$). Hence, in e^+e^- collisions, SUSY sparticles typically decay to their SM partner plus gravitinos. The Next-to-LSP (NLSP) is here, in general, either the lightest neutralino or slepton (*e.g.*, three degenerate NLSPs or the stau if its mixing is large). These are expected to be much lighter than the other SUSY sparticles and therefore the only ones accessible at LEP.

The lifetime of the NLSP depends on the gravitino mass (or, equivalently on the SUSY-breaking scale $\sqrt{F}$). For quite heavy gravitinos the decay length associated to the lifetime can be comparable to or even larger than the size of the LEP detectors. For such a reason, topological searches enabling to identify a long-lived or even stable NLSP have been developed. A partial list of experimental topologies considered is given in table 4.

NLSP	Production	Decay mode	NLSP Lifetime	Exp. Topology
χ_1^0	$e^+e^- \to \chi_1^0\chi_1^0$	$\chi_1^0 \to \gamma\tilde{G}$	$c\tau << \ell_{\text{detector}}$	Acoplanar γ's
			$c\tau \sim \ell_{\text{detector}}$	Non Pointing γ
			$c\tau >> \ell_{\text{detector}}$	Invisible
$\tilde{\ell}$	$e^+e^- \to \tilde{\ell}\tilde{\ell}$	$\tilde{\ell} \to \ell\tilde{G}$	$c\tau << \ell_{\text{detector}}$	Acoplanar ℓ's
			$c\tau \sim \ell_{\text{detector}}$	Large impact parameter tracks
			$c\tau >> \ell_{\text{detector}}$	Heavy Stable Charged Particles
$\tilde{\ell}$	$e^+e^- \to \chi_1^0\chi_1^0$	$\chi_1^0 \to \tilde{\ell}\ell \to \ell\ell\tilde{G}$	$c\tau << \ell_{\text{detector}}$	Multi-ℓ's (2 hard and 2 soft)
			$c\tau \sim \ell_{\text{detector}}$	Not yet studied
			$c\tau >> \ell_{\text{detector}}$	Not yet studied

Table 4: Final state topologies studied in GMSB.

No evidence for any such processes has been found in the data and lower limits on the sparticle masses have been set. The stau is excluded up to a mass of 80 GeV for any lifetime. In the case of neutralino NLSP the limit depends strongly on the neutralino lifetime. For lifetimes short enough the neutralino decays via

$\chi_1^0 \to \gamma\tilde{G}$ and can be detected directly. The searches for acoplanar photons and non pointing single-photons [11] set a lower limit on $M_{\chi_1^0}$ of about 70 GeV for $c\tau$ up to 10 m. For longer lifetimes only indirect searches can be used and the lower limit on the neutralino mass is close to the one obtained in the MSUGRA model.

It has been shown that photonic final states can probe theories with extra spatial dimensions [11]. Here, one expects additional contributions to $e^+e^- \to \gamma\gamma$ due to virtual graviton exchange as well as direct production of the latter via $e^+e^- \to \gamma G$. Single-photon final states naturally accommodate also signatures induced by light, so-called, 'sgoldstinos' [12][1].

3.1.3 MSSM and dark matter

The extensive searches performed at LEP have ruled out a large fraction of the MSSM parameter space interesting for cold dark matter [13]. The LEP results are compatible over a small region of the parameter space with cosmological constraints and with the SUSY interpretation of the disagreement between the expected and measured values of the muon anomalous magnetic moment.

3.2 Beyond the MSSM: MSSM* and NMSSM.

The model embodying SUSY need not be minimal. Indeed, several 'extensions' of the MSSM have been considered in literature. By extensions, we mean here theoretical setups which embed a number of parameters in the SUSY Lagrangian larger than those appearing in the canonical MSSM. For example, this can be done by either dismissing the assumption that the mentioned soft SUSY-breaking terms are real (hence taking these as complex) [14] or adding one singlet Higgs field (and its SUSY counterpart) [15][2]. Hereafter, we denote the first category of models as MSSM* and the second as NMSSM (for Next-to-MSSM).

MSSM* scenarios rely on cancellations [16] among SUSY contributions to the electron and neutron Electric Dipole Moments (EDMs) [17], in order to be realistic[3]. NMSSM settings have been introduced as a possible solution to the so-called μ-problem of the MSSM, *i.e.*, the 'unnatural' presence of the $\mu\hat{H}_u\hat{H}_d$ term in the soft SUSY Lagrangian ($\hat{H}_{u,d}$ are the Higgs(ino) Superfields).

3.2.1 MSSM* and NMSSM at LEP and future colliders

In respect to LEP physics, the effect in either scenario is mainly to alter the phenomenology of the Higgs sector, by inducing a modification to the Higgs masses and couplings, via mixing effects affecting the ordinary neutral Higgs fields of the MSSM, either among each other (MSSM*) or with new ones (NMSSM). In the MSSM*, this is achieved through one-loop effects [21], induced by explicit CP-violation in the third generation of squarks, so that the three neutral Higgs states are no longer either positive or negative CP-eigenstates, rather a superposition of the two. In this scenario, *e.g.*, for low and intermediate $\tan\beta$ (say, below 7), the

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[1] In fact, in Supersymmetric extensions of the SM with a very light gravitino, the effective theory at the EW scale should contain not only the Goldstino, but also its partners from SUSY, the sgoldstinos (two neutral spin-less sparticles).

[2] We do not consider here the possibility of additional Higgs doublets or triplets: see, *e.g.*, Ref. [7].

[3] Despite the scope for very large phases has significantly been reduced recently [18], in view of the mercury EDM measurement [19], the extended model has gathered much interest lately [20].

lightest Higgs boson mass may be as low as 80–90 GeV and can have escaped LEP searches because of its reduced couplings to Z^0 bosons, while the second lightest Higgs mass could be consistent with the 115 GeV excess (at low $\tan\beta$) [22]. In the NMSSM too, the coupling of the lightest Higgs scalar to gauge bosons can be small, so that, again, it is the second lightest Higgs state the observable one [23]. For appropriate combinations of the (reduced) Higgs couplings, the outcome here can be the same as in the previous case, with an unobservable light Higgs state and the next one lying at 115 GeV.

At future hadronic machines, the phenomenology of either the MSSM* or the NMSSM have not been investigated yet in great detail. Only some theoretical studies exists to date and they all focus on the Higgs sector: for the MSSM* see [24] whereas for the NMSSM see [25].

4 Leptoquarks (LQs)

These are bosonic fields carrying simultaneously leptonic and baryonic quantum numbers. They provide a clear signature of models attempting to explain the observed symmetry between leptons and quarks, with respect to the multiplet structure of the EW interactions, such as technicolor [26], compositeness [27], Grand Unification Theories (GUTs) [28] and Superstring-inspired scenarios [29]. Evidence of these particles has been searched for (in vain) at LEP, both directly, *i.e.*, via pair and single LQ production, as well as through t, u-channel contributions to, *e.g.*, quark pair production (LQ exchange). A review of LEP results and their comparison with the ones obtained at Tevatron and Hera is given in [30].

5 Searches at Tevatron (Run 2) and LHC

The experimental program at Tevatron and LHC is largely focused on the detection of new physics. Detailed studies [31] show that the expected sensitivity at the Tevatron collider in direct searches for SUSY particles is slightly beyond the LEP2 constraints and not sufficient to guarantee full coverage of the SUSY spectrum. In contrast, if SUSY exists at the TeV scale, it is expected not to escape experimental detection at the LHC. Besides, it has been pointed out, see [32], that LHC experiments will also be able, in some cases, to determine the mechanism of SUSY breaking and the SUSY parameters themselves in various scenarios.

The reach in discovery of a light neutral Higgs state (in the SM or, alternatively, in the MSSM in the low $\tan\beta$ region) at the Tevatron collider (Run 2) seems to be very promising. In particular, it has been shown in [31] that a 3σ sensitivity for a 115 GeV Higgs mass (about the same reached at LEP) can be achieved with 3 fb^{-1}, corresponding to about two years of data taking.

Given the strong expectations at both these colliders concerning the possible detection of a light Higgs boson, it is of extreme importance the ability to rely on accurate theoretical predictions. In this respect, it is worth recalling that important progress has recently been made in the QCD calculation of the NNLO corrections to $gg \to$ Higgs [33]. Similarly, one should expect also the QCD NLO corrections to $q\bar{q}, gg \to Q\bar{Q}$ Higgs (with $Q = b, t$) to become available soon[4].

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[4] See Ref. [34] for a review of the status of the other two main Higgs production channels in hadron-

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