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SEARCHES FOR NEW PARTICLES

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Abstract

Searches for Standard Model and Supersymmetric Higgs, supersymmetric particles and leptoquark at HERA, LEP and TEVATRON colliders are reviewed. No evidence for a positive signal is seen, but significant and constraining limits are placed. In particular the Standard Model Higgs boson must be heavier than 77.5 GeV and the lightest neutralino heavier than 14.0 GeV for all $\tan\beta$ and all sneutrino masses. A lower limit on the mass of a first generation scalar leptoquark of 225 GeV at 95% C.L. has also been obtained.

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1 Introduction

I present a short review on searches for new particles from the data accumulated at the High Energy Colliders LEP, HERA and TEVATRON.

Since the last Lepton-Photon Conference, the LEP e^+e^- collider, very important for new particle searches, has doubled its c.m. energy (LEP2). Each LEP experiment has collected around 6 pb^{-1}at c.m. energies of 130 and 136 GeV, 10 pb^{-1}at the W-pair threshold of 161 GeV, 10 pb^{-1}at 172 GeV and about 72 pb^{-1}at 183-184 GeV [1)]. Moreover results from the TEVATRON are based on 110 pb^{-1}proton antiproton annihilations at c.m. energy of 1800 GeV, while those from HERA are based on 20 pb^{-1}e^+p collisions at 300 GeV of c.m. energy.

I am impressed by the tremendous amount of high quality experimental results on searches for new particles presented in this Conference. These include searches for Standard Model Higgs, supersymmetric (SUSY) Higgses and other SUSY particles, excited fermions, leptoquark, heavy leptons and stable massive charged particles.

The experimental scenario from colliders of the last two years have been again characterized by "the irresistible rise of the Standard Model (SM)". Yet the Higgs boson has not been found so the mechanism of electroweak symmetry breaking is still unproved. Therefore the Higgs search is still today one of the crucial searches for new particles and it will be discussed in section 2.

Besides the Higgs, I selected the other subjects driven by some measurements not yet explained by the SM.

As a matter of fact, besides the stunning success of the Standard Model, there have been few experimental results with some disagreement with its predictions:

i. excessive beauty production in Z decays [1] (the $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ problem) which has been found end of 1995;
ii. an unexpected mass peak around 105 GeV, in the di-jet mass from the four jet events, found by ALEPH during the 130-136 GeV LEP run at the end of 1995 [2];
iii. the observation of a spectacular event at CDF, containing two electrons and two photons all with high E_t and a large amount of missing transverse energy, found April 1995 [3];
iv. an excess of deep-inelastic e^+p scattering events at HERA, at a domain of Q^2 values not previously explored, found in February 1997 [4].

However with four new measurements the R_b discrepancy has been today much reduced [5].

On the other hand, to better understand the four jet enhancement, from September 29th LEP returned to 130-136 GeV c.m. energy for one week and collected the same amount of data as before.

The new results indicate strongly that the events seen by ALEPH in 1995 were a statistical fluctuation.

The two remaining discrepancies still alive, triggered great theoretical interest in the possibility that either supersymmetric or leptoquark models might be playing a role.

Therefore in the following I will concentrate on searches for Higgs, supersymmetric particles and leptoquarks. For sure some of the issues that I leave out would have deserved a better treatment.

It is worth noticing that new results at large Q^2 values from HERA have been

[1)] The 183 GeV data were in fact taken after the Conference, in the second half of 1997. Only results based on 130-172 data will be given here.

presented at this Conference and can be found in the proceedings [6]. In this review I will not discuss the HERA excess but rather describe the TEVATRON and LEP searches, motivated by the HERA results, within the contest of leptoquark models. Interpretations in the context of contact interactions and SUSY parity violation processes can be found in the Conference proceedings [7].

I will then end this review with prospects for future searches at the colliders and a summary of the most relevant achievements.

2 Higgs Bosons

The electroweak symmetry breaking requires the existence of a Higgs boson which gives mass to the gauge bosons and fermions. In the SM there is one neutral scalar Higgs boson [8]. In extensions to the SM with two Higgs doublets [9], there are five Higgs, two of which are charged scalars ($H^{\pm}$), two neutral scalars (h and H) and one a neutral pseudoscalar (A).

2.1 The Standard Model Higgs Boson

The SM Higgs searches have so far been hopeless at HERA and the TEVATRON mainly due to small cross sections and/or huge QCD backgrounds. Therefore LEP is the only place where these searches can be conducted today.
At LEP2 the dominant production mechanism is the Higgsstrahlung process $e^+e^- \to HZ$ with an on-shell Z boson and with a cross section up to 1 pb for 70 GeV Higgs mass.
Depending on the H and Z decay modes, HZ production leads to various topologies of which three are the most important :

- 4 jets, when both H and Z decay into hadrons, 70% of the cases;
- acoplanar jets plus missing energy, when H goes to hadrons and Z goes to $\nu\bar{\nu}$, 20% of the cases;
- two isolated energetic leptons plus hadrons when H goes to hadrons and Z goes to l^+l^-, 6% of the cases.

A crucial feature is the large decay branching ratio of the Higgs into $b\bar{b}$, 85%. The tagging of the b is therefore vital and a big effort has been invested by the LEP experiments in increasing their sensitivity with sophisticated b-tagging methods. For a purity of 80%, efficiencies bigger than 80% have been reached.

A number of important differences between the situation at LEP2 and at the Z peak, LEP1, are worth noticing :

i. the Z boson is produced on-shell, while it was highly virtual at LEP1. This additional mass constraint allows bigger discriminating power against the background;
ii. the 4 jets topology had not been considered at LEP1 because of the overwhelming background from hadronic Z decays, with a signal to background ratio of 10^{-6}. At LEP2 on the contrary, this ratio is of order 10^{-2}, which makes worthwhile to search in this channel;
iii. besides the $q\bar{q}\gamma$ background ($\sigma = 100$ pb), WW ($\sigma = 12$ pb) and ZZ ($\sigma = 0.4$ pb) events are the most important new backgrounds.

Typically, efficiencies of about 30% are achieved for a background expectation of one event. No signal has been observed and when the results of the four LEP experiments are combined, a 95% c.l. lower limit of 77.5 GeV is obtained [10].

2.2 Non Minimal Higgs bosons

The predictions of the two Higgs doublet models depend on the parameters $\tan\beta$, which is the ratio of the vacuum expectation values of the two Higgs doublets, the mass of the charged Higgs ($M_{H^\pm}$) and the quark top mass.
In these models , H^+ is predicted to decay predominantly to either $\tau\nu$ or $c\bar{s}$.

At LEP2, DELPHI excludes at 95% C.L. H^+ masses below 54.5 GeV independently of $\tan\beta$ [11].
If $M_{H^\pm} < M_t - M_b$, then the top quark can decay to H^+b which competes with the SM decay mode W^+b.
CDF searches for $p\bar{p} \to t\bar{t}$ with at least one top decaying in to H^+b, directly for large values of $\tan\beta$ ($\tan\beta > 10$), where $H^+ \to \tau\nu$, and indirectly for small values of $\tan\beta$ ($\tan\beta \leq 1$) where $H^+ \to c\bar{s}$ [12]. The direct search is performed by selecting those events with a hadronically decaying τ, two jets (one of which must be b-tagged) and a fourth object which can be either an electron, muon, another hadronically decaying τ, or a third jet. There must be large missing E_t, reflecting the presence of energetic neutrinos.

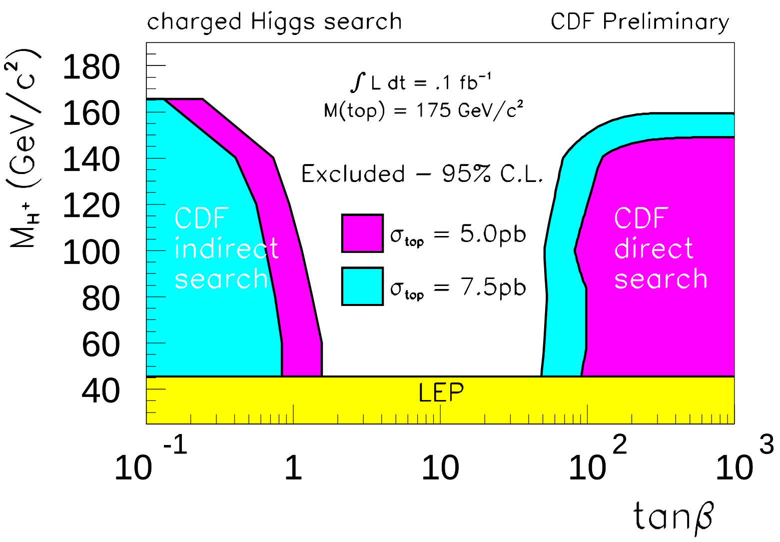


Figure 1: CDF $H^\pm$ mass limit as a function of $\tan\beta$ for the direct and indirect searches and for two assumed $\sigma_{t\bar{t}}$.

This selects 7 events from 109 pb^{-1}. The dominant background is from $W + jets$ events in which the hadronic jets fluctuate to fake a hadronically decaying tau.
The total expected backgrounds are 7.4 ± 2.0 events which is consistent with the observed number. Also for the indirect search the number of observed events is consistent with SM expectations.

Figure 1 shows the $H^\pm$ mass limit as a function of $\tan\beta$, for $M_t = 175$ GeV both for the direct and indirect searches. At large values of $\tan\beta$, $M_{H^\pm} < 158$ GeV is excluded for $\sigma(t\bar{t}) = 7.5$ pb.

In a more specific model like the Minimal Supersymmetric extension of the Standard Model (MSSM), the $H^\pm$ and H are predicted to be too heavy for LEP2.
The LEP analyses within this model are consequently restricted to search for the lighter Higgs boson h and A which can be produced by two complementary processes, the Higgsstrahlung process $e^+e^- \to hZ$, with a cross section proportional to $\sin^2(\beta - \alpha)$, where α is the mixing angle in the CP-even sector, and the associated pair production $e^+e^- \to hA$,

with cross section proportional to $\cos^2(\beta - \alpha)$.
The cross section for $M_A = 70$ GeV is 0.3 pb. Again a crucial feature is the large decay branching ratio of h and A into $b\bar{b}$, $B.R.(hA \to b\bar{b}b\bar{b}) = 85\%$.

No candidate events are found and 95% C.L. lower limit on the masses of $M_h > 62.5$ (59.5) GeV and $M_A > 62.5$ (51.0) GeV for $\tan\beta > 1$ are found by ALEPH (DELPHI) [13]. Finally, figure 2 presents the DELPHI exclusion regions in the (M_h, M_A) plane.

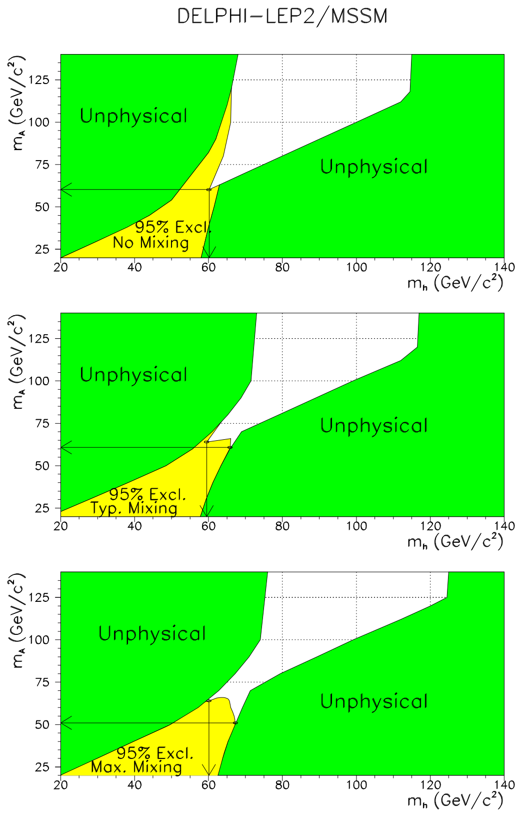


Figure 2: DELPHI regions in the (M_h, M_A) plane excluded at the 95% C.L. by the results of the searches in the hZ and hA channels. Three different hypotheses for the mixing in the stop sector are presented. The regions not allowed by the MSSM model for $m_{\tilde{q}} = 1$ TeV are in the dark grey.

3 Supersymmetry

Supersymmetry is the most widely studied extension of the SM which introduces a symmetry between bosons and fermions [14]. This symmetry results in a doubling of the number of particles, much like the one seen, once before, when anti-matter was discovered in the 1930's.
The super-partner has spin which differs by 1/2 from its SM partner but it otherwise has the same quantum numbers.
Ordinary and supersymmetric particles are distinguished by their R-parity, a multiplicative quantum number, which is assumed to be conserved to ensure lepton and baryon number conservation. The R-parity violation scenario [15] will not be addressed in this report.
As a consequence, supersymmetric particles are produced in pairs and decay to the Light-

est Supersymmetric Particle (LSP), which is weakly interacting and escapes detection. Thus missing energy is the "footprint of SUSY".

Besides the many theoretical desirable features, SUSY models have to deal with a large number of free parameters. In the MSSM, which is the minimal supersymmetric extension of the SM, in addition to the Higgs sector described in section 2, the partners of the photon, Z and neutral Higgs bosons mix to form four mass eigenstates called neutralinos, $\chi_1^\circ, \chi_2^\circ, \chi_3^\circ$ and χ_4° in order of increasing masses.
Similarly, charged Gauginos and Higgsinos form charginos, $\chi_1^\pm$ and $\chi_2^\pm$. This sector, the Gaugino Higgsino sector, is parametrized by the four parameters $\tan\beta$, the gaugino masses M_1 and M_2 and the supersymmetric Higgs mass term μ. Moreover the scalar sector is parametrized by many mass parameters.

In the limit of exact SUSY, the masses of particles and their supersymmetric partners would be equal. However, the negative experimental results from the colliders tell us that SUSY must be badly broken. Different SUSY breaking leads to different models. In the following I just summarize the main consequences of two of such models.

In the Gravity Mediated Models [16], the gravitino, the super partner of the graviton, is heavy and neutralino χ_1°, or s-neutrino $\tilde{\nu}$, is the LSP (the neutralino LSP scenario).
Under gaugino masses unification at GUT scale, the neutralinos and charginos masses only depend on the three parameters $\tan\beta$, μ and $m_{1/2}$, the common gaugino mass parameter. Furthermore, under scalar masses unification at GUT scale, the sfermion masses only depend on the three parameters $\tan\beta$, $m_{1/2}$ and m_0, the common scalar mass parameter.

Alternatively there are SUSY models which postulate that the LSP is the gravitino (the gravitino LSP scenario).

In these models the χ_1° decays to an essentially massless gravitino ($M_{\tilde{G}} < 1$ MeV) and a photon with a 100% branching ratio. Examples include the "No-Scale Supergravity" (LNZ model) [17] and models with Gauge Mediated Supersymmetry Breaking (GMSB) [18].

A variety of searches for SUSY particles have been performed at HERA, LEP and TEVATRON colliders. In the first subsection I will sketch the experimental strategy which addresses the key issues of the searches. I will then present, as example, only the chargino and neutralino cases. In the second subsection the interpretations of the results in the MSSM model are given and in the third subsection I will discuss searches for SUSY particles with photons plus missing energy.

3.1 SUSY Searches in the Neutralino LSP Scenario

The large variety of SUSY processes arrange themselves in a few clear topologies as shown in figure 3 for the LEP case.

The main experimental challenge is given by the fact that the visible energy, the charged multiplicity, the missing P_t and others experimental observables are dependent on the mass difference between the sparticle and the LSP ($\Delta M = M_{sp} - M_{LSP}$).
Therefore the trigger and selection efficiencies are mostly dependent on ΔM. Below 10 GeV of ΔM, the decrease in multiplicity and visible energy produces an important loss for both trigger and selection efficiencies.

The experimental strategy is therefore to perform different analyses for the different topologies at different ΔM ranges. This is shown in figure 4 which gives the ALEPH selection efficiency as a function of ΔM for the chargino search [19].
For small ΔM the main background comes from $\gamma\gamma$ interactions, while for very large ΔM the signal resembles W pair production.

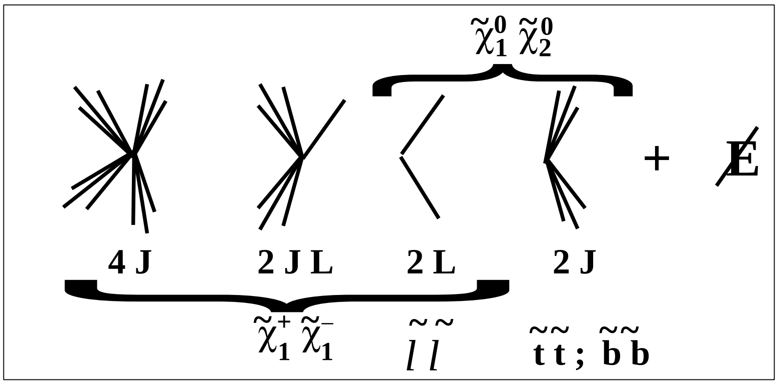


Figure 3: Topologies of SUSY processes at LEP.

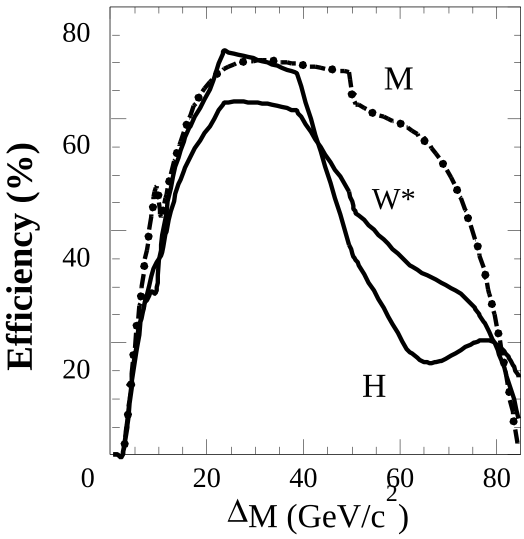


Figure 4: Chargino efficiency for the ALEPH chargino selections as a function of ΔM, for $M_{\chi_1^\pm} = 85$ GeV, at $\sqrt{s} = 172$ GeV . Efficiencies are plotted for mixed (M), hadronic (H) and combined, assuming W branching ratios (W^*), selections.

In both cases we have a big loss of efficiency due to tighter cuts needed to cope with these two particular backgrounds.

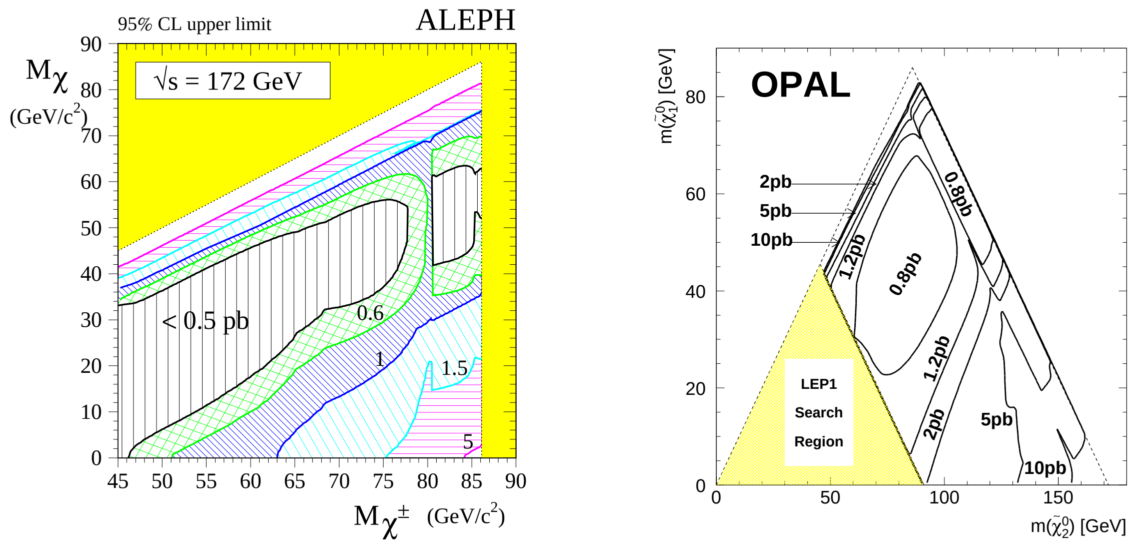
At LEP2, charginos are pair produced by virtual photon or Z exchange in the s-channel, and sneutrino exchange in the t-channel. The s and t channels interfere destructively, so that low sneutrino masses lead to smaller cross sections with values from 0.2 to 10.0 pb.

Neutralinos are produced by s-channel Z exchange and t-channel selectron exchange. Here the s and t channels interfere constructively for most of the parameter space. As a consequence, cross sections are usually higher if selectrons are light with cross sections from 0.2 to 5.0 pb.

Moreover charginos decay to a neutralino and a lepton-neutrino or $q\bar{q}$ pair. If all sfermions are heavy (large m_0), the decay proceeds mainly through the exchange of a virtual W. The second lightest neutralino χ_2° decays to a neutralino and a fermion-antifermion pair. Again if all sfermions are heavy, the decay proceeds mainly through the exchange of a virtual Z.

On the contrary when sleptons are light, leptonic chargino and neutralino decays are enhanced. Therefore the results are separately presented for the two scenario of heavy and light sleptons.
No signal was detected above background in any of the LEP searches.

In the specific case of large slepton masses, upper limits on sparticle production cross sections can be derived in a fairly model independent way.



(a) (b)

Figure 5: (a) the ALEPH 95% C.L. upper limit on the cross section for chargino pair production, in the $(M_{\chi_1^\pm}, M_{\chi_1^\circ})$ plane; (b) the OPAL 95% C.L. upper limit on the cross section for neutralino pair production, in the $(M_{\chi_2^\circ}, M_{\chi_1^\circ})$ plane.

Figure 5 (a) shows the ALEPH 95% C.L. upper limit on the cross section for the chargino pair production in the $(M_{\chi_1^\pm}, M_{\chi_1^\circ})$ plane [19]. Figure 5 (b) shows the OPAL 95% C.L. upper limit on the cross section for $\chi_2^\circ\chi_1^\circ$ production in the $(M_{\chi_2^\circ}, M_{\chi_1^\circ})$ plane [20]. Similar plots are also presented for the sleptons, sbottom and stop and also from DELPHI and L3 [21].

At the TEVATRON both CDF and D0 have searched for direct production of chargino neutralino pairs with subsequent decays of the chargino and neutralino into leptons which gives an experimentally very clean signature of trilepton topology. This comes from $p\bar{p} \to \chi_1^\pm \chi_2^\circ \to l^\pm \nu \chi_1^\circ l^+ l^- \chi_1^\circ$ [22].

Both experiments have used the electron and muon data with tight cuts on the missing E_t of the leptons and mass cuts around the Z, J/ψ and Υ to remove SM events. No events are selected and the D0 cross section limit is presented in figure 6.

The TEVATRON, with its hadron beams and large center of mass energy, is also ideally suited to search for the strongly interacting squarks and gluinos.
This is done by CDF and D0 searching for multijet plus missing E_t [23]. Again no signal has been found.

The SUSY search in ep collisions at HERA, with the presence of a lepton and quark in the initial state, complements those made in the other two colliders. Preliminary results on selectrons and squarks have been presented by H1 and ZEUS from acoplanar electron-jet plus missing energy events [24]. No signal was observed and preliminary exclusion limits on selectron-squark production were derived at 95% confidence level.

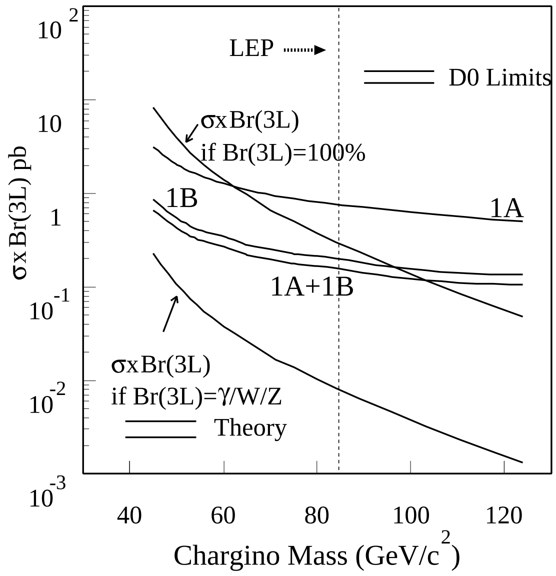


Figure 6: D0 cross section limits on $\chi_1^{\pm}\chi_2^{\circ}$ production. $1A + 1B$ is the limit from the 1992-1995 data.

3.2 Interpretation in the MSSM

The cross section limits previously shown can be translated into exclusion region in the MSSM parameter space. Chargino and neutralino masses and cross sections are determined by the parameters μ and M_2, for given values of $\tan\beta$ and m_0.

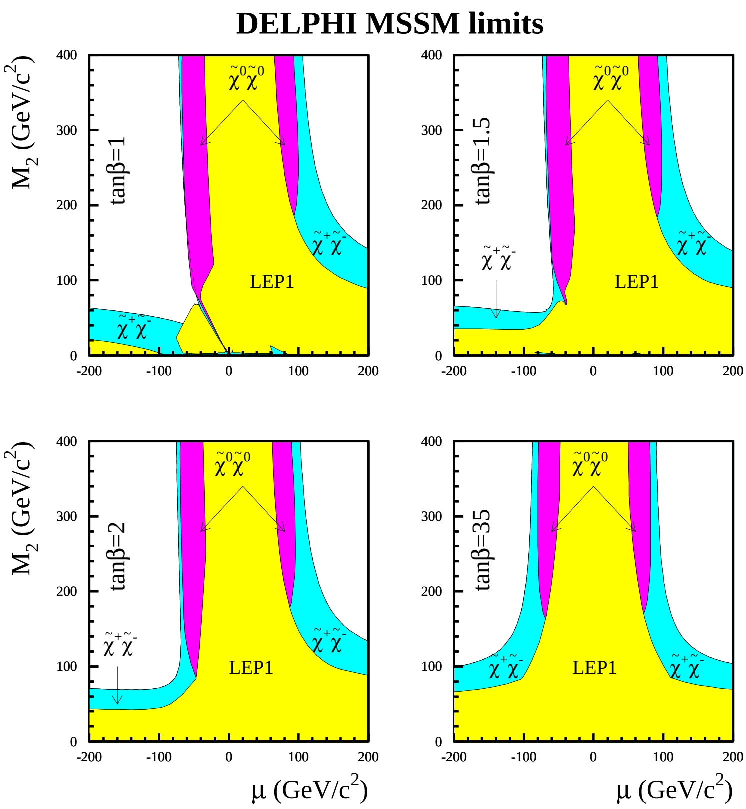


Figure 7: Regions in the (μ, M_2) plane excluded at the 95% C.L. for different values of $\tan\beta$ assuming $m_0 = 1$ TeV.

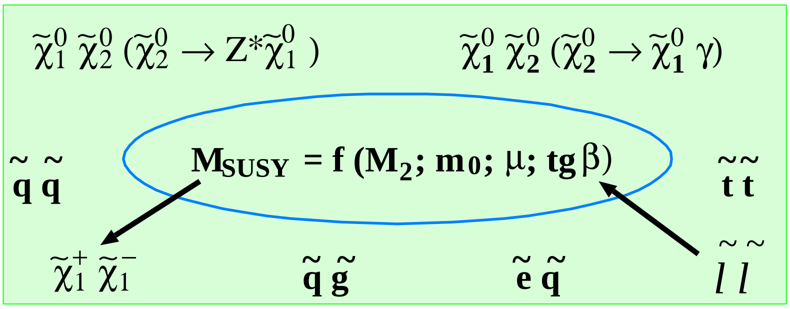


Figure 8: Sketch of the mass dependence on SUSY parameters.

DELPHI limits on the production of charginos and neutralinos constrain these parameters, as depicted in figure 7 for the given values of $\tan\beta$ and $m_0 = 1$ TeV [25].
The remaining holes in that plane are possibly filled with the interplay of all the reactions using their mass dependence on SUSY parameters as sketched in figure 8. We can thus exclude mass values even beyond the kinematical limits.

Figure 9 (a) shows the ALEPH limit on the chargino mass as a function of sneutrino mass [19]. For light sneutrino, as noticed above, when the mass difference is too small, no exclusion is obtained. Here the limit from the slepton search excludes the region where no limit can be obtained from the chargino search.

Much in the same way, indirect lower limits on the mass of the lightest neutralino are derived from the LEP experiment. Figure 9 (b) shows the ALEPH lower limit as a function of $\tan\beta$ for a series of m_0 values.
A lower limit of 14 GeV valid for all $\tan\beta$ and sneutrino masses is obtained [26]. It is worth noticing that this result relies on the assumption of universal gauge fermion and slepton masses. The LSP neutralino is a viable candidate for dark matter and the new limit is almost twice as high as before.

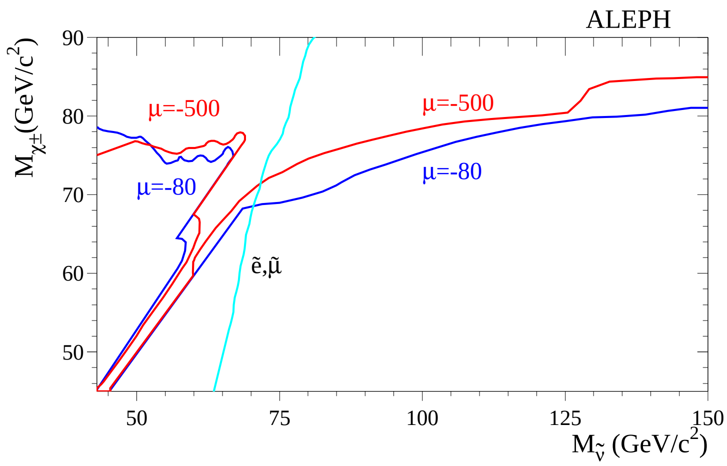
To summarize, SUSY mass limits for all the direct searches are fairly close to the kinematical limits. The chargino mass limit is already above the W mass value, slepton, sbottom and stop mass limits go from 50 to 70 GeV and squarks and gluino masses, as measured at CDF and D0, when equal, are heavier than 260 GeV, which is the D0 lower mass limit.

3.3 Search for single and diphoton events plus missing energy

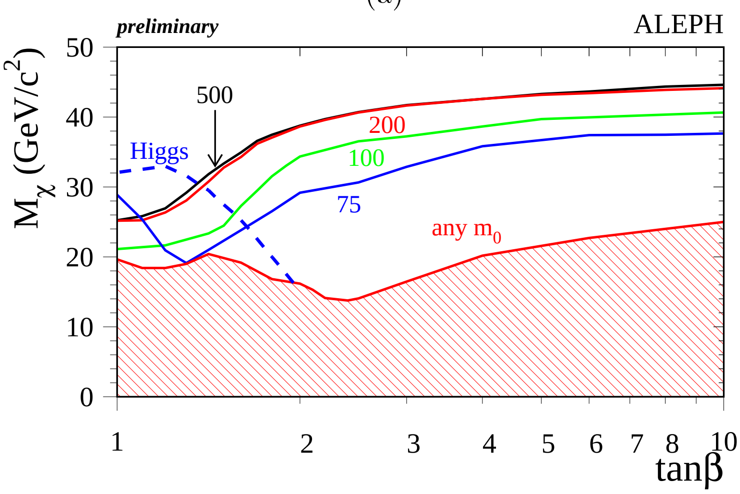
It was already pointed out as early as 1985 [27], that in certain regions of the SUSY parameters space, the next to lightest supersymmetric particle can decay radiatively to the LSP.
Interest in such a scenario rekindled following the observation by CDF of the event, shown in figure 10 and already discussed in the introduction, which can be accommodated by the SUSY models mentioned above.

In the neutralino LSP scenario the event could be explained by the Drell-Yan process $q\bar{q} \to \tilde{e}\tilde{\bar{e}} \to e^+e^-\chi_2^\circ\chi_2^\circ \to e^+e^-\chi_1^\circ\chi_1^\circ\gamma\gamma$ which has a sizeable branching fraction in a corner of MSSM parameter.
In the Gravitino LSP models, the CDF event could be explained by $q\bar{q} \to \tilde{e}\tilde{\bar{e}} \to e^+e^-\chi_1^\circ\chi_1^\circ \to e^+e^-\tilde{G}\tilde{G}\gamma\gamma$.

These models also postulate anomalous production of events with large E_t missing and two photons at the TEVATRON collider and single or diphoton events plus missing energy at LEP.



(a)



(b)

Figure 9: (a) The limit on the chargino mass as a function of sneutrino mass in the gaugino region, for $\tan\beta = \sqrt{2}$. The limit from selectron and smuon searches for $\tan\beta = \sqrt{2}$ and $\mu = -80$ GeV is also indicated. (b) Lower limit on the mass of lightest neutralino as a function of $\tan\beta$, for a series of m_0 values. The curve labelled "any m_0" shows the result obtained allowing m_0 to be free.

Both CDF and D0 have undertaken a systematic study of E_t missing distribution in diphoton events [22]. Figure 11 shows the CDF E_t missing distribution of all events having two identified photons, each with $E_t > 25$ GeV, and compared with the distribution from $Z \to e^+e^-$ events, which should have similar biases. Only the event of figure 10 has E_t missing in excess of 30 GeV.
The plot also shows the expectation from one parameter set from the model of Ambrosanio et al. [28] where one would expect many more events. D0 finds similar results.

The four LEP experiments have also searched for anomalous single photon and two photon production and no evidence for it is found [29].
Figures 12 (a) and (b) show the L3 recoil mass distribution for single and multiphoton events in the barrel and barrel+end caps regions [30].

The number of candidate events is 106 when the expected SM $\nu\bar{\nu}\gamma(\gamma)$ one is 101.1. Similar results are presented by ALEPH, DELPHI and OPAL. My conclusion is that the LEP data collected at 161 and 172 GeV show *no* signs of new physics in the photon(s)

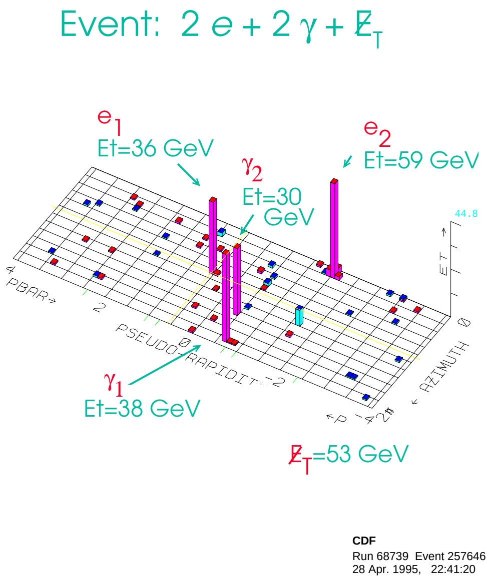


Figure 10: Event display of the $ee\gamma\gamma$ CDF event.

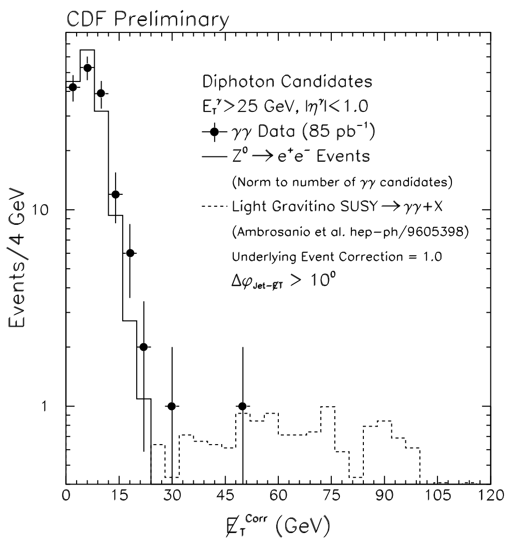
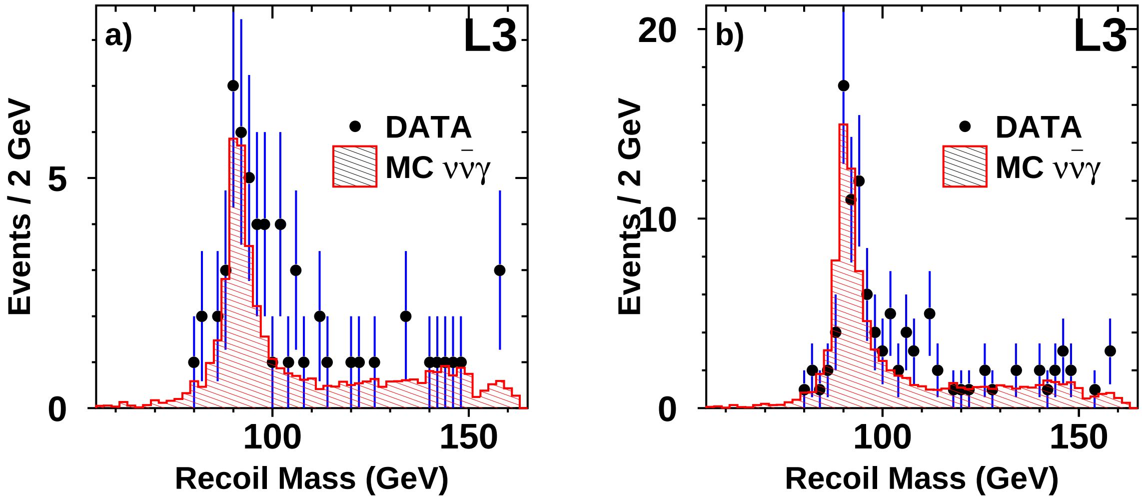


Figure 11: CDF distribution of missing E_t in all events with two final photons.

plus missing energy channels.
The $\nu\bar{\nu}\gamma(\gamma)$ process accounts for the $\gamma(\gamma)$ + missing energy events.

The excluded region for the four LEP experiment [31], in the neutralino, right-selectron mass plane is shown in figure 13. Overlaid is the "CDF region", corresponding to the one in which the properties of the CDF event are compatible with the gravitino LSP process seen above. Three quarters of the CDF region is already excluded at 95% C.L. by the combined LEP results.



(a) (b)

Figure 12: (a) The L3 recoil mass distribution for the single and the multi photon events in the barrel region; (b) the same distribution when the end caps are also included.

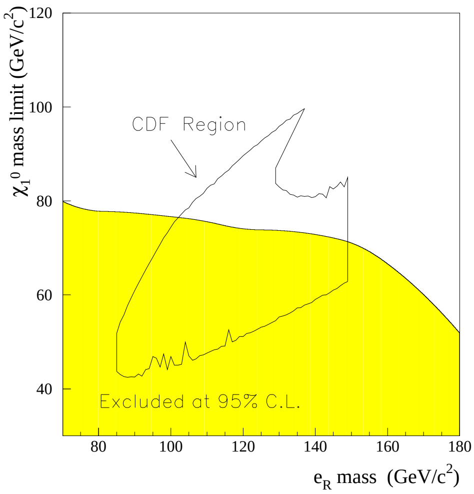


Figure 13: LEP combined exclusion region at the 95% C.L. in the $(M_{\tilde{e}_R}, M_{\chi_1^\circ})$ plane for a pure bino neutralino.

4 Leptoquarks

As mentioned in the introduction, the two HERA experiments H1 and ZEUS have observed an excess of events, in high energy collisions of positrons and protons, having large Q^2 and large x.
These events have an electron and a hadronic jet in the final state, and the invariant mass of the electron-jet system is about 200 GeV.
One of the possible interpretations for these events is the production of a first-generation leptoquark via electron-quark scattering in the s-channel, with the subsequent decay of the leptoquark to an electron and a quark in the final state.

I just recall here that leptoquarks are particles with both lepton and color quantum numbers with fractional charge [32]. They decay, via an unknown coupling λ, to a lepton and a quark.

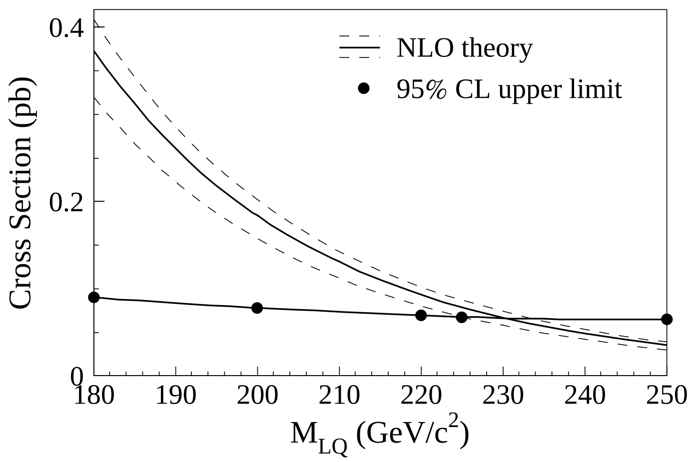


Figure 14: D0 upper limit on the leptoquark pair production cross section for 100% decay to eq.

In $p\bar{p}$ collisions the production of leptoquarks is insensitive to λ, provided $\lambda > 10^{-2}$.

Leptoquarks of one generation couple exclusively to leptons and quarks of the *same* generation. This avoids large Flavour Changing Neutral Current (FCNC) processes already excluded experimentally.

A free parameter is the branching fraction of the leptoquark to charge lepton plus quark, called β. If such a leptoquark exists, it can also be seen at TEVATRON with a cross section of about 0.2 pb at a mass of 200 GeV. At LEP2 we can have either a single production via electron-photon scattering or a t-channel production which induces effects on the total hadronic cross section.

At the TEVATRON both CDF and D0 have performed a search for such events, requiring two electrons and two jets with large transverse energies [33]. The electron-positron invariant mass must not lie in the Z mass range in order to suppress the $Z + jets$ background. In both searches the numbers of events found are in good agreement with the expected ones.
Figure 14 shows the 95% C.L. limit D0 obtains as a result, as a function of the leptoquark mass. This leads to a lower limit on the mass of a first generation leptoquark of 225 GeV with $\beta = 1$. In a similar way CDF finds 210 GeV mass lower limit. For $\beta = 0.5$, D0 in the search $e^{\pm} + \nu + jets$ finds a 95% C.L. mass lower limit of 158 GeV.

At LEP, OPAL [34] made a search for a single leptoquark production in the process $eq \to LQ$, where the leptoquark decays into an electron-quark or a neutrino-quark final state. The initial state quark originates from a hadronic fluctuation of a quasi-real photon which has been radiated by one of the LEP beams. Four candidate events are found in the $e^{\pm} + jets$ decay channel and two in the $\nu + jets$ one, in agreement with the expectations from SM processes.

The expected number of events, for $\lambda = \sqrt{4\pi\alpha_{em}}$ as a function of the mass M of the leptoquark and the 95% C.L. upper limit, taking into account the candidates, the background and the systematic errors, are shown in figure 15. This result implies a lower limit at the 95% C.L. of 131 GeV for both β equal to 1 and 0.5 on the mass of a first generation scalar leptoquark with λ larger than $\sqrt{4\pi\alpha_{em}}$. Limits from t-channel contributions can be found in the Conference proceedings [7].

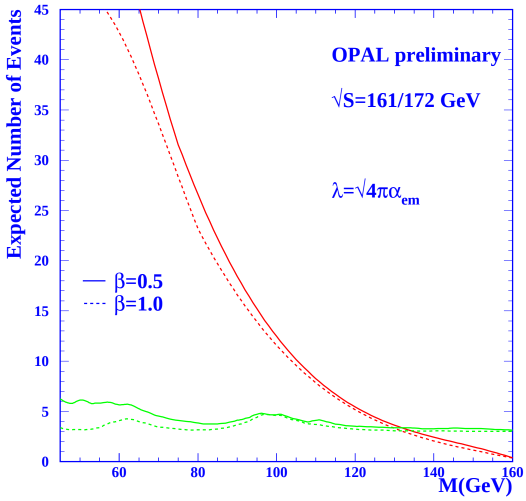


Figure 15: The upper curves show the OPAL expected number of events as a function of the mass M of the leptoquark for $\beta = 0.5$ (continuous curve) and $\beta = 1$ (dashed curve). The lower curves give the 95% C.L. upper limit taking to account the candidates, the backgrounds and the systematic errors.

5 Future Prospects

The future prospects for discovery at HERA will improve as long as the luminosity delivered continues to increase. This year each experiment will collect up to 30 pb^{-1}of integrated luminosity of e^+p collisions.

In 1998-99 HERA will operate with an e^- beam and the goal is to deliver about 50 pb^{-1}per experiment. Moreover HERA will undergo a major luminosity upgrade in the 1999-2000 shut-down, after which each experiment expects to collect a total of 1000 pb^{-1}.

In 1998 LEP should run at 190-192 GeV and collect 100-150 pb^{-1}per experiment. Then in the years 1999 and 2000 the machine could run at 200 GeV and deliver up to 150 pb^{-1}integrated luminosity per experiment. This will be a unique opportunity not only to explore up to 100 GeV mass range SUSY and other new particles, but also to push the Higgs search above 100 GeV and thus cover a mass region very difficult to explore for the future LHC experiments.

Figure 16 shows the luminosity needed per experiment, in pb^{-1}, for a combined 5 sigma discovery at three different center of mass energies [35].

At $\sqrt{s} = 200$ GeV, with 150 pb^{-1}per experiment, the LEP combined 5 sigma discovery potential reaches a SM Higgs mass of 100 GeV, whereas the 95% C.L. mass limit is 106 GeV.

Since this mass range contains the lower limit at which the SM Higgs particle can be searched for at LHC, this 200 GeV limit for the LEP2 energy is crucial for the overlap in the discovery regions of the two accelerators.

Run II for the TEVATRON collider is scheduled to begin in 1999 when both detectors will be significantly upgraded in the silicon vertex sub detector, including the addition of a solenoidal magnetic field to the D0 detector. All these will enhance their sensitivities to tagging b-quark decays, crucial, as already mentioned, in searching for Higgs particles. Both detectors expect to take about 2 fb^{-1} integrated luminosity over a couple of years of running and sensitivities to $\sigma(p\bar{p} \to WH)$ of $O(1)$ pb are expected for intermediate mass Higgs 80-130 GeV.

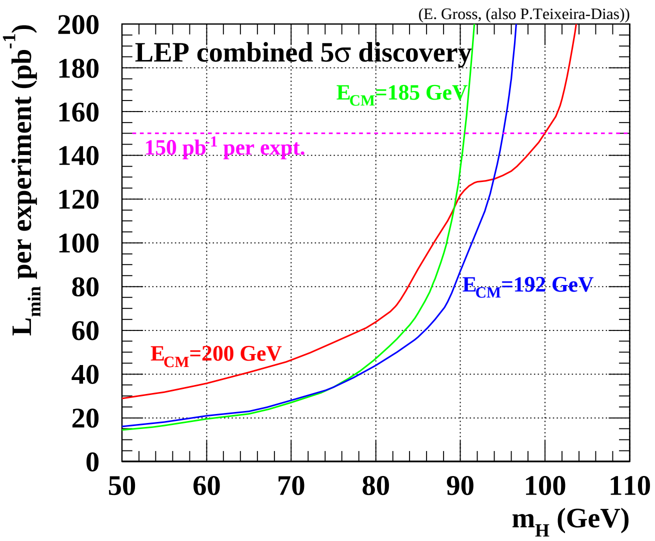


Figure 16: Minimal integrated luminosity needed per LEP experiment, in pb^{-1}, for a combined 5σ discovery as a function of the higgs boson mass for three center of mass energies.

To conclude the new particle searches at HERA, LEP and TEVATRON colliders, promise to be an exciting field in the coming years with very good discovery potential before the LHC turn-on.

6 Conclusions

Although strenuous efforts have been made to uncover chinks in its armour, the SM has so far not even been scratched by the searches at the colliders.

No discoveries: that is no excess of events beyond those expected from background processes are observed.

The standard SUSY searches continue to set new limits close to the kinematical boundary as soon as there is an increase of the center of mass energy.
Today the chargino lower mass limit is beyond the W mass and the neutralino, a good dark matter candidate, has a lower mass limit of 14 GeV for any m_0 and $\tan\beta$ values.
The light gravitino scenario has also been explored and the SUSY interpretation of the CDF event is already excluded in a substantial part of the parameter space by the LEP results.

The SM Higgs boson is heavier than 77.5 GeV, whereas M_h and M_A have a lower mass limit of 62.5 GeV.
Moreover the $H^{\pm}$ mass is nearing the top mass value.

In the leptoquark sector, D0 and CDF results rule out the interpretation of the HERA effect as a first generation leptoquark with $\beta = 1$ and make very unlikely the case with $\beta = 0.5$.

More data are coming and the journey continues.

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