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NEW PARTICLE SEARCHES

J.-F. Grivaz

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Rapporteur talk at the International Europhysics Conference on High Energy Physics, Brussels (Belgium), July 27 - August 2, 1995

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Results on new particle searches from LEP, HERA and the Tevatron are presented. Limits on standard and non-standard Higgs bosons, on supersymmetric particles with and without R-parity conservation, on leptoquarks, on additional leptons, quarks and gauge bosons are reported. In particular, the mass lower limit for the standard model Higgs boson is 65.2 GeV/c^2, it is 173 GeV/c^2 for the gluino and 650 GeV/c^2 for a Z′ with standard model couplings. Events with unexpected topologies were observed at LEP and at the Tevatron.

1 Introduction

The results on new particle searches presented at this conference have been obtained by the experiments installed at the three highest energy machines presently in operation: LEP at CERN, an e^+e^- collider with a centre-of-mass energy of 91.2 GeV, close to the Z mass; HERA at DESY, an asymmetric machine where 27 GeV positrons collide on 820 GeV protons, corresponding to a 300 GeV centre-of-mass energy; and the Tevatron at Fermilab, a $p\bar{p}$ collider with a centre-of-mass energy of 1.8 TeV. Although no energy increase took place at any of these machines recently, substantial luminosity improvements have been achieved, resulting in an enhanced sensitivity for a number of searches: the number of hadronic Z decays collected was almost doubled at LEP in 1994, with up to 3.7 million such events analyzed by a single experiment; at HERA, the luminosity integrated in 1994 was 3.2 pb^{-1}, to be compared to 0.6 pb^{-1} in 1993; and at the Tevatron, while less than 20 pb^{-1} had been accumulated up to 1993, results are now coming, based on the analysis of 70 pb^{-1}.

In the following, all the limits reported are given at the 95% confidence level.

2 The standard model Higgs boson

The search for the standard model Higgs boson is presently performed only at LEP, where the sole relevant production mechanism is the so-called bremsstrahlung process, $e^+e^- \to HZ^* \to Hf\bar{f}$. For Higgs boson masses of current interest, *i.e.* well beyond the $b\bar{b}$ threshold but also well below that for H → WW, the main Higgs boson decay mode is H → hadrons, of which ~ 95% into $b\bar{b}$, with the remaining ~ 9% into $\tau^+\tau^-$. The final state topology further depends on the Z^* decay products. Unfortunately, the $Z^* \to q\bar{q}$ mode, which accounts for ~ 70% of the Z^* decays, cannot be used because of the huge contamination from normal hadronic Z decays. It is also the case for the final states involving $Z^* \to \tau^+\tau^-$ decays, which contribute only ~ 3% and suffer in addition from the $\tau^+\tau^- q\bar{q}$ four-fermion final state background. In the end, the usable contributions come from the $Z^* \to e^+e^-$ and $Z^* \to \mu^+\mu^-$ modes, ~ 7% together, and mostly from the $Z^* \to \nu\bar{\nu}$ mode which accounts for 20% of the final states.

In 1994, Higgs boson mass lower limits were reported at the 60 GeV/c^2 level[1]. With a statistics almost doubled, a substantial improvement could be hoped for. However, for a Higgs boson mass of 65 GeV/c^2, the production cross-section is only 40% of what it is for a mass of 60 GeV/c^2. Therefore, only a few GeV/c^2 increase in the sensitivity range is to be expected.

2.1 Search in the (H → hadrons)($Z^* \to \nu\bar{\nu}$) channel

The main background to the (H → hadrons)($Z^* \to \nu\bar{\nu}$) channel comes from hadronic Z decays with missing energy either real, due to neutrinos from heavy quark decays, or fake, due to jet energy measurement fluctuations. The tools to cope with these backgrounds have been elaborated over the years and comprise typically: a selection of events well contained in the detector; these events should be acollinear, which rejects $q\bar{q}$ final states, and acoplanar, which rejects $q\bar{q}\gamma$ final states where the radiated photon escapes down the beam pipe; and to reject $q\bar{q}g$ final states, requirements on the isolation of the missing momentum and on the event aplanarity are imposed. In addition, detector dependent cuts may be applied to avoid "weak regions" such as the boundaries between calorimeter sub-systems.

To establish their selection methods, the four LEP experiments produce unbiased background Monte Carlo samples of a size similar to or somewhat larger than that of their data; they isolate potentially dangerous configurations and generate samples enriched accordingly and corresponding to an integrated luminosity typically an order of magnitude larger than that of the data. The statistical treatments applied at this point become unexpectedly different:

- OPAL[2] choose a set of classical cuts intended to be tight enough for the analysis to remain unchanged for the whole lifetime of LEP1, and indeed the modifications to the analysis they reported last year are rather minor.

- ALEPH[3] also use a set of cuts, but the cut values for the most critical variables are optimized every year in an automatic way in order to cope with the increase of the absolute background level brought with the additional data. To this end, they use the expectation value $\overline{N}_{95}(x)$ of the 95% CL upper limit on the number of signal events produced, calculated under the assumption of no signal contribution as

$$\overline{N}_{95}(x) = \Sigma_{n\geq 0}\mathcal{P}_{b(x)}(n)\mathcal{L}_{95}(n)/\varepsilon(x)$$

  Here, $\mathcal{P}_{b(x)}(n) = e^{-b(x)}b(x)^n/n!$ is the probability to observe n events, given a background expectation $b(x)$ for a cut location x; $\mathcal{L}_{95}(n)$ is the value of the 95% CL limit set when n events are detected, *i.e.* 3.00 for $n = 0$, 4.74 for $n = 1$, etc...; and $\varepsilon(x)$ is the signal efficiency for the cut location x. As the cut becomes tighter, the background level and the signal efficiency decrease simultaneously, and the value chosen is the one which minimizes $\overline{N}_{95}$.

- L3[4] now use a similar method. All cuts are simultaneously tightened in steps, and the optimization is performed on the step number.

- DELPHI[5] aim at casting all the information into a single variable, for instance the output of a neural net or, more recently, of a discriminant analysis, and they cut on this single variable to reduce the background to a given level; they need however to apply additional specific cuts both beforehand and afterwards.

Altogether, 13 million hadronic Z decays were analyzed by the four experiments, with efficiencies ranging from 16 to 31% and mass resolutions from 5 to 10 GeV/c^2, both for a 65 GeV/c^2 Higgs boson. Three candidate events were selected, while five were expected from background processes. The largest of the three candidate masses is[5] (38 ± 8) GeV/c^2.

2.2 *Search in the $(H \to l^+l^-)(Z^* \to \nu\bar{\nu})$ channel*

Here too, a large potential background comes from hadronic Z decays containing leptons from semileptonic heavy quark decays. This background can however be largely reduced by tight requirements on the energies and on the isolations of the two leptons.

Such a reduction does not occur, however, for the background from the process $e^+e^- \to l^+l^-q\bar{q}$, in the configuration where the four-fermion final state results from a Z decay into a high mass $q\bar{q}$ pair which radiates a virtual photon converting into an l^+l^- pair. Indeed, the topology of this background is indistinguishable from that of the signal, but the b-tagging technique fortunately provides an efficient discriminating tool: while most of the hadronic Higgs boson decays are expected to be into $b\bar{b}$, the four-fermion final state is reduced by an order of magnitude not only because only 22% of the hadronic Z decays are into $b\bar{b}$ but also because the emission of the virtual photon is reduced by the square of the electric charge, 1/3, of the b-quark.

In addition, the mass of a Higgs boson candidate can be reconstructed with high accuracy, better than 1 GeV/c^2 at 65 GeV/c^2, as the mass of the system recoiling against the lepton pair. As a result, any candidate event will contribute only within a restricted mass domain.

For masses in excess of 40 GeV/c^2, nine events are selected in 11 million hadronic Z decays[3,4,5] (OPAL did not analyse their 1994 data for this channel). This is somewhat on the low side compared to the expectation of fifteen events from background processes, but the uncertainty on this prediction is rather large, especially because of the poorly known QCD corrections to the four-fermion final state production. There is no particular mass accumulation among the nine candidate events.

2.3 *Higgs boson mass limits*

The limits reported by the four LEP experiments[2,3,4,5] are given in Table 1.

Table 1: 95% CL lower limits reported by the four LEP collaborations for the mass of the standard model Higgs boson, in GeV/c^2.

Experiment	ALEPH	DELPHI	L3	OPAL
Mass limit	63.1	55.4	60.2	59.1

The most straightforward way to determine whether a given Higgs boson mass is excluded by the four experiments considered simultaneously would be to simply add the numbers of signal events expected to be found in all three channels ($H\nu\bar{\nu}$, $H\mu^+\mu^-$ and He^+e^-) by all four experiments and to compare it with the number of candidate events reported contributing at that mass value (for instance, one could consider only those candidates lying within two standard deviations, and reduce the number of events expected by 5% accordingly). With such a method, a limit of about 65 GeV/c^2 would be set, with one candidate event contributing in that mass region.

This method can be criticized however because it does not result from the application of a well defined *a priori* prescription. For instance, while all collaborations unanimously decided long ago not to use the $Z^* \to q\bar{q}$

decays, they chose only progressively and not simultaneously to stop using the $H \to \tau^+\tau^-$ decays. Implicitly, the basis for such choices is that channels which bring too much background for too little added efficiency should not be used. This can be turned into a quantitative statement using the variable $\overline{N}_{95}$ defined previously[6]: given a set of analyses, each with its efficiency, its expected background level and its mass resolution, the subset to be chosen is the one which minimizes $\overline{N}_{95}$. With this prescription, it turns out that, out of the twelve analyses reported (three channels times four experiments), four should be removed from the combination. The result of this procedure is shown in Fig.1, where the mass information for the candidate events in the eight remaining analyses has been treated as advocated in Ref. 7. The resulting 95% CL lower limit for the mass of the standard model Higgs boson is 65.2 GeV/c^2.

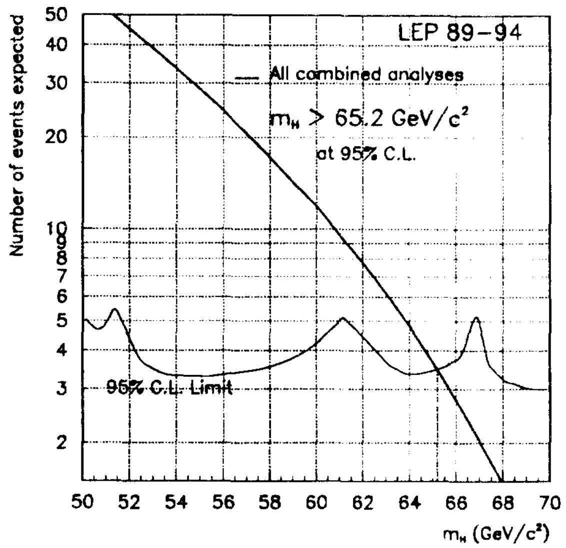

Figure 1: Number of events expected and 95% CL upper limit on the number of observed events in the eight selected analyses.

3 Non standard Higgs bosons

3.1 Search for $Z \to H\gamma$

In the standard model, the process $Z \to H\gamma$, which proceeds mainly *via* top quark and W boson loops, occurs with a rate far too low to be worth consideration, especially in view of the huge background from final state radiation in hadronic Z decays. This rate may however be enhanced in some extensions of the standard model, usually involving anomalous couplings, hence the analyses reported by DELPHI[8] and by OPAL[9]. Isolated energetic photons are selected in hadronic events, and a peak is looked for in the photon energy spectrum above the final state radiation continuum. As in the case of the Hl^+l^- final state, the search sensitivity is enhanced by an order of magnitude when b-tagging is applied. Decay rates thirty times larger than the standard model predictions are thus excluded for Higgs masses around 50 GeV/c^2.

3.2 Higgs bosons in the MSSM

In the minimal supersymmetric extension of the standard model, the MSSM, the neutral Higgs sector contains, as in any two-doublet model, two CP-even bosons, h and H with $m_h < m_H$, and one CP-odd boson, A. Their couplings are controlled by α, the mixing angle in the CP-even sector, and by $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs fields. At the tree level, the Higgs boson masses and the angles α and β can all be calculated from only two inputs, *e.g.* m_A and $\tan\beta$. Additional parameters are however needed in the calculation of the radiative corrections which, because of the large top quark mass, turn out to be quite substantial for the CP-even Higgs bosons. Besides m_t, these parameters are the average scalar top mass, $m_{\tilde{t}}$, and the amount of mixing in the scalar top sector, controlled by the parameters A_t and μ.

The cross-section for the process $e^+e^- \to hZ^*$ is equal to its standard model analogue, up to a reduction factor $\sin^2(\beta-\alpha)$. In addition, a new production mechanism takes place if kinematically allowed, $e^+e^- \to hA$, the cross-section of which is proportional to $\cos^2(\beta-\alpha)$, which renders the two processes complementary. For $\tan\beta > 1$, as theoretically preferred, the main decay modes of h and A are into $\tau^+\tau^-$ and $b\bar{b}$, with branching ratios not much different from those of the standard model Higgs boson. Exceptions arise when the channel $h \to AA$ is kinematically allowed, and then usually dominant, or when decay channels into supersymmetric particles are open, a possibility which will be discussed further down.

Searches for the MSSM Higgs bosons have been reported at this conference by ALEPH[10] and by L3[11]. Both use their most recent results on the standard model Higgs boson[3,4], and in addition updated their searches for $Z \to hA$ decays. For large h and A masses, the kinematic limit is reached using the $\tau^+\tau^- q\bar{q}$ final state which can be made essentially background free by suitable topological cuts. A similar sensitivity was also achieved by ALEPH in the $b\bar{b}b\bar{b}$ final state, using b-tagging in four-jet events. The L3 result is shown in Fig. 2 in the (m_h,m_A) plane for typical top and scalar top mass values, and the ALEPH result in Fig. 3 in the (m_h,$\tan\beta$) plane, with the dependence on the mixing in the scalar top sector also indicated.

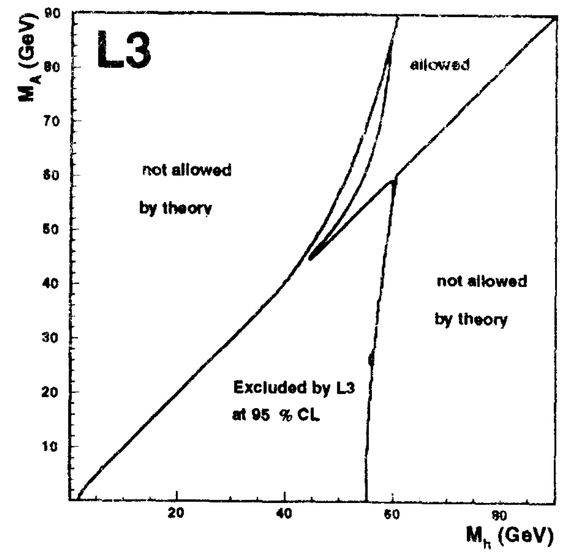

Figure 2: Domain excluded by L3, in the (m_h, m_A) plane and for $\tan\beta > 1$, for $m_t = 176$ GeV/c^2, $m_{\tilde{t}} = 1$ TeV/c^2, and no scalar top mixing.

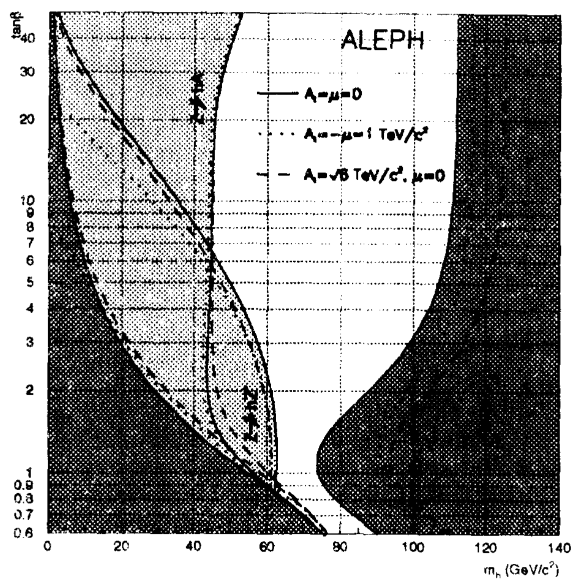

Figure 3: Domain excluded by ALEPH, in the $(m_h, \tan\beta)$ plane, for $m_t = 175$ GeV/c^2 and $m_{\tilde{t}} = 1$ TeV/c^2. The full lines correspond to the case of no scalar top mixing, and the dotted and dashed lines to cases of typical and maximal mixings, respectively.

For large $\tan\beta$, only $Z \to hA$ contributes; the search is then kinematically limited, except when $\tan\beta$ is so large that the h and A widths can no longer be neglected, allowing masses beyond $m_Z/2$ to be probed. The sensitivity at low $\tan\beta$ may still improve somewhat *via* the search for a standard model like Higgs boson in $e^+e^- \to hZ^*$.

3.3 *Invisible Higgs bosons and monojets*

The searches for the standard model Higgs boson are not sensitive to invisible Higgs boson decays. Such decays may occur, and even be dominant, for instance in supersymmetric models if the channel $h \to \chi\chi$ is kinematically accessible (χ is the lightest neutralino, commonly assumed to be the lightest supersymmetric particle), or in majoron models. However, the bremsstrahlung process $e^+e^- \to hZ^*$, with $Z^* \to f\bar{f}$, can still be used in that case if $f\bar{f}$ is an l^+l^- or a $q\bar{q}$ pair, but of course not if it is a $\nu\bar{\nu}$ pair. The topology is similar to the one expected from the production of a standard model Higgs boson with $Z^* \to \nu\bar{\nu}$, and the same analysis can therefore be used, extended to the monojet topology to cope with high mass invisible Higgs bosons and thus with low mass visible systems arising from the Z^* decay.

The result of such an analysis performed by OPAL[2] is shown in Fig. 4. It can be seen that, for a standard model like production cross-section, the excluded mass domain extends to 67.5 GeV/c^2, *i.e.* beyond the limit for the standard model Higgs boson; this is because the $Z^* \to q\bar{q}$ mode, with its large branching ratio, can be used here, in contrast to the case of the standard model Higgs boson search. For very light invisible Higgs bosons, the reduction in the production cross-section is of at least three orders of magnitude with respect to the standard model one. Similar results were also reported by L3[4].

Following their search for monojet events, performed initially in the context of a search for invisibly decaying Higgs bosons, ALEPH reported last year the observation of two unusual events[12]: a 3 GeV/c^2 mass e^+e^- pair and a 5 GeV/c^2 hadronic system, with momenta transverse to the beam axis of 20 and 18 GeV/c, respectively. They proposed an interpretation of these events as due to the process $e^+e^- \to \nu\bar{\nu}f\bar{f}$ which occurs predominantly *via* the so-called conversion diagram $e^+e^- \to Z^*\gamma^*$ with $Z^* \to \nu\bar{\nu}$ and $\gamma^* \to f\bar{f}$. The probability of observing such large transverse momenta was estimated to be at the few percent level. This year, DELPHI[13], L3[14] and OPAL[15,16] presented results from new dedicated searches for monojet events. They all found candidates, but with moderate transverse momenta and in agreement with standard model expectations.

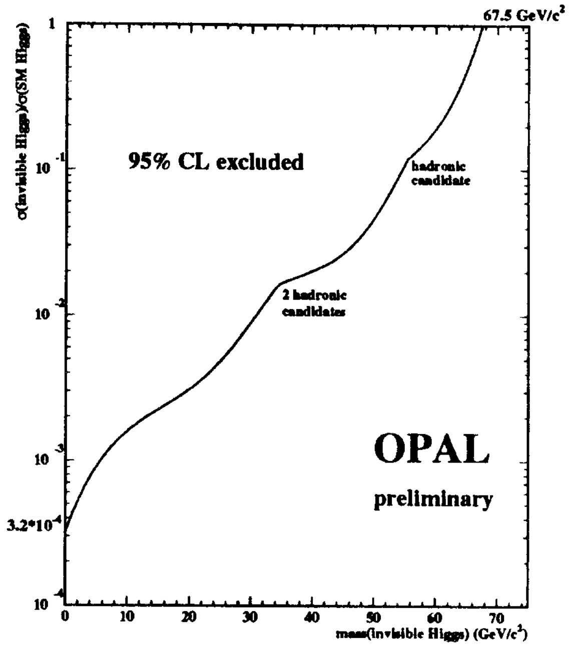

Figure 4: For an invisibly decaying Higgs boson, 95% CL upper limit reported by OPAL for the ratio of the production cross-section to its standard model analogue, as a function of the Higgs boson mass. The cusps correspond to the occurrence of candidate events.

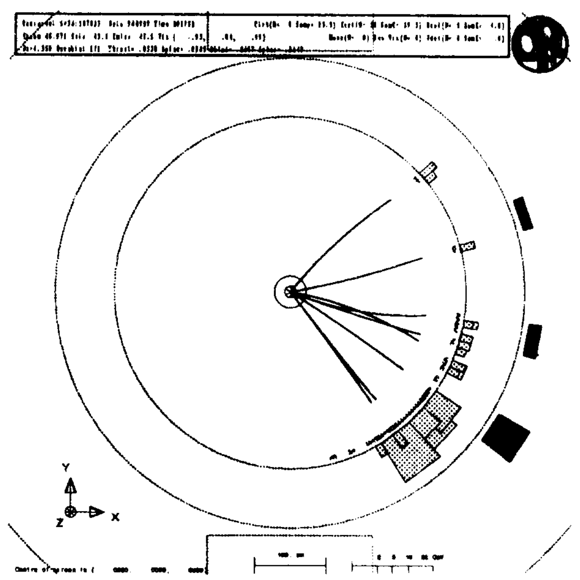

Figure 5: The OPAL monojet event, with unexpectedly large mass and transverse momentum

One highly atypical event was however reported by OPAL[16]. This event, an 18.4 GeV/c^2 mass hadronic system with a 28.3 GeV/c transverse momentum, is displayed in Fig. 5. There is essentially no longitudinal momentum, and the mass of the invisible recoiling system is 50 GeV/c^2. Although they expect about one event within their selection cuts, the probability for such large mass and transverse momentum values is only 2%, and this seemingly large level is obtained only once the W-photon scattering process $e^+e^- \to \bar{\nu}_e \bar{d} u e^-$ is included, with the spectator electron remaining undetected in the beam pipe.

4 Supersymmetric particles

In supersymmetric theories, any ordinary particle, or rather any of its degrees of freedom, has a supersymmetric counterpart of which it differs by half a unit of spin. Each charged lepton or quark thus has two scalar partners called sleptons, $\tilde{l}_R$ and $\tilde{l}_L$, or squarks, $\tilde{q}_R$ and $\tilde{q}_L$; and to each neutrino is associated a sneutrino, $\tilde{\nu}$. The gauge bosons have fermionic partners called gluino, $\tilde{g}$, photino, $\tilde{\gamma}$, wino, $\tilde{W}^\pm$ and zino, $\tilde{Z}$, and the Higgs bosons (two doublets at least are needed) also have fermionic partners called higgsinos. The winos and charged higgsinos mix to form two charginos, the lighter of which is denoted $\chi^\pm$, while the photino, the zino and the neutral higgsinos mix to form at least four neutralinos. In the MSSM, there are only two Higgs doublets and therefore only four neutralinos, denoted χ, χ', χ'' and χ''' in increasing mass order.

The lightest neutralino, χ, is commonly assumed to be the lightest supersymmetric particle, the LSP. It interacts only weakly with ordinary matter and, if R-parity is conserved, it is stable. R-parity, a new multiplicative quantum number which takes the value +1 for ordinary particles and −1 for their superpartners, is assumed to be conserved in the following, except when explicitly stated. By R-parity conservation, supersymmetric particles are produced in pairs and (cascade) decay until the LSP is reached. These stable, neutral, weakly interacting LSPs escape detection, which is at the origin of the celebrated signature of supersymmetry: missing energy.

4.1 Gluinos, squarks and stops

If light enough, squarks and gluinos, which are strongly interacting particles, should be abundantly produced at the Tevatron in reactions such as $p\bar{p} \to \tilde{q}\bar{\tilde{q}}X$, $p\bar{p} \to \tilde{q}\tilde{g}X$, $p\bar{p} \to \tilde{g}\tilde{g}X$. Depending on the mass hierarchy between squarks and gluinos, the subsequent decays will be: *i)* $\tilde{q} \to q\tilde{g}$ and $\tilde{g} \to q\bar{q}(\chi$ or $\chi^\pm$ or $\chi')$, or *ii)* $\tilde{g} \to q\tilde{q}$ and $\tilde{q} \to q(\chi$ or $\chi^\pm$ or $\chi')$. The branching ratios into the various charginos and neutralinos are highly model dependent and are usually calculated within the MSSM for specific parameter choices (in particular for μ, the higgsino mass term, and $\tan\beta$). The same parameters govern the subsequent χ' or $\chi^{\pm}$ decay chains.

By inspection of the squark and gluino decay patterns, it can be seen that the final state should exhibit a substantial number of jets, and also missing energy carried away by the LSPs. Both CDF[17] and D0[18] have updated their limits on squark and gluino production. As an example, the D0 selection requires a missing transverse energy of at least 75 GeV, three jets with a transverse energy in excess of 25 GeV, and no azimuthal correlation between the directions of the missing energy and of the jets. The background from W+jets, with $W \to l\nu$, is reduced by a veto on isolated leptons. The number of events selected in 13.5 pb^{-1} is fourteen, in agreement with expectation from standard model backgrounds. The domain thus excluded in the plane of the squark and gluino masses is shown in Fig. 6, where it is assumed that all but the top squarks are mass degenerate. The sensitivity to gluino pair production in the case of very large squark masses was increased by a complementary search where the requirement on the amount of missing energy is reduced to 65 GeV and that on the jet energies to 20 GeV, but in which at least four jets rather than three are required. Only five events remain, and the gluino mass limit thus obtained is 173 GeV/c^2.

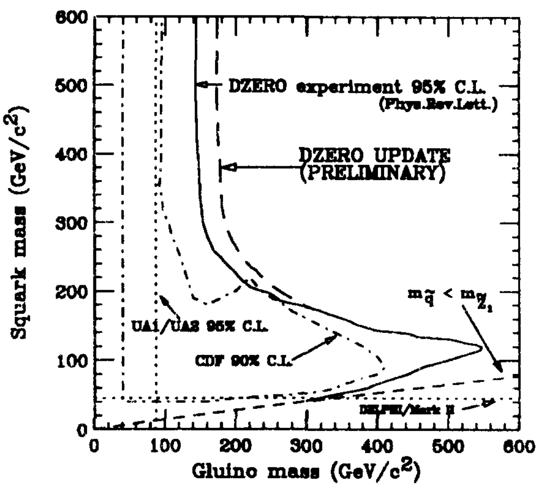

Figure 6: Squark and gluino mass limits obtained by D0. The full line results from the analysis requiring at least three jets, while the long dashed line indicates the improvement achieved when incorporating the analysis requiring at least four jets.

As stated above, these exclusion domains were determined for ten mass degenerate squarks. There are however reasons to believe that a supersymmetric partner of the top quark, dubbed stop, could be significantly lighter than the other squarks. Firstly, even if squark masses are assumed to be equal at unification scale, the stop masses get renormalized differently because of the large top Yukawa coupling, and the stops tend to become lighter in this process than the other squarks. Secondly, the off-diagonal terms in the squark mass matrix are usually neglected with respect to the diagonal terms; this is because they are proportional to the quark mass while the diagonal terms are proportional to the direct renormalized squark masses. This assumption is likely not to be valid in the case of stops because of the large value of the top quark mass, in which case one of the stop mass eigenstates will be significantly lighter than any of the diagonal mass terms. In addition, if the mass of this light stop is smaller than $m_b + m_{\chi^{\pm}}$ and than $m_b + m_W + m_\chi$, its main decay channel will be into $c\chi$ *via* a loop. The final state arising from stop pair production in $p\bar{p}$ collisions will therefore contain two c-jets and missing energy. Since the above described analyses require at least three jets, they are not sensitive to such a topology. A dedicated analysis has therefore been developed by D0[19] to cope with this particular signature, the results of which are shown in Fig. 7. The LEP limit has been somewhat improved to 45 GeV/c^2 by ALEPH[20] recently (not shown in Fig. 7).

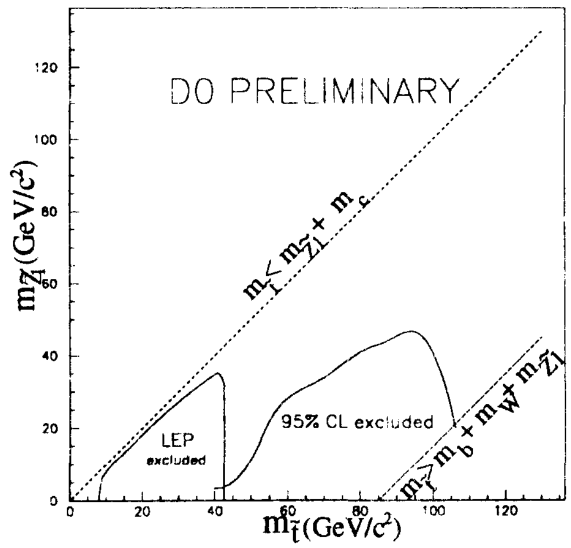

Figure 7: Domain excluded by D0 in the $(m_{\tilde{t}},\, m_\chi)$ plane.

First generation squarks can also be searched at HERA in ep collisions *via* the process $ep \to \tilde{e}\tilde{q}$ where a neutralino is exchanged in the t-channel. The topology of the final state is an acoplanar electron-jet pair and is easy to disentangle from the deep inelastic scattering background. The H1 analysis[21] excludes selectrons and squarks such that the sum of their masses is smaller than 100 GeV/c^2, provided that the exchanged neutralino mass is smaller than 30 GeV/c^2 and that this neutralino is dominantly gaugino-like.

4.2 Charginos and neutralinos

The Z coupling to charginos is large, so that the Z total width measurement at LEP is sufficient to exclude charginos with masses up to $m_Z/2$, irrespective of the model parameters. On the contrary, the couplings of the Z to the various neutralinos strongly vary with these parameters, and may become very small for some choices; for instance, the $Z\chi\chi$ coupling vanishes when χ is a pure photino. It is therefore worthwhile updating the neutralino searches as the number of Z decays collected increases. Results were reported at this conference by OPAL[2] and recently published by L3[22]. The kinematically most favourable decay channel $Z \to \chi\chi$ can be addressed only *via* the invisible Z width measurement. The channels investigated are therefore $Z \to \chi\chi'$ and $Z \to \chi'\chi'$, with subsequent $\chi' \to \chi f\bar{f}$ or $\chi' \to \chi\gamma$ decays. The L3 results are shown in Fig. 8 as excluded domains in the (M_2, μ) plane of the MSSM for two values of $\tan\beta$ (M_2 is the gaugino mass term associated with the $SU(2)_L$ gauge group).

Assuming unification of the gaugino masses, these results can be combined with the D0 gluino mass limit quoted above which basically excludes M_2 values smaller than 49 GeV/c^2. It then results a χ mass lower limit of 20 GeV/c^2.

Charginos and neutralinos have also been searched at the Tevatron where they could be produced *via* the process $q\bar{q} \to W^* \to \chi^+\chi'$. A clear signature arises when both gauginos decay into leptons: $\chi^+ \to \chi l\nu$ and $\chi' \to \chi l^+l^-$. The final state is characterized by three leptons, some missing energy and no jet activity. The results reported last year by CDF, based on 19 pb^{-1}, have not been updated[17]. The chargino mass limit they obtain, 45 GeV/c^2, is similar to that achieved at LEP. However, this limit is calculated within the MSSM and is strongly dependent on some of the model parameters, in particular those which determine the leptonic decay branching ratios of the charginos and neutralinos; the choice they make, $m_{\tilde{q}} = 1.2 m_{\tilde{g}}$, turns out to be quite favourable. Besides, when gaugino mass unification is assumed, the D0 gluino mass limit quoted above translates into a more constraining chargino mass limit, *e.g.* 60 GeV/c^2 for $\tan\beta = 2$, with $\mu = -400$ GeV/c^2 as chosen by CDF. The conclusion is that, at the Tevatron, the direct gluino search is presently more sensitive than the gaugino search *via* the trilepton signature.

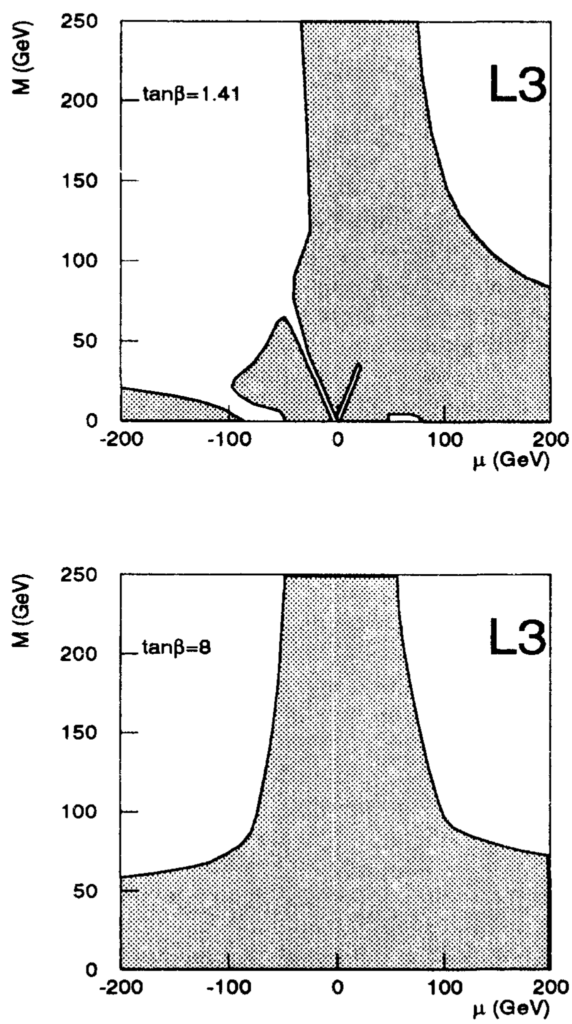

Figure 8: Domains excluded by L3 in the (M_2, μ) plane of the MSSM, for two values of $\tan\beta$, using the full and invisible Z width measurements and direct searches for neutralinos.

4.3 R-parity violation

In the MSSM, the superpotential contains the terms

$$hLH_1\overline{E},\ h'QH_1\overline{D},\ h''QH_2\overline{U}$$

which are responsible for the Yukawa couplings of the Higgs fields to the ordinary fermions, and thus for the fermion masses. In the above expression, the generation indices have been dropped for simplicity. Other terms are however allowed by the general constraints of supersymmetry, renormalizability and gauge invariance, namely

$$\lambda LL\overline{E},\ \lambda' LQ\overline{D},\ \lambda''\overline{U}\overline{D}\overline{D}.$$

In contrast to the MSSM terms, they violate the lepton or baryon numbers and would lead, if simultaneously present, to proton decay at an unacceptable rate. R-parity conservation, with $R = (-1)^{3B-L+2S}$, was introduced to forbid all such terms, but this may be viewed as a somewhat *ad hoc* prescription to which there are alternatives, for instance B-parity conservation which forbids only the $\lambda'' \overline{U}\overline{D}\overline{D}$ terms. When R-parity conservation is not enforced, the phenomenological analysis becomes extremely intricate unless the further assumption is made that one of the R-parity violating couplings dominates over all the others, in a fashion similar to the top Yukawa coupling in the R-parity conserving sector. The main consequence of R-parity violation is that the LSP is no longer stable. For instance, and introducing now the generation indices, a dominant λ_{123} coupling will induce decays such as $\chi \to \tau^- \mu^+ \bar{\nu}_e$, and a dominant λ'_{131} coupling decays such as $\chi \to \mathrm{d}\bar{\mathrm{b}}\bar{\nu}_e$.

A comprehensive search for signals of supersymmetry in Z decays was performed recently by ALEPH[23], under the assumption of a dominant λ-type term. The LSP, assumed to be the lightest neutralino, decays to two charged leptons and a neutrino. The final state signatures therefore become multileptons with moderate missing energy, instead of the usual large missing energy. Slepton, sneutrino and squark pair productions lead to six-lepton, to four-lepton and to four-lepton+two-jet final states, respectively. The associate $\chi\chi'$ production leads to six-lepton or four-lepton+two-jet final states. But the most dramatic change occurs with the LSP pair production, $\mathrm{Z} \to \chi\chi$, which, instead of being addressed only *via* the invisible Z width measurement, can now be detected with four leptons in the final state. The result of these analyses is that all limits on supersymmetric particles are at least as constraining as in the MSSM case. An example is shown in Fig. 9 where the effect of the detectability of the $\chi\chi$ final state is demonstrated.

Resonant production of single supersymmetric particles is also a feature of models with R-parity violation. This has been addressed at HERA where squarks could be produced by positron-quark fusion, *e.g.* $\mathrm{e^+ d} \to \tilde{\mathrm{u}}$ if a λ'_{111} coupling is dominant. If the produced squark subsequently decays *via* the same R-parity coupling, $\tilde{\mathrm{u}} \to \mathrm{e^+ d}$, the final state will exhibit a positron-jet coplanar pair; the deep inelastic scattering background is reduced by the requirement of a high y value, and a peak in the positron-jet mass is then searched over the remaining continuum. If the squark decays to a quark and to the LSP *via* a gauge coupling, $\tilde{\mathrm{u}} \to \mathrm{u}\chi$, the LSP further decays with R-parity violation, $\chi \to \mathrm{e^+ d\bar{u}}$ or $\chi \to \mathrm{e^- \bar{d} u}$; in the latter case, the decay electron has the wrong sign with respect to the beam, which leads to a background free topology. Both signatures have been analysed by H1[24]. Since the R-parity violating coupling is involved in the production mechanism, the squark mass limit depends on the value of that coupling. Results obtained with 3.15 pb^{-1} are shown in Fig. 10 where it can be seen that squark masses up to 240 GeV/c^2 are excluded for $\lambda'^2_{111}/4\pi = \alpha_{em}$.

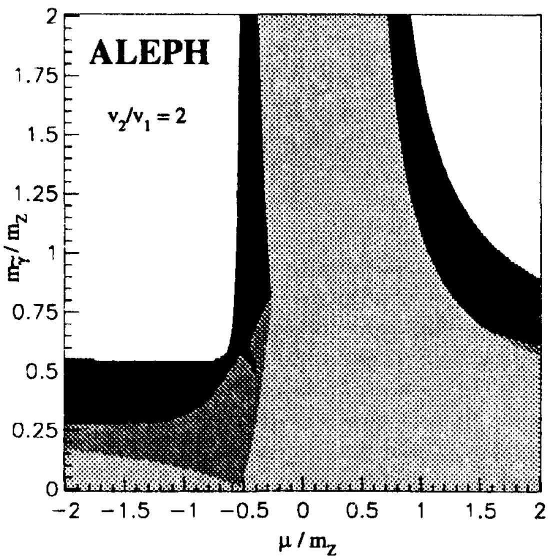

Figure 9: Domain excluded by ALEPH in the ($m_{\tilde{\gamma}}$, μ) plane in the case of R-parity violation with a λ-type coupling: from the Z width measurement (light grey), from the search for neutralinos in the $\mathrm{Z} \to \chi\chi'$ and $\mathrm{Z} \to \chi'\chi'$ modes (heavy grey), and from the search in the $\mathrm{Z} \to \chi\chi$ mode (black).

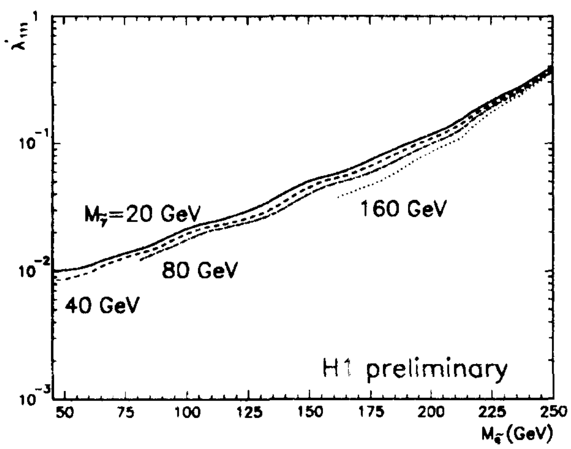

Figure 10: Domain excluded by H1 in the ($m_{\tilde{q}}$, λ'_{111}) plane.

5 Pot pourri of other non-standard particles

5.1 Heavy gauge bosons

Extra Z-like bosons, denoted Z′, are predicted in most extensions of the standard model based on extended gauge groups (but not in the simplest SU(5) GUT). Extra W-like bosons may also occur in such extensions, either of the sequential type, denoted W′, or mediating right-handed currents, denoted W_R. In the latter case, right-handed, and probably heavy, neutrinos are also expected.

Heavy Z′ bosons can be easily detected at the Tevatron through the reactions $q\bar{q} \to Z' \to e^+e^-$ or $\mu^+\mu^-$. They should show up as a peak in the lepton pair mass over the Drell-Yan continuum. A recent CDF[17] analysis, based on 70 pb^{-1}, excludes a Z′ with standard-model like couplings up to 650 GeV/c^2.

If heavy enough, extra W bosons of the sequential type will decay to a W-Z pair. CDF[17] have investigated in 67 pb^{-1} the topology arising from subsequent $W \to e\nu$ and $Z \to q\bar{q}$ decays, namely a high energy electron, substantial missing transverse energy and a pair of energetic jets. The mass reconstructed from these four ingredients should show a jacobian peak at the mass of the W′. The data are compatible with the background from W+jets production, which excludes such an extra W in the range from 205 to 400 GeV/c^2.

Heavy right-handed W bosons have been searched by D0[25] in 13.5 pb^{-1}of data. They look for the decay chain $W_R \to e\nu_R \to eeq\bar{q}$ in two ways. The inclusive electron spectrum should show an excess at high energy, uncorrelated with any significant missing energy, in contrast to the W+jets background. For large ν_R masses, the direct electron becomes too soft, but the complete final state, two electrons and two jets, can be resolved and easily disentangled from the background, mostly due to Z+two-jets production. As can be seen in Fig. 11, a W_R with mass smaller than 500 GeV/c^2 is excluded as long as the associated right handed neutrino mass is smaller than 240 GeV/c^2.

5.2 Isosinglet heavy neutrinos

In many extensions of the standard model, ordinary neutrinos are massive and mix, *e.g via* a see-saw mechanism, with heavy right handed neutrinos. Such isosinglet neutrinos can be produced in Z decays only through their small mixing with ordinary neutrinos. Therefore, associate production of a light and a heavy neutrino is favoured over pair production of heavy neutrinos not only for phase space reasons but also because only one power of the mixing angle is involved in the amplitude. Once produced, the heavy neutrino decays into a neutrino or charged lepton and a fermion pair, with a lifetime also controlled by the mixing angle. Many topologies are therefore to be considered, depending on the decay mode of the heavy neutrino, its mass and its lifetime. For instance, monojets emerging from a vertex detached from the interaction point could occur. DELPHI[13] have performed a comprehensive analysis of all these topologies, the result of which is shown in Fig. 12.

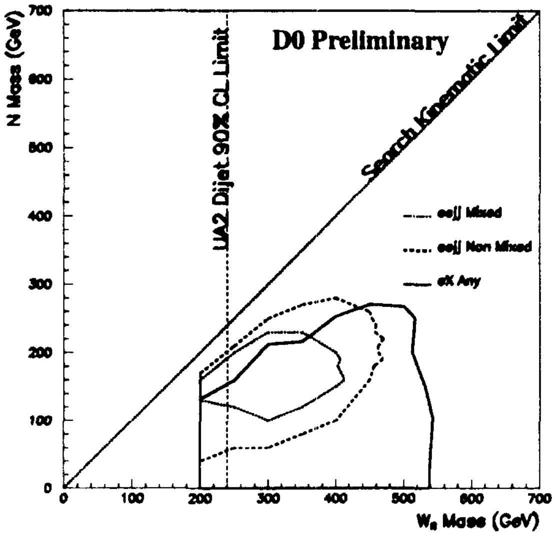

Figure 11: Domain excluded by D0 in the plane of the W_R mass *vs.* the ν_R mass.

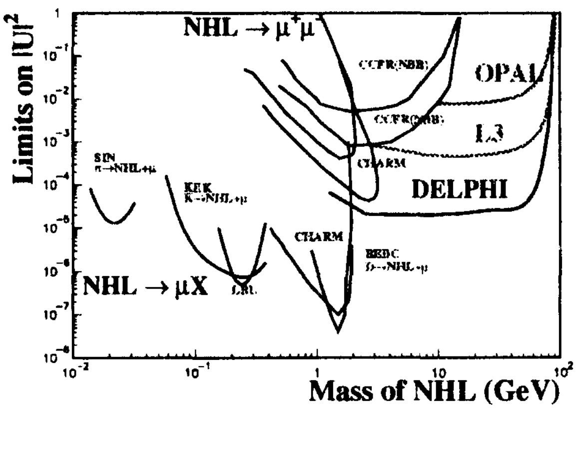

Figure 12: Domains excluded by DELPHI and by other experiments in the plane of the isosinglet neutrino mass *vs.* the square of the mixing angle.

5.3 Leptoquarks

Extended gauge group and compositeness models often predict particles carrying both lepton and baryon numbers, and called leptoquarks. Such leptoquarks decay into a charged lepton or neutrino and a quark, all within a given generation, with model dependent branching ratios.

Being coloured objects, leptoquarks can be abundantly pair produced in $p\bar{p}$ collisions. CDF[17] updated their limits on second generation leptoquarks, using 67 pb^{-1} of data. The signature they considered is the one which arises when both produced leptoquarks decay into a muon and a quark: two muons and two jets, all with transverse energy larger than 20 GeV, and with the muon pair mass not falling near the Z mass. For a branching ratio into μq of 100%, they exclude leptoquark masses smaller than 180 GeV/c^2. The limits obtained for other values of the branching ratio are shown in Fig. 13.

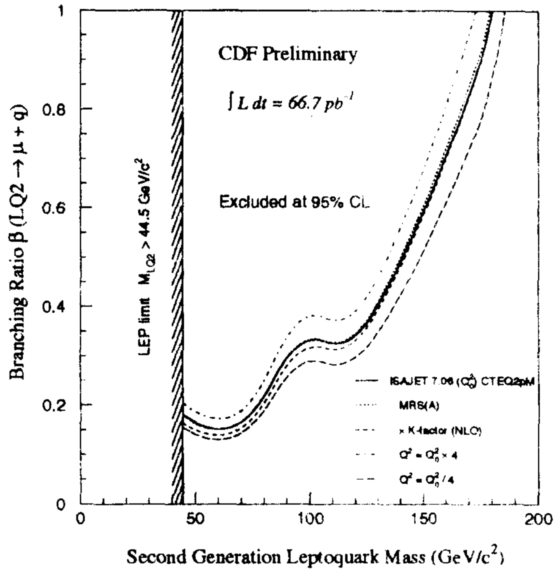

Figure 13: Domain excluded by CDF in the plane of the second generation leptoquark mass *vs.* the branching ratio into a muon and a quark.

Limits on first generation leptoquarks were set by D0[26] who consider not only the case where both leptoquarks decay into an electron and a quark, but also that where one of the two leptoquarks decays into a neutrino and a quark. The latter topology is selected requiring an electron and two jets, all with transverse energy above 20 GeV, a missing transverse energy larger than 40 GeV and a transverse mass of the electron-neutrino system larger than 105 GeV/c^2 in order to remove the W+jets background. With 14 pb^{-1} of data analysed, a mass lower limit of 131 GeV is set if the branching ratio into an electron and a quark is 100%.

First generation leptoquarks can also be produced by electron or positron-quark fusion at HERA. The production mechanism and the decay signatures are very similar to those involved in the search, discussed above, for squarks produced with R-parity violation. The results reported by H1[27] extend the D0 limit on first generation leptoquarks as soon as the coupling at the production vertex is larger than about a tenth of the electromagnetic coupling.

5.4 Excited leptons and quarks, axigluons

Excited leptons and quarks are a common feature of compositeness models. At HERA, excited electrons can be resonantly produced in electron-photon collisions, where the photon is radiated by the proton beam. The excited electron e^* can decay into $e\gamma$ or, if its mass is sufficient, into eZ or νW. The final state topology is then a coplanar $e\gamma$ pair, an electron-jet-jet system or an acoplanar pair of jets with missing transverse energy, where the two jets result from a Z or W decay. These characteristic signatures have been investigated by ZEUS[28] who set improved limits on the compositeness scale as a function of the excited electron mass. H1[29] achieve similar limits in the case of $e^* \to e\gamma$.

Excited quarks could be produced at the Tevatron. Their decay into a quark and a gluon would lead to a peak in the jet-jet mass distribution, at the mass of the excited quark, over the QCD continuum. The level of this continuum can be inferred from a fit to the side bands in order to minimize the theoretical uncertainties. CDF[17] analysed this way 70 pb^{-1} of data, from which they exclude excited quarks with masses up to 600 GeV/c^2. This same analysis allows limits to be set on various objects decaying into two jets, as shown in Fig. 14. For instance, axigluons, a feature of "chiral colour" models where colour-SU(3) is viewed as the diagonal group of $SU(3)_L \times SU(3)_R$, are excluded up to masses of 1 TeV/c^2. This is a rather unexpectedly high value for a limit from a direct search in the pre-LHC era...

6 For the record

A number of results were submitted, which are not discussed in detail here due to lack of time. These include new limits on:

- Lepton flavour violations in Z decays[30];
- Z decays[31] to $\eta\gamma$, $\eta'\gamma$ and $\gamma\gamma\gamma$;
- High mass $\gamma\gamma$ resonances[32] in $e^+e^- \to l^+l^-\gamma\gamma$, $\nu\bar{\nu}\gamma\gamma$, $q\bar{q}\gamma\gamma$;
- Invisible resonances[33] in $e^+e^- \to \gamma X$;

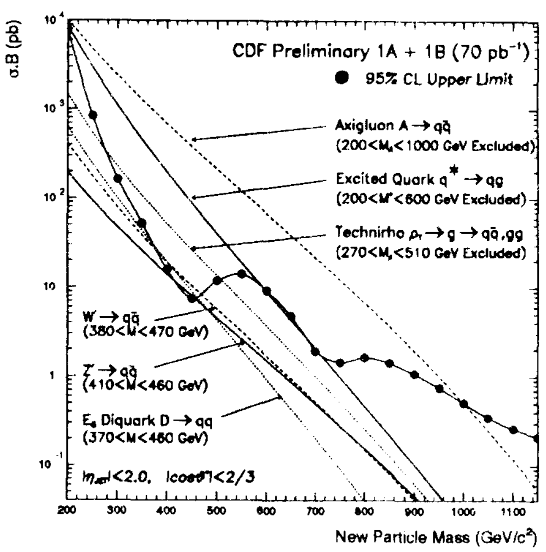

Figure 14: Upper limits obtained by CDF on the cross-sections for various new particles.

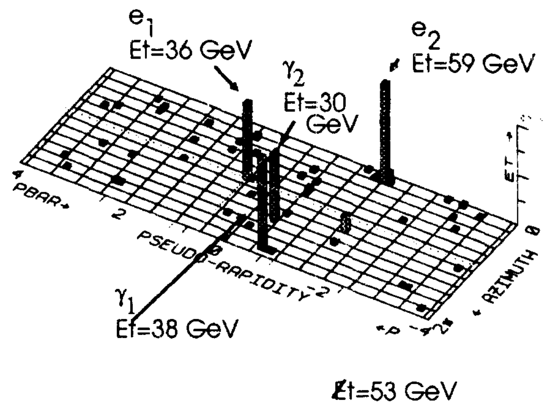

Figure 15: One of the CDF zoo events.

- Fourth generation Dirac neutrinos[34], mixing dominantly with electron-type neutrinos, and produced in $u\bar{d} \to W \to e\nu_4$;
- Excited neutrinos[35] in $Z \to \bar{\nu}\nu^* \to \bar{\nu}\nu\gamma$;
- Particles with anomalous charge in Z decays[36].

Some relevant results were reported in other sessions:

- A contact interaction analysis of deep inelastic scattering in ep collisions by H1[37];
- A search for new particles decaying into $t\bar{t}$ by CDF[38];
- A search for strangelets in Pb-Pb collisions at 158 A GeV/c at the SPS[39].

Finally, two "zoo events" were presented by CDF[17], for which no clear standard model interpretation is available. The first event, shown in Fig. 15, contains two electrons and two photons, all well isolated and with transverse energies in excess of 30 GeV; in addition, there is no jet activity and there are 53 GeV of missing transverse energy. The other event contains three isolated leptons, one muon and two electrons, with transverse energies of 27, 23 and 182 GeV, a jet with an 83 GeV transverse energy, and 106 GeV of missing transverse energy.

7 Outlook

Next year, LEP data collected in Fall '95 at a centre-of-mass energy of 140 GeV should allow chargino masses up to almost 70 GeV to be probed, even with only a few pb^{-1} of integrated luminosity. By the end of Run Ib, both CDF and D0 will have accumulated a wealth of new data, with integrated luminosities well in excess of 100 pb^{-1}, of which all new particle searches should largely benefit. It will be interesting to watch whether the population of the zoo will stabilize or keep increasing.

The forthcoming years will be even more exciting for new particle searches, and in particular for Higgs hunting, with the advent of LEP2 in 1996 and its foreseen energy upgrades up to 192 GeV, and with the main injector coming into operation at Fermilab toward the end of the millenium.

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