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Report of the 1997 LEP2 Working Group on 'Searches'

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Report of the Working Group on 'Searches'

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Abstract. The Searches Working Group discussed a variety of topics relating to present and future measurements of searches at LEP 2. The individual contributions are included separately.

1. Introduction

The 'Searches' working group addressed the prospects for searches for supersymmetry, higgs boson production and leptoquark production at LEP 2. The present status of Higgs searches, SUSY searches and Supergravity were well covered in the plenary talks by P Igo-Kemenes, S Katsanevas and G G Ross in these proceedings.

The working group met together for seminar presentations which set the agenda for the main themes of study. One of the working subgroups subsequently formed to concentrate on the issues of higgs production, where realistic prospects for discovery or for setting mass limits are presented in section 2. Other subgroups addressed prospects for supersymmetry through theoretical studies of radiative corrections to chargino production, section 3, constraints on model parameters arising from colour and charge breaking, section 4, and theoretical issues relating to R-parity non-conservation,

section 5. Also addressed were the experimental prospects for supersymmetry in the contexts of slepton production, section 6 and R-parity violating production of single sneutrinos in section 7. The renewed interest in leptoquark searches was motivated by recent reports from the HERA experiments and a summary is included below, in section 8. The working group contribution is summarised by J Ellis in the final section.

2. Prospective sensitivity of Higgs boson searches at LEP 2 in 1997 and beyond

P Igo-Kemenes, W Murray, A Normand and P Teixeira-Dias

Abstract.

A reassessment of the luminosity and centre-of-mass energy conditions needed to exclude/discover a Higgs boson signal at LEP 2 is presented, both for the neutral Higgs boson predicted in the context of the Standard Model and for the lightest neutral Higgs boson of the Minimal Supersymmetric Standard Model. This reconsideration is based on the results prepared before the start of LEP 2 and on recent studies incorporating more up-to-date knowledge of the performance of the four LEP experiments at LEP 2 energies.

2.1. Introduction

The search for Higgs bosons is one of the major topics being pursued at LEP 2. Since the end of the first phase of LEP, which operated from 1989 to 1995 at energies around the Z resonance, the collider has run at centre-of-mass energies of 130–136, 161 and 172 GeV.

So far, no evidence of Higgs particles has been found and the four LEP experiments have set lower limits, at the 95% confidence level (C.L.), on the mass of a Standard Model (SM) Higgs boson in the range 65–71 GeV/ c^2 [1]. A preliminary estimate of the combined result of the four LEP experiments yields $m_H > 77 \text{ GeV}/c^2$ (95% C.L.) [2].

In 1997 LEP will operate at $\sqrt{s} = 183 \text{ GeV}$ and a further increase of around 10 GeV in the centre-of-mass energy is expected in 1998. Here we consider the prospects for experimentally excluding or discovering a Higgs boson at LEP 2 in 1997 and beyond. Results are presented in terms of the two relevant collider parameters, the average integrated luminosity delivered to the experiments, \mathcal{L} , and the centre-of-mass energy, \sqrt{s} . We first examine the case of the SM Higgs boson and then consider the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM).

2.2. Standard Model Higgs boson

The results presented here are based on

- (a) the studies, prepared before the start of LEP 2, of the integrated luminosity needed to exclude or to discover a Higgs boson signal with a given mass, m_H , at centre-of-mass energies of 175, 192 and 205 GeV [3];
- (b) a similar, but more recent, study prepared for the 1997 LEP Performance Workshop [4], incorporating new information from the four LEP experiments based on the analysis of the first data collected at LEP 2 energies, extrapolated to 185 and 189 GeV.

The comparison of (a) and (b) shows that the Higgs search sensitivity of the LEP experiments has improved from the predictions in reference [3]. Quantitatively we note that, for given \mathcal{L} and \sqrt{s} conditions, the Higgs boson mass sensitivity in (b) is better by, on average, approximately $1.2 \text{ GeV}/c^2$ than in (a). The values in the latter have therefore to be corrected as

$$m_H^{(b)} = m_H^{(a)} + 1.2 \text{ GeV}/c^2,$$

except that $m_H^{(b)}$ is constrained not to exceed the previous mass limit for a given \sqrt{s} at high luminosity. This improvement is largely due to the effort invested by the experimental collaborations in increasing their sensitivity to a possible Higgs boson signal by using, for example, more sophisticated b-tagging methods and optimised selections.

Figure 1(a) shows iso-sensitivity contours for exclusion at the 95% C.L. of a Higgs boson of given mass, projected on to the \mathcal{L} - \sqrt{s} plane. From this it can be concluded that the 95% C.L. exclusion limit is driven by the centre-of-mass energy provided that more than a certain luminosity, $\mathcal{L}_{\text{threshold}} \simeq 50 \text{ pb}^{-1}$, is delivered to each experiment. Above this threshold the excluded Higgs boson mass varies essentially linearly with \sqrt{s} :

$$m_H^{\text{excl}} = (\sqrt{s} - 91) \text{ GeV}/c^2.$$

The 5σ discovery potential, as defined in [3], for the SM Higgs boson is shown in figure 1(b). For instance, for the discovery of a Higgs particle with mass $m_H \simeq m_Z$ there is a slight preference for a centre-of-mass energy $\sqrt{s} \simeq 195 \text{ GeV}$. While such a signal could be discovered at this energy with approximately 85 pb^{-1} per experiment, a larger luminosity of around 100 pb^{-1} per experiment would be required at $\sqrt{s} = 205 \text{ GeV}$. This can be explained by the behaviour with \sqrt{s} of the signal and effective background cross-sections. For $m_H \simeq m_Z$, the effective background (i.e. the background remaining after the experimental event selections) is dominated by the irreducible ZZ background. Table 1 shows the contributions to the cross-section for the $e^+e^- \rightarrow b\bar{b}\mu^+\mu^-$ process, for example, obtained by calculating the HZ and ZZ diagrams separately, and the total calculated cross-section. It can be seen from this table that the ratio of signal to background cross-sections falls continuously above

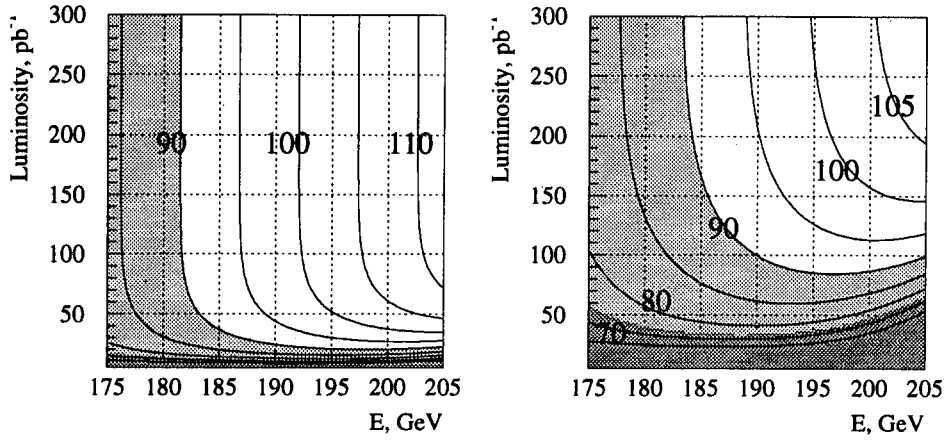


Figure 1. (a) The integrated luminosity per experiment and centre-of-mass energy conditions required to exclude, at the 95% C.L., the existence of a SM Higgs boson of given mass, as indicated by the contours, with the four LEP experiments combined; (b) same as in (a) for a 5σ discovery. The dark and light shaded areas indicate the anticipated 95% C.L. excluded regions after the 1996 and 1997 data-taking respectively, assuming 100 pb per experiment in 1997.

$\sqrt{s} \simeq 185$ GeV, thereby increasing the integrated luminosity that would be required to discover a Higgs boson of mass $m_H \simeq m_Z$.

Table 1. Contributions to the cross-section for the process $e^+e^- \rightarrow b\bar{b}\mu^+\mu^-$ obtained by calculating the HZ and ZZ diagrams separately when $m_H = 90$ GeV/ c^2 , and the total calculated cross-section. Values are obtained from the WPHACT1.0 generator [5] with cuts $(50 < m_{b\bar{b}} < 300)$ GeV/ c^2 and $(m_Z - 25 < m_{\mu^+\mu^-} < m_Z + 25)$ GeV/ c^2 .

\sqrt{s} (GeV)	175	185	192	195	200	205
σ_{HZ} (fb)	0.39	6.66	10.6	11.5	12.3	12.6
σ_{ZZ} (fb)	0.82	4.81	8.65	9.65	10.8	11.5
σ_{total} (fb)	1.20	11.5	19.3	21.1	23.1	24.1

During 1997, LEP 2 will operate at $\sqrt{s} = 183$ GeV and it is expected that a luminosity of approximately 100 pb^{-1} will be delivered to each of the experiments. Under these conditions, the combined sensitivity of the four LEP experiments to the SM Higgs boson after the 1997 run would reach $m_H \simeq m_Z$ for 95% C.L. exclusion and $m_H \simeq 85$ GeV/ c^2 for the case of a 5σ discovery [2].

2.3. MSSM Higgs sector

In the Higgs sector of the MSSM, two complex doublets of scalar fields are needed with vacuum expectation values (VEVs) v_1 and v_2 , coupling to down-type and up-

type fermions respectively. One of the parameters of the model is the VEV ratio $\tan\beta = v_2/v_1$. The Higgs spectrum consists of five mass eigenstates, h , A , H and H^\pm . The lightest CP-even neutral scalar, h , and the CP-odd neutral scalar, A , may be detected at LEP 2.

Excluded areas of the $(m_h, \tan\beta)$ plane are shown in figure 2 [4]. Unphysical regions excluded by all of the three benchmark stop mixing configurations (minimal, typical and maximal mixing [3]) are indicated in black. The projected 95% C.L. excluded areas are shown for integrated luminosities of 50 pb^{-1} and 100 pb^{-1} per experiment.

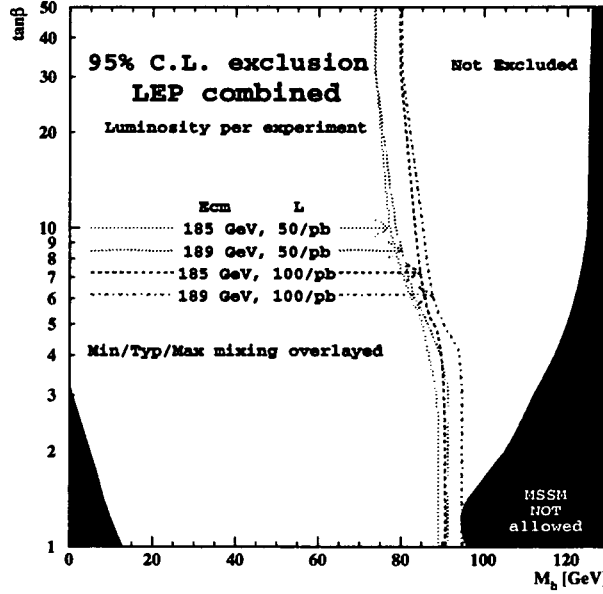


Figure 2. 95% C.L. exclusion sensitivity in the MSSM with four LEP experiments combined. The theoretically allowed region is defined as the set of all $(m_h, \tan\beta)$ points allowed by at least one of the three (minimal, typical, maximal) stop mixing scenarios. (Figure supplied by the Joint LEP Higgs Working Group.)

The experimental sensitivity in the **high** $\tan\beta$ ($\gtrsim 5$) region is dominated by searches for the pair-production process $e^+e^- \rightarrow hA$. From figure 2 it can be seen that the exclusion there is essentially driven by the accumulated luminosity rather than the centre-of-mass energy. Although LEP 2 is expected to improve the excluded region for high $\tan\beta$, it will not do enough to bridge the gap between the currently excluded and theoretically forbidden regions. This will be an important part of the LHC research programme.

The **low** $\tan\beta$ region is covered by searches for the Higgs-strahlung process. SM searches for $e^+e^- \rightarrow HZ$ can be interpreted as MSSM searches for $e^+e^- \rightarrow hZ$, albeit with lower sensitivity because of the additional factor $\sin^2(\beta - \alpha)$ in the cross-section for the latter, where α is a mixing angle in the CP-even Higgs sector. Typically, the exclusion limits for the h boson will be 1–2 GeV lower than for the SM Higgs boson.

The expected LEP running conditions of 1997 will allow the experiments to probe

the low $\tan\beta$ range almost to the upper bound on m_h . This is interesting in particular in the context of the MSSM b - τ Yukawa coupling unification scenario [3, 6]. In this scenario only the ranges $1 \lesssim \tan\beta \lesssim 3$ and $\tan\beta \gtrsim 50$ are allowed, other $\tan\beta$ values being incompatible with current measurements of the top quark mass [7].

The first of these $\tan\beta$ ranges can be probed at LEP 2 if sensitivity to m_h between 95 and 112 GeV/ c^2 is achieved (figure 2). An h boson with $m_h = 95$ GeV/ c^2 can be excluded at the 95% C.L. by the four LEP experiments combined if, for example, $\sqrt{s} = 188$ –189 GeV and an integrated luminosity of 100 pb $^{-1}$ per experiment is obtained. From the SM Higgs boson results (figure 1(a)) and accounting for the lower sensitivity of the MSSM hZ searches, one can conclude that the same exclusion can be achieved with about 50 pb $^{-1}$ per experiment if $\sqrt{s} = 192$ GeV. Similarly, by running at $\sqrt{s} = 205$ GeV with 120 pb $^{-1}$ per experiment the four experiments could exclude an MSSM signal up to about $m_h = 110$ GeV/ c^2 , thus eliminating a very large fraction of the lower $\tan\beta$ range allowed in the b - τ unification scenario.

Attention should be drawn to the fact that the above results were obtained for $m_t = 175$ GeV/ c^2 . Varying m_t by ± 5 GeV/ c^2 has the effect of shifting the theoretical upper bound on m_h by about ± 5 GeV/ c^2 at low $\tan\beta$ [3].

Finally, we point out that the exclusion/discovery curves used here assume that a given luminosity was accumulated at some \sqrt{s} and do not take into account data gathered at lower energies. As experimental searches usually retain some sensitivity even at energies above that at which they were originally applied, this would have the effect of slightly improving the SM and MSSM results presented here. This can, in fact, be seen from figure 1(a), where the current 95% C.L. exclusion limit on m_H after the collection of approximately 10 pb $^{-1}$ of data by each experiment at both 161 GeV and 172 GeV exceeds the prediction for 10 pb $^{-1}$ collected at 175 GeV alone. It should also be noted that effort is continuously invested by all experiments in increasing their efficiencies for detecting a Higgs boson, which will result in further improvements in the mass sensitivity compared to these predictions.

References

- [1] Barate R *et al.*, The ALEPH Collaboration, "Search for the Standard Model Higgs boson in e^+e^- collisions at $\sqrt{s} = 161, 170$ and 172 GeV", CERN-PPE/97-070, submitted to *Phys.Lett. B*
 Abreu P *et al.*, The DELPHI Collaboration, "Search for neutral and charged Higgs bosons in e^+e^- collisions at $\sqrt{s} = 161$ GeV and 172 GeV", to be submitted to *Z.Phys. C*
 Acciarri M *et al.*, The L3 Collaboration, "Search for the Standard Model Higgs boson in e^+e^- interactions at 161 GeV < \sqrt{s} < 172 GeV", L3 preprint 127, to be submitted to *Phys.Lett. B*
 Ackerstaff K *et al.*, The OPAL Collaboration 1997 *Phys.Lett. B* **393** 231
- [2] The Joint LEP Higgs Working Group 1997 Private communication
- [3] Accomando E *et al.* 1996 *Physics at LEP 2* vol 1 ed G Altarelli *et al.* (Geneva) report CERN 96-01 p 351
- [4] Wells P S 1997 *Proc. LEP Performance Workshop (Chamonix)* ed J Poole (Geneva) report CERN-SL/97-006 p 137
- [5] Accomando E and Ballestrero A 1997 *Comp. Phys. Comm.* **99** 230
- [6] Carena M, Pokorski S and Wagner C E M 1993 *Nucl.Phys. B* **406** 59
- [7] Barnett R M *et al.* 1996 *Phys.Rev. D* **54** 1
 Abe F *et al.* 1995 *Phys.Rev.Lett.* **74** 2626
 Abachi S *et al.* 1995 *Phys.Rev.Lett.* **74** 2632

3. Radiative Corrections to Chargino Production at LEP 2

M A Diaz, S F King, and D A Ross

3.1. Introduction

The e^+e^- colliders such as LEP provide a clean environment for searching for the charginos predicted by the Minimal Supersymmetric Standard Model (MSSM) [1]. Several authors have considered at tree level the production of charginos at e^+e^- colliders at the Z pole [2] and beyond [3]. On the other hand, from an accurate measurement of the chargino production cross-section, much information could be obtained about the MSSM [4, 5]. An intensive experimental search is being performed with negative results, which translates into a lower bound on the chargino mass. According to the latest published results, we have taken $m_{\tilde{\chi}_1^\pm} > 75$ GeV as long as the lightest neutralino mass is not too close to the chargino mass [6].

Given the importance of a precise measurement of the chargino production cross-section in e^+e^- experiments, it is clearly necessary to be able to calculate this cross-section as accurately as possible. Although this cross-section does not contain any coloured particles, and so is immune to QCD corrections, there are other radiative corrections which, as we shall see, may give large corrections to the cross-section. Although electroweak corrections may be expected to give contributions of order 1%, there are additional radiative corrections coming from loops of top and bottom quarks and squarks which are important due to their large Yukawa couplings and it is these corrections which form the subject of the present paper. Radiative corrections to chargino masses have been calculated [7], nevertheless, the radiative corrections to chargino production in e^+e^- experiments have not so been considered in the literature.

3.2. The Calculation

We consider the pair production of charginos with momenta k_1 and k_2 in electron-positron scattering with incoming momenta p_1 and p_2 :

$$e^+(p_2) + e^-(p_1) \rightarrow \tilde{\chi}_a^+(k_2) + \tilde{\chi}_b^-(k_1)$$

In the MSSM charginos can be produced in the s-channel with intermediate Z -bosons and photons, and in the t-channel with an intermediate electron-sneutrino $\tilde{\nu}_e$. The tree level cross section is determined by the following parameters: the center of mass energy \sqrt{s} , the $SU(2)$ gaugino mass M , $\tan\beta$ defined as the ratio of the two Higgs vacuum expectation values, the supersymmetric Higgs mass μ , and the sneutrino mass $m_{\tilde{\nu}_e}$. In practice we eliminate $|\mu|$ from the set of independent parameters in favour of the lightest chargino mass $m_{\tilde{\chi}_1^\pm}$.

In our calculation of the one-loop radiative corrections we work in the approximation where only top and bottom quarks and squarks are considered in the

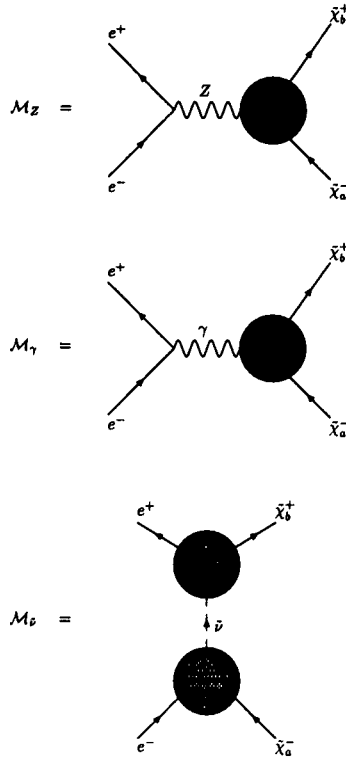


Figure 3. One-loop renormalized M_Z , M_γ and M_{ν_e} amplitudes.

loops. This implies, for example, that the electron-positron vertices, Γ_{Zee}^μ and $\Gamma_{\gamma ee}^\mu$, do not receive triangular corrections, and the tree level vertex can be identified with the one-loop renormalized vertex. In the presence of radiative corrections, the amplitude for $e^+e^- \rightarrow \tilde{\chi}_b^+ \tilde{\chi}_a^-$ may be expressed as the sum of three amplitudes M_Z , M_γ , M_{ν_e} as shown in Fig. 3. The shaded bubbles in that figure are one-loop renormalized total vertex functions defined as $i\mathcal{G}_{Z\chi\chi}^{ab}$, $i\mathcal{G}_{\gamma\chi\chi}^{ab}$ and $i\mathcal{G}_{\nu_e e\chi}^{\pm a}$, respectively. In the total vertex functions we include the tree level vertex, the one-particle irreducible vertex diagrams plus the vertex counterterm, and the one-particle reducible vertex diagrams plus their counterterms. We work in the \overline{MS} scheme, where the parameters in the lagrangian are promoted to running parameters, working at the scale $Q = m_Z$. Nevertheless, it should be stressed that the chargino mass values presented here correspond to the pole mass. Although the detailed expressions for the total vertex functions is quite complicated, by exploiting the possible Lorentz structures of the diagrams it is possible to express them in terms of just a few form factors.

3.3. The Results

We present results for a center of mass energy of $\sqrt{s} = 192$ GeV relevant for LEP 2, and consider the case $\mu < 0$. Radiative corrections to this cross section are parametrized by the squark soft masses which we take degenerate $M_Q = M_U = M_D$, and by the trilinear soft mass parameters $A \equiv A_U = A_D$, also taken degenerate. This choice is

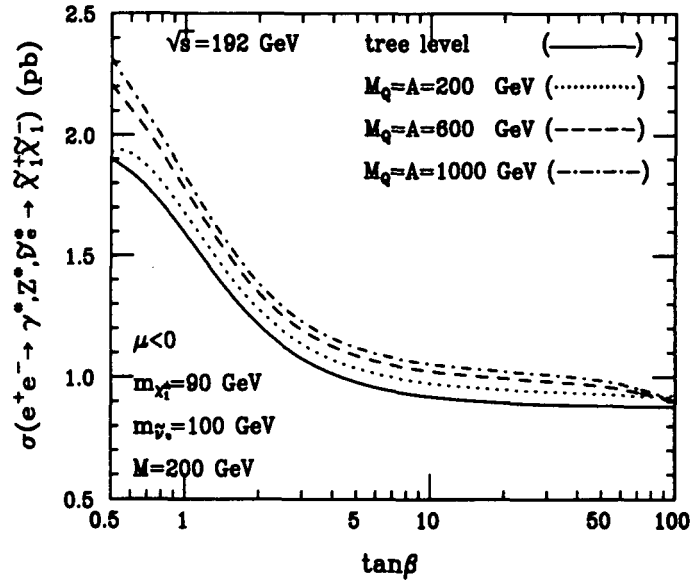


Figure 4. One-loop and tree level chargino production cross section as a function of $\tan \beta$.

taken at the weak scale and it is made for simplicity, *i.e.*, it should not be confused with universality of minimal supergravity at the unification scale.

In Fig. 4 we plot $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-)$ as a function of $\tan \beta$, for a constant value of the chargino mass $m_{\tilde{\chi}_1^\pm} = 90$ GeV, the electron-sneutrino mass $m_{\tilde{\nu}_e} = 100$ GeV, and the gaugino mass $M = 200$ GeV. The tree level cross section is in the solid line and decreases from 1.9 pb. to 0.9 pb. when $\tan \beta$ increases from 0.5 to 100. Three radiatively corrected curves are presented, and they are parametrized by $M_Q = A = 200$ GeV (dots), $M_Q = A = 600$ GeV (dashes), and $M_Q = A = 1$ TeV (dotdashes). For the chosen parameters we observed that corrections are positive varying from a few percent at large $\tan \beta$ to about 22% at small $\tan \beta$. As expected, the correction grows logarithmically with the squark masses, and are maximum when $M_Q = A = 1$ TeV.

In Fig. 5 we explore the dependence of the radiatively corrected cross section $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-)$ as a function of the chargino mass $m_{\tilde{\chi}_1^\pm}$. We fix the value $\tan \beta = 10$ and the rest of the independent parameters are taken as in the previous figure. Quantum corrections increase with the chargino mass, starting from 11% at $m_{\tilde{\chi}_1^\pm} = 75$ GeV and increasing slowly as we approach the kinematic limit for the chargino production, where the total cross section drops to zero.

In conclusion, we have calculated radiative corrections to chargino pair production at LEP 2 and found that one-loop contributions coming from top and bottom

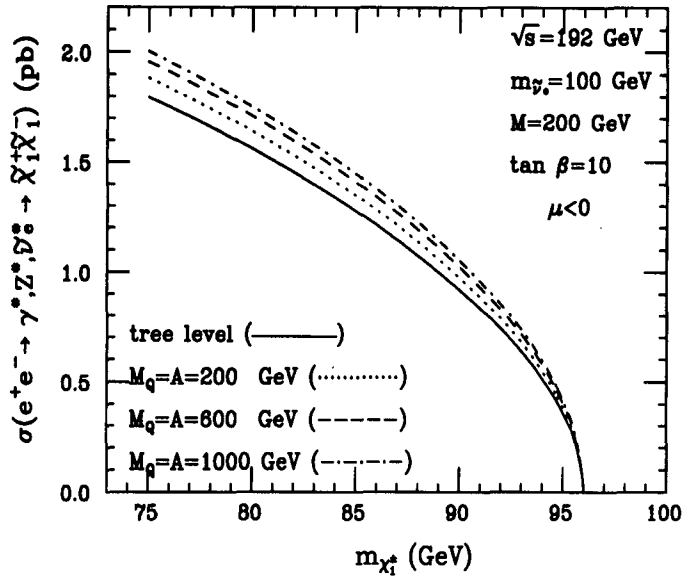


Figure 5. One-loop and tree level chargino production cross section as a function of the chargino mass $m_{\chi_1^\pm}$.

quarks and squarks increase the cross section by up to about 20%. Although a detailed exploration of the parameter space is being carried out [8], the preliminary results presented here are enough to conclude that quantum corrections must be included in order to extract correctly the fundamental parameters of the theory from measurements of the chargino mass and cross section [5].

3.4. References

- [1] H.P. Nilles, *Physics Reports* **110**, 1 (1984); H.E. Haber and G.L. Kane, *Physics Reports* **117**, 75 (1985); R. Barbieri, *Rivista del Nuovo Cimento* **11**, 1 (1988).
- [2] H. Komatsu and J. Kubo, *Phys.Lett.* **162B**, 379 (1985); R. Barbieri, G. Gamberini, G.F. Giudice, and G. Ridolfi, *Phys.Lett.* **195B**, 500 (1987); M.S. Carena and C.E.M. Wagner, *Phys.Lett.* **195B**, 599 (1987); H. Konig, U. Ellwanger, and M.G. Schmidt, *Z.Phys.* **C36**, 715 (1987); A. Bartl, W. Majerotto, and N. Oshimo, *Phys.Lett.* **B216**, 233 (1989); A. Bartl, S. Stippel, W. Majerotto, and N. Oshimo, *Phys.Lett.* **B233**, 241 (1989); A. Bartl, W. Majerotto, N. Oshimo, and S. Stippel, *Z.Phys.* **C47**, 235 (1990); K. Hidaka and P. Ratcliffe, *Phys.Lett.* **B252**, 476 (1990).
- [3] A. Bartl, H. Fraas, and W. Majerotto, *Z.Phys.* **C30**, 441 (1986); A. Bartl, H. Fraas, and W. Majerotto, *Nucl.Phys.* **B278**, 1 (1986); A. Bartl, H. Fraas, W. Majerotto, and B. Mosslacher, *Z.Phys.* **C55**, 257 (1992); M.H. Nuss, M. El-Kishen, and T.A. El-Azem, *Mod.Phys.Lett.* **A7**, 1535 (1992); J. Feng and M. Strassler, *Phys.Rev.* **D51**, 4661 (1995); A.S. Belyaev and A.V. Gladyshev, Report No. JINR-E2-97-76, Mar. 1997.
- [4] H. Baer and X. Tata, Report No. FSU-HEP-921222, Dec. 1992, published in Erice 1992, 23rd Eloisatron workshop, Properties of SUSY particles, p. 244-271;

- J.L. Feng and M.J. Strassler, *Phys.Rev.* **D55**, 1326 (1997);
M.A. Diaz, *Mod.Phys.Lett.* **A12**, 307 (1997).
[5] M.A. Diaz and S.F.King, *Phys.Lett.* **B349**, 105 (1995);
M.A. Diaz and S.F.King, *Phys.Lett.* **B373**, 100 (1996).
[6] D. Buskulic *et al.*, ALEPH Collaboration, *Phys.Lett.* **B373**, 246 (1996);
D. Buskulic *et al.*, ALEPH Collaboration, *Phys.Lett.* **B384**, 461 (1996);
P. Abreu *et al.*, DELPHI Collaboration, *Phys.Lett.* **B382**, 323 (1996);
M. Acciarri *et al.*, L3 Collaboration, *Phys.Lett.* **B377**, 289 (1996);
G. Alexander *et al.*, OPAL Collaboration, *Phys.Lett.* **B377**, 181 (1996);
K. Ackerstaff *et al.*, OPAL Collaboration, *Phys.Lett.* **B389**, 616 (1996);
G. Alexander *et al.*, OPAL Collaboration, *Z.Phys.* **C73**, 201 (1997).
[7] A.B. Lahanas, K. Tamvakis, and N.D. Tracas, *Phys.Lett.* **B324**, 387 (1994);
D. Pierce, A. Papadopoulos, *Phys.Rev.* **D50**, 565 (1994), and *Nucl.Phys.* **B430**, 278 (1994).
[8] M.A. Diaz, S.F. King, and D.A. Ross, in preparation.

4. Charge and Colour Breaking Minima in the MSSM

B C Allanach

Abstract. Here, we review constraints that may be placed upon the parameters of the MSSM by requiring that the vacuum lies in a bounded colour and charge conserving global minimum of the scalar potential. The weakening of these constraints originating from the possibility of a meta-stable charge and colour conserving minimum are also presented.

4.1. Introduction

At a minimum of the scalar potential of a general model, the value of each scalar field is either:

- non-zero, in which case each symmetry under which the scalar field has non-zero quantum numbers (i.e. the scalar is not a singlet) is spontaneously broken
- zero, in which case the scalar does not correspond to any spontaneously broken symmetries.

The scalar potential of the MSSM includes, as well as the usual two Higgs doublets that break the electroweak symmetry, squark and slepton fields. At the minimum of the full scalar potential, if the vacuum expectation values (VEVs) of charged sleptons are non-zero then electromagnetism will be spontaneously broken. If any squark fields have non zero VEVs, this corresponds to a situation where QCD and electromagnetism have been broken [1]. This obviously disagrees with a vast amount of experimental results which indicate that QCD and electromagnetism are good symmetries and so this situation is empirically ruled out. The terms that we will be interested in are:

$$\begin{aligned}
 W &= \mu H_1 H_2 + y_t Q_{L3} H_2 \tilde{t}_R \dots \\
 V_{soft} &= \left(-y_t A_t \tilde{Q}_3 H_2 \tilde{t}_R + h.c. \right) + m_{\tilde{t}_L}^2 |\tilde{t}_L|^2 + m_{\tilde{t}_R}^2 |\tilde{t}_R|^2 + m_2^2 |H_2|^2 +
 \end{aligned}$$

$$\sum_{i=1,2,3} m_{\tilde{L}_i}^2 |\tilde{L}_i|^2 + \dots \quad (1)$$

The scalar potential of squarks and sleptons is determined by the soft parameters in the MSSM, and so certain ranges of these parameters have been ruled out by several authors [1, 2, 3] on the grounds that they would induce charge and colour breaking (CCB) minima. A restrictive bound of this type involving top squarks is

$$A_t^2 + 3\mu^2 < 3M^2, \quad (2)$$

where

$$M^2 \equiv m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2. \quad (3)$$

4.2. Meta-Stable Vacuum

There is however a possible get-out clause to some of these banned parameter ranges. If the global minimum of the scalar potential is CCB but if there is a local minimum of the scalar potential which conserves QCD and electromagnetism but the global minimum is CCB, then we could not necessarily rule out the scenario if the tunneling rate from the conserving to the CCB minima was longer than the age of the universe. If this were the case, it is possible that the universe rests in the meta-stable conserving vacuum and would never tunnel through to the global minimum, thus being consistent with experiment. The calculation of the tunneling rate has only been solved numerically by calculating the 'bounce' solution [2]. The calculation is beyond the scope of this review, but it was noticed in ref. [2], that roughly speaking, the true constraint from this effect changes the inequalities upon the MSSM parameters to

$$A_t^2 + 3\mu^2 < 7.5(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2) \quad (4)$$

It should be noted that if the relation in Eq.4 is used, a few points in parameter space that should be banned will be allowed and vice versa but on the whole Eq.4 provides a good rule of thumb. This is illustrated [2] in Fig. 6, where all of the plotted points correspond to a CCB global minimum. The plot is really a hyperplane through a multi-dimensional space of MSSM parameters. The stars correspond to the case where there exists a meta-stable charge and colour conserving vacuum whose lifetime is long compared to the age of the universe. The boxes indicate points for which the conserving vacua should have decayed into the CCB vacuum via quantum tunneling.

Aside from the constraints coming from the CCB minima, we can also place bounds upon MSSM parameters which incur unphysical potentials that are unbounded from below (UFB) [3]. This occurs when the minimum of the potential lies on a value of infinity for the VEV of a scalar field. The first (tree-level) UFB constraints found [4] were

$$m_2^2 - \mu^2 + m_{\tilde{L}_i}^2 \geq 0. \quad (5)$$

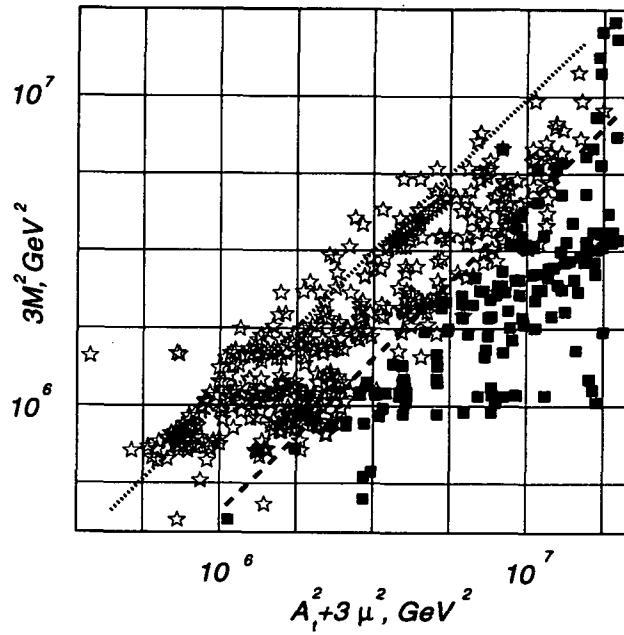


Figure 6. The dotted line represents the simple criterion in Eq.2 for the absence of the global CCB minima. Taking into account the tunneling rates relaxes this constraint to Eq.4 (roughly), shown as the dashed line. The scale is logarithmic.

In ref [3], several CCB and UFB minima are found in addition to the one discussed above (including the other squarks etc.) One loop corrections are also discussed there.

4.3. References

- [1] J. M. Frere, D. R. T. Jones and S. Raby, *Nucl.Phys.* **B222**, 11 (1983);
L. Alvarez-Gaume, J. Polchinski and M. Wise, *Nucl.Phys.* **B221**, 495 (1983);
M. Drees, M. Gluck and K. Grassie, *Phys.Lett.* **B157**, 164 (1985);
J. F. Gunion, H. E. Haber and M. Sher, *Nucl.Phys.* **B306**, 1 (1988);
P. Langacker and N. Polonsky, *Phys.Rev.* **D 50**, 2199 (1994);
A. J. Bordner, KUNS-1351 (hep-ph/9506409);
A. Strumia, *Nucl.Phys.* **B482** (1996) 24.
- [2] A. Kusenko, P. Langacker and G. Segre, *Phys.Rev.* **D54** (1996) 5824;
A. Kusenko, *Nucl.Phys.Proc.Supp.* **52A** (1997) 67.
- [3] J.A. Casas, A. Lleyda and C. Munoz, *Nucl.Phys.* **B471** (1996) 3.
- [4] H. Komatsu, *Phys.Lett.* **B215** (1988) 323.

5. Effect of R-Parity Violation upon Unification Predictions

B C Allanach and H Dreiner

Abstract. We present preliminary results on the possible effects of a particular, possibly large, R-parity violating (RPV) coupling in the MSSM. We focus on the effects upon the unification predictions of $\tan\beta$ and $\alpha_S(M_Z)$, as compared to the R-parity conserving (RPC) case. We find that $\alpha_3(M_Z)$ can be lowered by $\sim 3\%$, bringing the prediction more in line with data. Bottom-tau Yukawa unification becomes possible for any value of $\tan\beta$, rather than the restricted ranges allowed in the RPC model.

5.1. R-parity Violation

In the RPV scenario, many of the RPV couplings are required to be very small due to various constraints arising from flavour changing neutral currents [1]. However, data still allows some of the couplings to be large, of order 1. Here, we shall focus upon the effects of one RPV interaction for which the strongest bound is often merely the perturbative limit:

$$W = \lambda'_{333} L_3 Q_3 D_3. \quad (6)$$

We consider the case where the full superpotential is that of the MSSM plus the piece in Eq.6. λ'_{333} affects the renormalisation group evolution of the gauge couplings to two loops and the third family Yukawa couplings of the MSSM to one loop order.

It is well known that grand unified theories (GUTs) [2] predict

$$\frac{3}{5}\alpha_1(M_U) = \alpha_2(M_U) = \alpha_3(M_U), \quad (7)$$

i.e. the unification of the gauge coupling constants at the GUT scale M_U . We will view [3] Eq.7 as leading to predictions of $\alpha_S(M_Z)$, M_U from the inputs $\alpha_{em}(M_Z) = 127.9$ and $\sin^2\theta_w = 0.2315$. Using these inputs in the RPC MSSM we obtain (to two loop accuracy):

$$\begin{aligned} (\alpha_3(M_Z))^{RPC} &= 0.125 \\ (\alpha_i(M_U))^{RPC} &= 0.042 \\ (M_U)^{RPC} &= 2.46 \times 10^{16} \text{ GeV}. \end{aligned} \quad (8)$$

Note that while the prediction of $\alpha_3(M_Z)$ in Eq.8 seems to be in disagreement with the present experimental value of 0.118 ± 0.003 , much of the discrepancy can be explained by approximations such as the assumptions of a degenerate SUSY spectrum

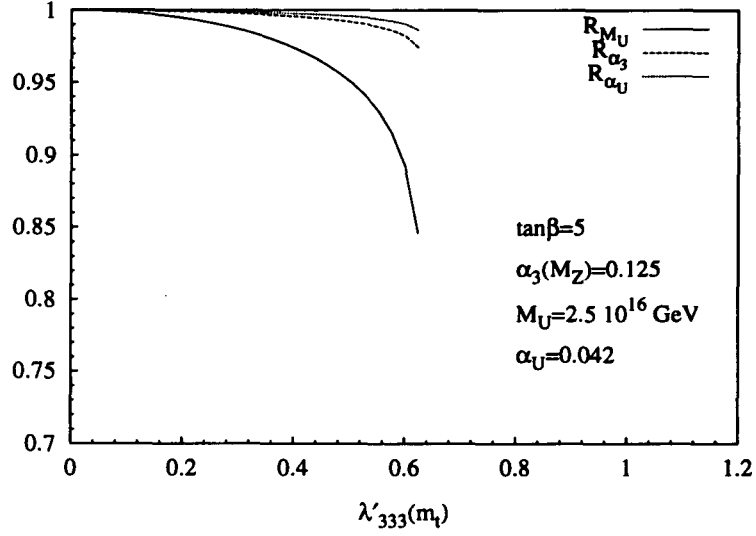


Figure 7. Effect of the RPV coupling λ'_{333} upon unification predictions. Input/output parameters are indicated on the figure.

at $m_t = 176$ GeV and the absence of high scale threshold effects, which may be as high as $+0.01$ [4].

GUTs also predict the relation

$$\lambda_b(M_U) = \lambda_\tau(M_U), \quad (9)$$

where λ_b, λ_τ are the bottom and tau Yukawa couplings respectively. Using inputs $m_b(m_b) = 4.25 \pm 0.15$ GeV, $m_\tau(m_\tau) = 1.777$ GeV and m_t , we turn Eq.9 into a prediction for $\tan\beta$. In the RPC MSSM [2], there are two possible ranges of $\tan\beta$ † consistent with this constraint: $1 < \tan\beta < 3$ or $\tan\beta > 40$.

To illustrate the difference between the RPC and RPV cases, we form the ratios

$$\begin{aligned} R_{M_U} &\equiv \frac{(M_U)^{RPV}}{(M_U)^{RPC}} \\ R_{\alpha_U} &\equiv \frac{(\alpha_{GUT})^{RPV}}{(\alpha_{GUT})^{RPC}} \\ R_{\alpha_3} &\equiv \frac{(\alpha_3(M_Z))^{RPV}}{(\alpha_3(M_Z))^{RPC}} \\ R_{b/\tau} &\equiv \frac{\lambda_b(M_U)}{\lambda_\tau(M_U)} \end{aligned} \quad (10)$$

where λ_t is the top quark Yukawa coupling. We now pick $\tan\beta = 5$, for which the RPC MSSM cannot unify the bottom and tau Yukawa couplings while maintaining the

† $\tan\beta$ is a SUSY parameter of the ratio of two Higgs vacuum expectation values.

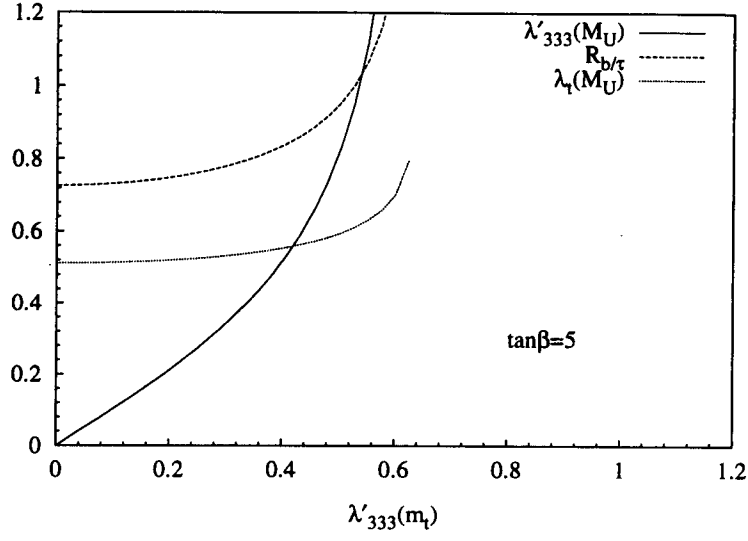


Figure 8. Dependence of GUT scale predictions upon $\lambda'_{333}(m_t)$

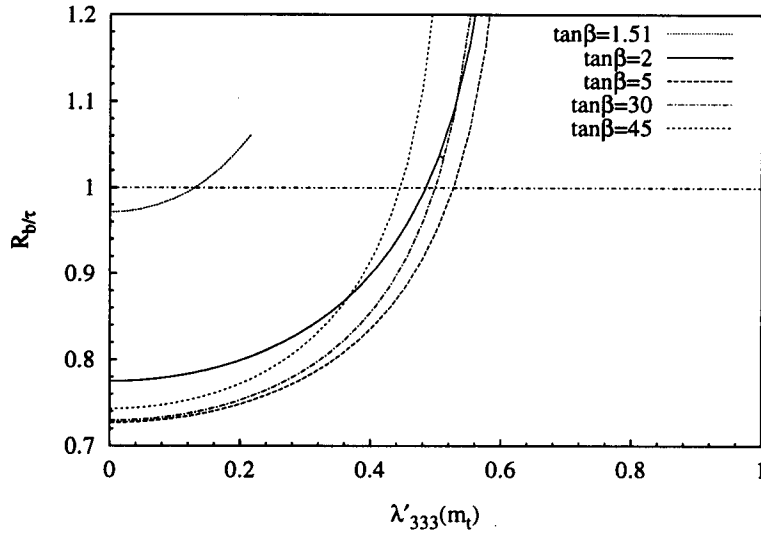


Figure 9. $R_{b/\tau}$ for various different values of $\tan\beta$. The horizontal line at 1 marks the GUT prediction $R_{b/\tau} = 1$.

correct top quark mass. We choose various values of $\lambda'_{333}(m_t)$ and perform a semi-two loop analysis† to calculate the R_i defined in Eq.10 from the constraints in Eqs.7,9. Fig.7 shows that $\alpha_s(M_Z)$ can be decreased by up to 3% by adding the RPV coupling, the unification scale by 15% and the unified gauge coupling by 2%. The perturbative limit is shown as the right-hand end of the lines in Fig.8, where $\lambda'_{333} \approx 0.6$. $\lambda_t(M_U)$ is shown to be large, but has to be smaller than the case of RPC to yield the same top quark mass. Fig.8 also shows that for $\tan \beta = 5$ and $\lambda'_{333}(m_t) = 0.53$, it is possible to satisfy the bottom-tau Yukawa unification constraint, unlike in the RPC MSSM. In fact, Fig.9 illustrates that for *any* value of $\tan \beta$, a value of $\lambda'_{333}(m_t)$ may be chosen to yield $R_{b/\tau} = 1$.

5.2. References

- [1] G. Bhattacharyya, *Nucl.Phys.Proc.Supp.* **52A** (1997) 83.
- [2] P. Langacker and N. Polonsky, *Phys.Rev.* **D50** (1994) 2199.
- [3] P. Langacker and N. Polonsky, *Phys.Rev.* **D47** (1993) 4028.
- [4] D.M. Pierce, J.A. Bagger, K.T. Matchev and R.J. Zhang, *Nucl.Phys.* **B491** (1997) 3.
- [5] B.C. Allanach, H. Dreiner and H. Pois, work in progress.

6. Searches for Pair-Produced New Particles: Trade-Off Between Integrated Luminosity and Centre-Of-Mass Energy

T Wyatt

Abstract. When searching for massive, pair-produced, new particles close to the kinematic limit at LEP, achieving the maximum possible centre-of-mass energy E_{CM} has the benefit of giving the highest possible production cross-section. However, because of, e.g., operational instabilities when running at the highest possible energy, a larger integrated luminosity (\mathcal{L}) may be achieved when running at a somewhat lower E_{CM} . It therefore becomes interesting to consider the possible trade-off between E_{CM} and \mathcal{L} .

6.1. Introduction

It is impossible to predict with any certainty the actual choices that we may be faced with in 1999/2000. For example, how much luminosity will we already have collected by then and at what centre-of-mass energy? How stable will the operation of the superconducting cavity system have become? Also, the dependence of cross-section on E_{CM} depends on the spin and mass of the pair-produced, new particles being considered. The selection efficiency and expected background level also depends on these and possibly other factors (such as, in searches for supersymmetric particles,

† The running of gauge couplings and MSSM Yukawa couplings is to two loops. λ'_{333} is only run at one loop accuracy. The results from a full two-loop calculation will be published elsewhere [5].

the mass of the Lightest Supersymmetric Particle). However, by considering a few specific cases it is possible to notice some interesting features and to draw some general conclusions that should be largely independent of these details.

6.2. Examples

As a first example, let us consider the production of smuon pair events.

$$e^+e^- \rightarrow \tilde{\mu}^+ \tilde{\mu}^-,$$

$$\tilde{\mu}^\pm \rightarrow \mu^\pm \tilde{\chi}_1^0,$$

The standard experimental signature is the observation of events containing a pair of muons and significant missing momentum transverse to the beam direction. The dominant backgrounds arise from two-photon processes and W pairs and are roughly independent of E_{CM} . The expected selection efficiency depends on $m_{\tilde{\mu}}$ and $m_{\tilde{\chi}_1^0}$, but for given values of these parameters is roughly independent of E_{CM} . The sensitivity of the search therefore depends mainly on \mathcal{L} and the expected production cross-section, which is approximately proportional to β^3/s (shown in figure 10).

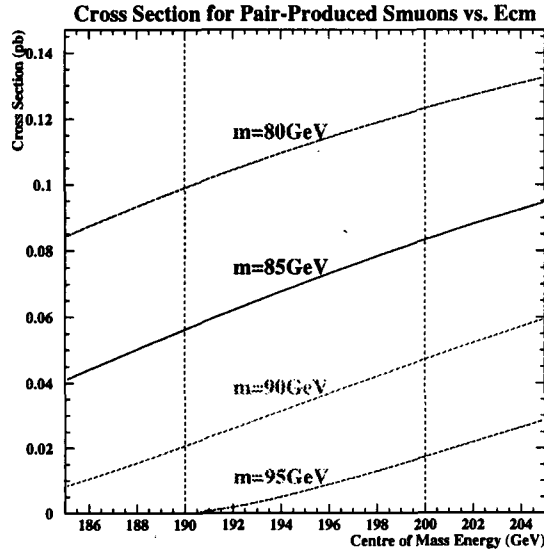


Figure 10. The expected production cross-section for smuon pairs as a function of E_{CM} for various smuon masses, assuming a β^3/s dependence of the cross-section.

If we take as an example $m_{\tilde{\mu}} = 90$ GeV we can see that the expected cross section at $E_{CM} = 200$ GeV is roughly double that at $E_{CM} = 190$ GeV. This might lead us naively to conclude that in searching for smuons with $m_{\tilde{\mu}} = 90$ GeV we could

afford to loose only a factor of two in \mathcal{L} in exchange for the higher energy. In fact this would be incorrect, because it neglects the fact that we will already have collected an appreciable amount of luminosity at $E_{CM} = 190$ GeV. As we will see below, this increases the relative value of new data at a higher E_{CM} compared to merely increasing the integrated luminosity already collected at a lower energy.

We will calculate the expected 95% CL lower limit on $m_{\tilde{\mu}}$ obtainable by combining the data from the four LEP experiments under the following assumptions:

- (i) The expected signal efficiency is 50% and the remaining background from Standard Model processes is 0.1 pb independent of E_{CM} . (This corresponds to a reasonable guess for the performance in the region of low $m_{\tilde{\chi}_1^0}$, where the signal events are rather difficult to distinguish kinematically from the W pair background.
- (ii) An integrated luminosity of 200pb^{-1} per experiment has already been collected at $E_{CM} = 190$ GeV and the limit is calculated by combining this data with new data at three possible values of E_{CM} : 190, 195 or 200 GeV.
- (iii) The number of observed candidate events is equal to the number expected due to background from Standard Model processes. Background is subtracted using the standard PDG recipe.

The results are given in figure 11. The expected 95% CL lower limit on $m_{\tilde{\mu}}$ is plotted as a function of the *additional* integrated luminosity collected per experiment. The three curves correspond to three possible choices of E_{CM} at which this *additional* luminosity is collected. By comparing the curves for $E_{CM} = 190$ GeV and $E_{CM} = 200$ GeV we can see that if the additional data is collected at the higher E_{CM} we can achieve the same limit on $m_{\tilde{\mu}}$ with only about one third as much integrated luminosity. The signal:noise ratio is larger in the higher energy data and this is why it wins out by a larger factor than the simple ratio of the expected production cross-sections.

As a second example, let us consider the pair production of charginos. For this search the arguments in favour of higher E_{CM} over higher \mathcal{L} are overwhelming. Charginos are fermions and, therefore, are produced with a cross-section proportional to β/s , which has a very sharp turn-on above the kinematic threshold. The expected production cross-section is model dependent, but there is a sizable cross-section (of the order of 1 pb) over much of the parameter space of the MSSM. For example, with only 10pb^{-1} collected at $E_{CM} = 172$ GeV the LEP experiments have already been able to place stringent limits on chargino production at close to the kinematic limit. (See the talk of Sylvie Rosier-Lees at the XXXIInd Rencontres de Moriond, Les Arcs, France, March 1997.) Of course, one can always pick a region of parameter space which results in very small production cross-section or detection efficiency, but it seems more likely that we will discover charginos by collecting a few tens of pb^{-1} at a new high E_{CM} than by further running at an E_{CM} at which one already has collected hundreds of pb^{-1} .

In conclusion, when searching for particles that do not show a sharp rise of the production cross-section at the kinematic threshold, the potential loss in integrated

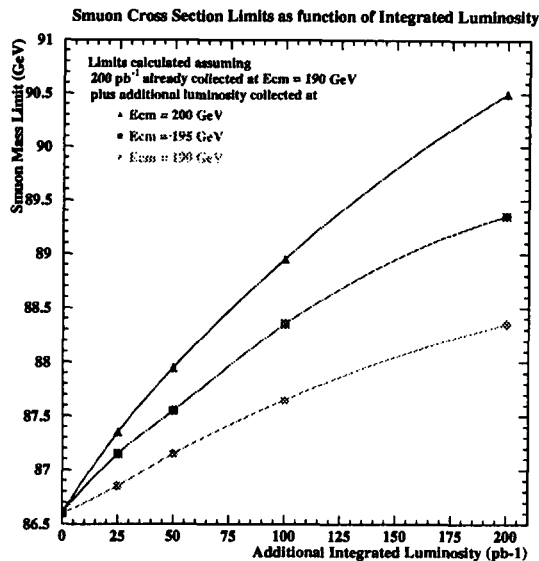


Figure 11. The expected 95% CL lower limit on $m_{\tilde{\mu}}$ obtainable by combining the data from the four LEP experiments, plotted as a function of the *additional* integrated luminosity collected per experiment. The three curves correspond to three possible choices of E_{CM} at which this *additional* luminosity is collected.

luminosity that might result from running at the highest possible E_{CM} must be taken into account when assessing the optimal running strategy. When performing such studies it is important to take into account the fact that we will already have collected (hopefully) a few hundred pb^{-1} at around $E_{CM} = 190$ GeV and that the final limit/discovery will result from the combination of all the available data. Failure to do this may underestimate the relative worth of collecting data at the highest possible E_{CM} . In searching for particles such as charginos, which may well be produced with a large cross-section that rises sharply at the kinematic threshold one would have to bet on the highest possible E_{CM} as the factor most likely to produce a discovery.

7. Single Sneutrino Production at LEP 2

B.C. Allanach, H. Dreiner, P. Morawitz and M.D. Williams

Abstract. We propose a new method of detecting supersymmetry at LEP 2 when R-parity is violated by an LLE operator. We present the matrix element for the process $\gamma e \rightarrow \tilde{\nu}_j e_k$ and calculate the cross-section in e^+e^- collisions. A preliminary Monte-Carlo analysis is undertaken to investigate the possible sensitivity to this signal and we present the 5σ discovery contours in the $m_{\tilde{\nu}_j}$ vs. coupling plane.

7.1. Introduction

If R-parity is violated it becomes possible for supersymmetric particles to be produced singly via the R_p couplings. Although the production cross-section is suppressed by the coupling, the higher kinematic reach means that this can provide a complimentary approach to the study of pair production. Here, we consider the possible detection of R-parity violating supersymmetry through the operator†

$$W_{LLE} = \lambda_{ijk} L_i L_j E_k^c \quad (11)$$

where i, j, k are family indices and gauge indices have been suppressed. This operator has been studied previously [1] in the context of resonant production of single sneutrinos via the couplings λ_{121} and λ_{131} and in terms of alterations to the distributions of dilepton events. The mechanism that we propose is not as effective for these couplings, but is applicable to other couplings. The scenario we consider is one in which a photon from one of the beam electrons interacts with the other beam electron to produce a single sneutrino and a lepton.

7.2. The Matrix Element

Using the Weizsäcker-Williams approximation [2], the appropriate diagrams are shown in Figure 12. We now calculate the matrix element for the process

$$\begin{aligned} \gamma(p_1) + e_1(p_2) &\rightarrow e_y(q_1) + \tilde{\nu}_x(q_2) \\ e_y = \mu, \tau &\quad \tilde{\nu}_x = \tilde{\nu}_{\mu, \tau}. \end{aligned} \quad (12)$$

Neglecting fermion masses, the Mandelstam variables are then defined as

$$s = (p_1 + p_2)^2 \quad t = (p_1 - q_1)^2 \quad u = (p_1 - q_2)^2 \quad (13)$$

where we have assumed the Weizsäcker-Williams approximation of an on-shell photon and a real sneutrino. The matrix element squared (where the photon is approximately on-shell) is

$$|\bar{M}|^2 = e^2 \lambda^2 \left[1 + \frac{u}{t} + \frac{u}{s} + \frac{u^2}{st} - \frac{t}{2s} - \frac{s}{2t} \right]. \quad (14)$$

λ is the R-parity violating coupling probed. The matrix element in Eq.14 is spin-averaged.

7.3. Cross-section Evaluation

The cross-section for $e^+e^- \rightarrow e\tilde{\nu}$ is obtained from that for $\gamma e \rightarrow l\tilde{\nu}$ by

$$\sigma(s; e^+e^- \rightarrow e\tilde{\nu}) = \int f_\gamma(y) \sigma(ys; \gamma e \rightarrow l\tilde{\nu}) dy \quad (15)$$

† Here L and E are the SU(2) doublet and singlet lepton superfields respectively.

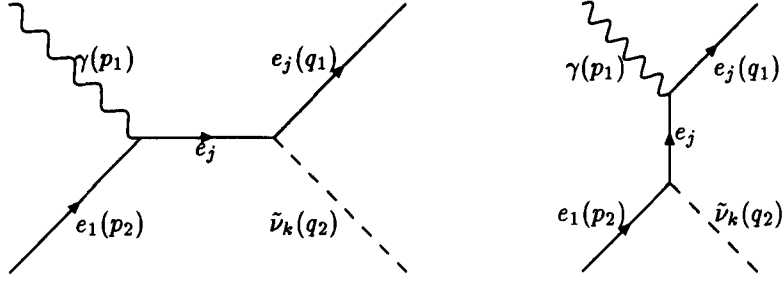


Figure 12. Contributing diagrams. The other initial lepton has been neglected.

where $f_\gamma(y)$ is the photon distribution in the electron at a given fraction, y , of the electron momentum. We use the following version of the Weizsäcker-Williams distribution [3]:

$$f_\gamma(y) = \frac{\alpha_{em}}{2\pi} \left\{ 2(1-y) \left[\frac{m_e^2 y}{E^2(1-y)^2\theta_c^2 + m_e^2 y^2} - \frac{1}{y} \right] + \frac{1 + (1-y)^2}{y} \log \frac{E^2(1-y)^2\theta_c^2 + m_e^2 y^2}{m_e^2 y^2} \right\} \quad (16)$$

where θ_c is the maximum scattering angle of the beam electron and E is the beam energy. We take the value of θ_c to be 30 mrad which is a typical value for the coverage of the luminosity monitors in a LEP experiment. If we were to allow the full range of scattering angles the cross-sections would be higher by about 20%, but the Weizsäcker-Williams approximation would not be such a good one.

If fermion masses are neglected the differential cross-section has a singularity at $t = 0$, but this can be avoided by including the mass of the exchanged fermion in the divergent diagrams. This results in a larger total cross-section for the process $e^+e^- \rightarrow e\mu\tilde{\nu}$ than for $e^+e^- \rightarrow e\tau\tilde{\nu}$. The two cross-sections are plotted as functions of the sneutrino mass in Fig.13 for a value of the coupling $\lambda_{ijk} = 0.05$.

7.4. Final States from Single Sneutrino Production

The signal $e^+e^- \rightarrow el\tilde{\nu}$ is characterised by the electron continuing along the beam pipe, so that the only particles visible in the detector are the lepton l and the decay products of the sneutrino. The sneutrino can either decay directly, $\tilde{\nu} \rightarrow el$, or indirectly via lighter charginos or neutralinos, eg. $\tilde{\nu} \rightarrow \nu\chi$. The final state depends upon both the coupling involved and the flavour of sneutrino produced. This information is summarised in Table 2.

For a coupling λ_{ijk} the lightest neutralino can decay to the following final states:

$$\tilde{\chi}_1^0 \rightarrow \begin{cases} l_i^- \bar{\nu}_j l_k^+ \\ l_i^+ \nu_j l_k^- \\ \bar{\nu}_i l_j^- l_k^+ \\ \nu_i l_j^+ l_k^- \end{cases}$$

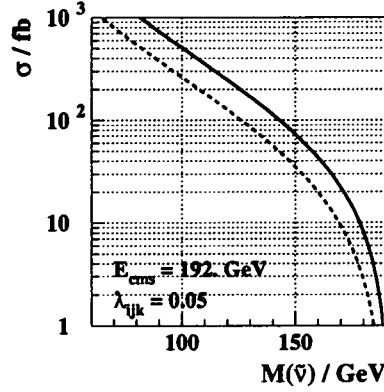


Figure 13. The cross-section for single sneutrino production at a centre of mass energy of 192 GeV and for $\lambda_{ijk} = 0.05$ as a function of the sneutrino mass. The solid line is the cross-section when the final state lepton is a muon; the dashed line is the cross-section when the final state lepton is a tau.

Coupling	Direct Decays		Indirect Decays	
	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$
122	$e\mu^+\mu^-$	-	$\mu\nu\chi$	-
123	$e\tau^+\tau^-$	-	$\tau\nu\chi$	-
132	-	$e\mu^+\mu^-$	-	$\mu\nu\chi$
133	-	$e\tau^+\tau^-$	-	$\tau\nu\chi$
231	$e\tau^+\tau^-$	$e\mu^+\mu^-$	$\tau\nu\chi$	$\mu\nu\chi$

Table 2. The final states for production of different sneutrino flavours via different couplings. The entries marked with a dash are those for which that sneutrino flavour cannot be produced by that coupling.

So that the indirect decays via the lightest neutralino will contain three charged leptons and two neutrinos.

7.5. Investigation of Final State Signals

To investigate the viability of searching for these signals we have written a Monte Carlo capable of generating the different final states and including interfaces to JETSET, for the decays, and PHOTOS, for final state radiation. Several simple analyses to discriminate the signal from the dominant backgrounds were developed.

The most important backgrounds are two photon processes, but four fermion events are also significant. Direct decays have a similar signature to $\gamma\gamma \rightarrow \mu\mu$ or $\tau\tau$ with a single tagged electron. In the case of the signal the electron is produced from the decay of a massive sneutrino and is apparently scattered through a large angle. In addition, the average transverse momentum of the tracks is larger than for a typical $\gamma\gamma$ event. For direct decays to $e\mu$ a large visible mass can be required and

the invariant mass of the sneutrino can easily be constructed. The distribution of this invariant mass for a sneutrino of 100 GeV is shown in Fig.14 where we have assumed an invariant mass resolution of 2.5 GeV. Large missing transverse momentum can be required for direct decays to $e\tau$.

For the indirect decays substantial missing energy is expected because of the presence of an energetic neutrino. This neutrino also means that the missing momentum is often not along the beam pipe. The decay products of the neutralino depend upon the choice of coupling. For a λ_{122} coupling there are three leptons in the event and this can be used to reduce the background. For a λ_{133} coupling the visible mass and total charged energy is small. For a sneutrino of 100 GeV and, for the cascades, a neutralino of 50 GeV the following performances are obtained by our selections:

- Direct decays to $e\mu$: efficiency of 45% and background of 18 fb.
- Direct decays to $e\tau$: efficiency of 43% and background of 28 fb.
- Indirect decays λ_{122} : efficiency of 49% and background of 8 fb.
- Indirect decays λ_{133} : efficiency of 42% and background of 23 fb.

Using these simple selections and parameterising the variation of the efficiency with sneutrino mass we can derive expected discovery (5σ) contours in the plane $(m_{\tilde{\nu}}, \lambda)$. In Fig.14 these contours are shown assuming 100 pb^{-1} of data are collected at a centre of mass energy of 192 GeV. A combination of the four LEP experiments would significantly improve the results. In addition, much better performance could be obtained for the case of direct decays to $e\mu$ by including the mass distribution of the events. These results should be compared with the available limits upon R-parity

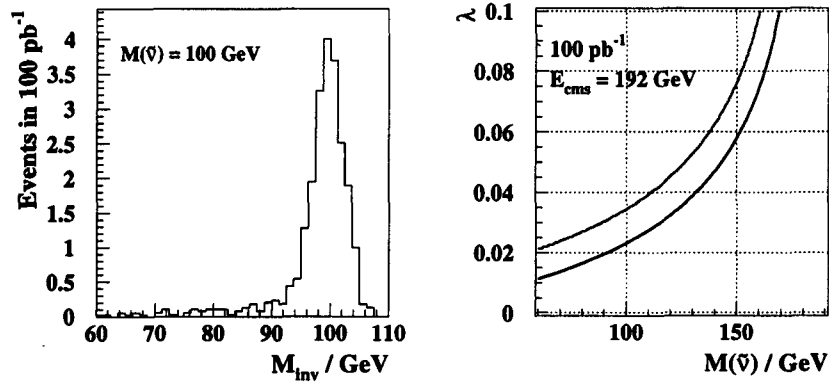


Figure 14. The left hand plot shows the distribution of the invariant mass of the electron and muon from a sneutrino decay. In the right hand plot the discovery contours for the best case (indirect decays with λ_{122}) are shown in black and for the worst case (direct decays to $e\tau$) in grey.

violating couplings. The best current limits on λ_{ijk} in Eq.11 are† [4]

$$\lambda_{12n} < 0.05 \quad \lambda_{131} < 0.06 \quad \lambda_{132} < 0.06 \quad \lambda_{133} < 0.004 \quad \lambda_{23n} < 0.06 \quad (17)$$

for a SUSY mass of 100 GeV. It can be seen that these limits are not sufficient to exclude the possibility that sneutrinos with masses beyond the kinematic limit for pair production may be probed via this process.

7.6. Conclusion

We have calculated the matrix element for $\gamma e \rightarrow \tilde{\nu}_j e_k$ via an R-parity violating coupling of type *LLE* and obtained the cross-section in e^+e^- collisions. The expected final states from such processes at LEP 2 have been listed and a preliminary investigation made. In view of the encouraging results derived here, a future experimental analysis to address this possibility is very welcome.

7.7. Acknowledgements

We are grateful for useful discussions with M. Seymour and M. Kraemer from which this paper has benefitted.

7.8. References

- [1] J. Kalinowski et. al., hep-ph/9703436
- [2] C.F. Weiszäcker, *Z.Phys.* **88** (1934) 612; E.J. Williams, *Phys.Rev.* **45** (1934) 729
- [3] S. Frixione et. al. *Phys.Lett.* **B319** (1993) 339
- [4] V. Barger, G. F. Giudice and T. Han, *Phys.Rev.* **D40** (1989) 2987; G. Bhattacharyya, *Nucl.Phys.Proc.Supp.* **52A** (1997) 83; H. Dreiner, hep-ph/9707435

8. Searches at LEP 2 related to possible HERA effect

G W Wilson

Abstract. The recent observations by the HERA experiments have revived interest in the phenomenology of particles with leptoquark like couplings. Leptoquarks or R-parity violating squarks in supersymmetric theories or contact interactions were discussed as possible exotic explanations of the observations, and we briefly review the relevance of related indirect and direct searches at LEP 2 .

† The bounds on λ_{12n} are at the 2σ level; all others are at 1σ .

8.1. Introduction

This article addresses the following two questions :

- (i) **IF** the excess of events at HERA at high (x, Q^2) in $e^+ p \rightarrow e^+ \text{ jet } X$ [1, 2] is confirmed and establishes a particle of mass exceeding 180 GeV **THEN** is there a role for experiments at LEP 2 in establishing or eliminating some of the possibilities?
- (ii) Independent of the actual relevance of possible LEP 2 searches to the HERA effect, are there some searches inspired by models discussed in this context that should be considered anyway at LEP 2 and have so far received little experimental attention? This is most important if the experimental signature is not covered by the established search analyses.

There has been “much ado about leptoquarks” in recent preprints[3, 4]. Among the more relevant ones to LEP 2 research are [3, 5, 6]. Perhaps the most compelling recent works include one[7] which contests the mutual consistency of the two HERA experiments, let alone the consistency with a resonance, and a publication prior to [1, 2] which suggests searching for single leptoquark production at LEP 2 in electron-photon scattering[8].

8.2. Related searches at LEP 2

Many things can be done at LEP 2 , but the reader should be careful to assess, whether such searches are complementary or not to similar searches at the Tevatron or at HERA which have the advantage of a higher possible kinematic reach. The “standard” pair-production search possibilities and estimated sensitivities are discussed in [9].

Leptoquark like new particles could be pair-produced at LEP 2 through their coupling to the photon and the Z. This has the great advantage of a production cross-section which is independent of the Yukawa coupling, and sensitivity to all generations. (All HERA limits on leptoquarks depend on this coupling and are relevant to first generation leptoquarks). But of course the mass reach is limited to the beam energy. So, one could imagine testing for all sorts of leptoquarks up to at most 100 GeV. This search faces stiff competition from the Tevatron which also has the advantage of a cross-section independent of the Yukawa coupling. For example the first generation scalar leptoquark limit for 100% branching fraction to electron-quark is 225 GeV at 95% CL [10]. The weakest limit from the Tevatron in the ℓ - ℓ -jet-jet searches is for a third generation leptoquark, the $\tau\tau$ jet-jet mode, (99 GeV from CDF [11]) - this would be worth doing better. The presently only partially covered region by the Tevatron, partly because it is more difficult experimentally, is the search in the $\nu\bar{\nu}$ -jet-jet mode for all three generations. Some leptoquark like objects, have a 100% branching ratio to neutrino-quark, because they couple only to neutrinos and quarks, so making them inaccessible in single production from ep and $e\gamma$ interactions at HERA and at LEP 2 respectively. The perfect place to look for these up to the beam energy is in pair production at LEP 2 . This search is already well covered since the experimental signature is identical to the Higgs missing energy channel.

As already discussed, the most intriguing prospect at LEP 2 for direct searches possibly relevant to the HERA observation, is the single production of leptoquark like particles via electron-photon scattering. This depends on the flux of Weizsacker-Williams photons from one beam (QED), the parton distribution function in the photon, which parametrises the splitting probability and energy fraction for the photon splitting to a quark-antiquark pair, and again λ , the strength of the Yukawa coupling between the leptoquark-e-quark. This method can test all the possible e-quark interactions at HERA for both e^+ and e^- and for charge 1/3 and 2/3 quarks and antiquarks. OPAL has carried out a “demonstrator” preliminary analysis[12] using 20 pb $^{-1}$ at 161 and 172 GeV with this technique in both the electron-jet and neutrino-jet topologies (these are complementary to existing searches) and find a limit of 131 GeV for scalar first generation leptoquarks of charge 1/3 or 5/3 for couplings $\lambda > \sqrt{4\pi\alpha_{em}}$. It seems feasible to eventually probe Yukawa couplings of electro-magnetic strength up to about 10-20 GeV from the kinematic limit. This seems to be one more case amongst the many good ones for pushing LEP 2 as far as possible in energy.

The most discussed method for LEP 2 to constrain possible new physics beyond the LEP 2 kinematic limit is from deviations in the measured cross-sections and angular distributions for two-fermion production. This field is usually considered in two approximations. For new physics with mass scale $m_X \gg \sqrt{s}$ one parametrises the new physics as an effective four-fermion contact interaction. This approach has been followed for many years. The most recent experimental publication relevant to this is [13]. For cases where the mass scale is not much higher than the centre-of-mass energy, one needs to take into account the diagram from t-channel exchange of a virtual leptoquark like particle in the process $e^+e^- \rightarrow q\bar{q}$. See [3] for more details. All LEP experiments are fairly active in pursuing this line, and the finalised publications containing the multi-hadron cross-section measurement from 1996 LEP 2 running are likely to address both possibilities. This approach looks to be quite constraining on the possible interpretation of the HERA observation arising from e^+ /sea-quark interactions with large λ [5]. However the much lower values of λ , $\lambda \approx 0.1\sqrt{4\pi\alpha_{em}}$, implied by considering models with e^+ /valence-quark at HERA will not be constrained by future LEP 2 data with this approach.

8.3. Summary

There are quite a few topics which can be addressed at LEP 2 in the context of possible new physics being accessed at HERA. There are also many searches awaiting the eager searcher keen to discover/constrain R-parity violating supersymmetry [14]. However, it is difficult to conceive of an experimental topology which could not be produced by R-parity violating supersymmetry.

It is most important to repeat the HERA experiments and establish if anything is actually awry. However, the obvious conclusion is that direct searches at LEP 2 with presently foreseen beam energies have no role if the only new particles that exist have mass above about 200 GeV. In that case, a higher energy e^+e^- collider would be an ideal tool to explore such phenomena[3].

The main new experimental signatures, suggested by single leptoquark production,

are the lepton-jet and neutrino-jet topologies.

8.4. References

- [1] H1 Collab., C. Adloff et al., *Z. Phys.* C74 (1997) 191.
- [2] ZEUS Collab., J. Breitweg et al., *Z. Phys.* C74 (1997) 207.
- [3] J.L. Hewett and T.G. Rizzo, hep-ph/970337.
- [4] P.H. Frampton, hep-ph/9706220 from June 1997 catalogues 30 related preprints from early 1997.
- [5] G. Altarelli et al., hep-ph/9703276.
- [6] H. Dreiner and P. Morawitz, hep-ph/9703279. J. Kalinowski et al., hep-ph/9703288. C.G. Papadopoulos, hep-ph/9703372. S. Jadach, B.F.L. Ward and Z. Was, hep-ph/9704241.
- [7] M.Drees, hep-ph/9703332.
- [8] M.A. Doncheski and S. Godfrey, *Phys. Lett.* B393(1997)355. M.A. Doncheski and S. Godfrey, hep-ph/9703285.
- [9] S. Ambrosanio et al. in CERN 96-01, Vol 1, Ed. G. Altarelli et al, pp506-510.
- [10] D0 Collab., B. Abbott et al, hep-ex/9707033.
- [11] CDF. Collab., F. Abe et al, *Phys. Rev. Lett* 78 (1997) 2906.
- [12] S. Soeldner-Rembold, hep-ex/9706003.
- [13] OPAL Collab., K. Ackerstaff et al., *Phys. Lett.* B391 (1997) 221.
- [14] These proceedings.

9. Summary

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Abstract. Aspects of searches at LEP 2 are reviewed and summarized, with particular emphasis on the gains from running LEP at 200 GeV, and on alternative paradigms for supersymmetric phenomenology, such as models with violation of R parity.

9.1. Introduction

The primary search at LEP 2 [1] is that for the Higgs boson of the Standard Model [2], whose prospects are discussed in section 2 of this report. Many other new particles have been conjectured, and may also be hunted at LEP 2 under exceptionally clean and well-understood conditions. During the time available, this Working Group was unable to study all these alternatives, and made a selection of quarries that was guided largely by the subjective research interests of the participants.

Foremost among these interests was supersymmetry [3], which many theorists consider to be the best motivated possible extension of the Standard Model at accessible energies. Supersymmetry predicts the existence of several different Higgs bosons, as also discussed in section 2, as well as many new supersymmetric particles, the lightest of which may well be produced at LEP 2. Section 3 discusses the radiative corrections to the production of charginos at LEP 2, and section 6 discusses the prospects for slepton detection.

A novelty at this workshop was the increased interest attracted by supersymmetric models in which R parity is violated, motivated in large part by the apparent excess of events at large Q^2 observed by the H1 and ZEUS collaborations at HERA [4], reviewed here in section 8, which could be interpreted as the single production of some squark flavour by an R -violating Yukawa coupling. This opens up the possibilities of single leptoquark or squark production at LEP 2 and of interference effects due to the exchanges of virtual heavier leptoquarks or squarks, as also mentioned in section 8. There is also the possibility of single sneutrino production, as discussed in section 7. Theoretical upper limits on the possible magnitudes of such R -violating couplings are discussed in section 5 of this report, and other theoretical constraints on supersymmetric model building are discussed in section 4.

It is not the purpose of this summary to repeat all the interesting analyses presented in these previous sections. Rather, I select a few specific important points that appear to merit further emphasis, adding further remarks in a few cases. Most of these are related to the present drive to run LEP at 200 GeV ('LEP 200'), if possible during both the years 1999 and 2000, or to alternative paradigms for supersymmetric phenomenology, including those suggested by the CDF $e^+e^- \gamma\gamma$ event [5], as well as by interpretations of the HERA large- Q^2 events [4].

9.2. Searches for Higgs Bosons

The search for the Standard Model Higgs boson at LEP 2 has been reviewed in section 2. It is worth emphasizing that the precision electroweak data indicate a preference for a Higgs boson weighing within a factor of 2 or so of 140 GeV [6], as seen in Fig. 15. It is also well known that masses below about 130 GeV are among the most delicate for the LHC, making the most severe demands on the electromagnetic calorimetry and/or on b tagging. For these two reasons, maximizing the physics reach of LEP 2 is of capital importance. It is also important to recall that substantial luminosity will be required at $E_{CM} = 200$ GeV if the discovery potential of LEP 200 is to be realized fully, because of the need to overcome the Z decay background.

As is well known, the minimal supersymmetric extension of the Standard Model (MSSM) predicts the appearance of a Higgs boson h with mass below about 150 GeV [7], consistent with the indications from the precision electroweak data. This upper limit may be reduced to about 100 GeV in models with a small ratio of Higgs vacuum expectation values $\tan\beta \lesssim 2$ as favoured in many theoretical speculations refining the MSSM. By extending the search region for the Higgs boson beyond 100 GeV, LEP 200 would expand significantly the domain of MSSM parameter space accessible to LEP.

Comparing with Fig. 2 of section 2 of this report, Fig. 16 displays the domains of the MSSM parameters $(m_h, \tan\beta)$ that are excluded theoretically (dark hatching) and those that could be explored by LEP 200 searches for supersymmetric Higgs bosons (light hatching) [8]. We see that LEP 200 would provide significant gains. In particular, the lightest Higgs boson could be found with certainty for $\tan\beta \lesssim 2$, even for unfavourable choices of other MSSM parameters.

The additional coverage available to LEP 200 would also complement the LHC in

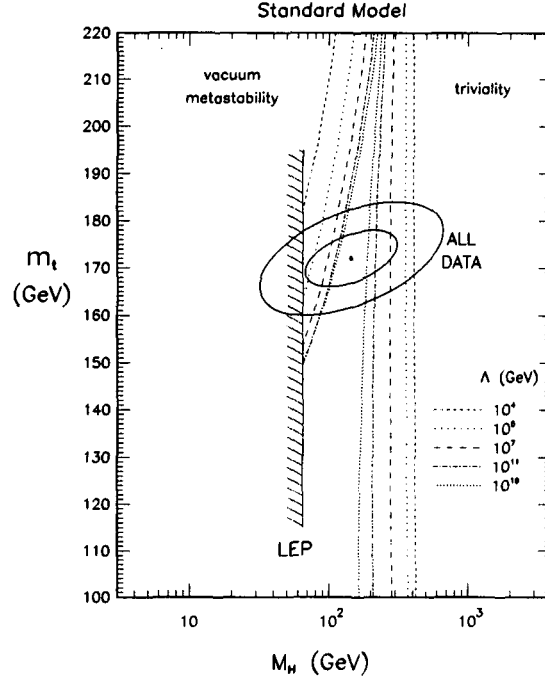


Figure 15. A global fit of m_H to precision electroweak data and Fermilab measurements indicates a preference for a mass around 140 GeV, with an uncertainty of a factor of 2 [6], consistent with the validity of the Standard Model up to a very high scale Λ , or with supersymmetry.

regions of MSSM parameter space where the LHC Higgs searches are particularly delicate and might require combining data, from both ATLAS and CMS, taken over several years of running at the highest luminosity [9], as seen in Fig. 17.

9.3. Searches for Supersymmetric Particles

As is well known, supersymmetry [3] is one of the most motivated possible extensions of the Standard Model - since it may help understand the hierarchy of mass scales in physics without excessive fine tuning [10] - and inspires many of the current new physics searches at LEP 2. In addition, LEP 1 has provided two suggestions that supersymmetry may be on the right track. One is the consistency of the global fit to precise electroweak measurements shown in Fig. 15 with supersymmetric predictions [6], and the other is the consistency of measurements of the gauge coupling strengths with supersymmetric grand unified theories [11].

Although the full range of possible supersymmetric particle masses can only be explored using the LHC, particular interest attaches to masses around 100 GeV, in the transition region between LEP and the LHC, where additional LEP 2 running at the

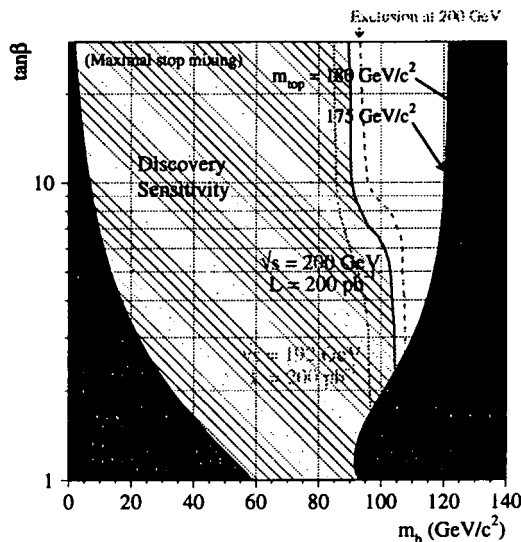


Figure 16. Regions of the $(m_h, \tan\beta)$ plane characterizing supersymmetric Higgs bosons, indicating (dark hatching) regions that are excluded theoretically for different assumed values of the top quark mass, and regions where supersymmetric Higgs bosons could be discovered by LEP running at 192 or 200 GeV, or excluded by running at 200 GeV [8].

highest possible energy could have significant impact. This is because the fine tuning required to stabilize the gauge hierarchy becomes worse for heavier sparticles. For this reason, there is a preference for many of them to be lighter than the maximum of about 2 TeV that can be explored at the LHC. In any given model, the amount of fine tuning can be quantified as the proportional sensitivity of the Z mass to variations in the input parameters [12]. As seen in Fig. 18, if m_Z is not to vary more than 10 times more rapidly than the input parameters, the lightest supersymmetric partners of the electroweak gauge bosons and Higgs bosons - charginos and neutralinos - are expected to weigh less than about 100 and 60 GeV respectively. LEP 200 will enable this range of chargino masses to be explored thoroughly.

The calculations reported in section 3 will enable the future LEP 2 searches for charginos to be interpreted more reliably in terms of lower limits on the chargino mass: running LEP at 200 GeV in the centre of mass would increase the chargino mass reach by about 4 GeV. The analysis of section 6 illustrates the gain in smuon mass range that could be attained by running LEP at an energy of 200 GeV in the centre of mass. For example, assuming that the smuon decays into the lightest neutralino, and that this is stable, an additional 100 pb^{-1} of integrated luminosity at 200 GeV would enable the physics reach for the smuon mass to be extended by about 2 GeV. As a further example in the stable-neutralino context, Fig. 19 shows that LEP 200 would extend the searches for the selectron and the lighter stop squark up above 90 GeV [13]. The latter is particularly interesting in the context of supersymmetric models that attempt to make a significant contribution to the Z decay rate into $b\bar{b}$ final states [14]. Finally, we recall that the lightest neutralino is a prime candidate for the cold dark matter favoured by cosmology and models of structure formation in the Universe.

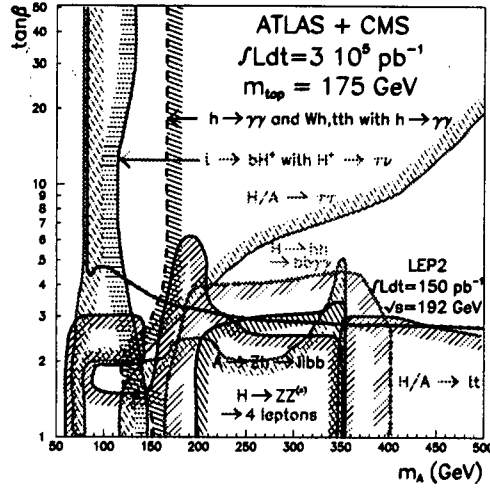


Figure 17. Regions of the $(m_A, \tan\beta)$ plane that are accessible to various searches for MSSM Higgs bosons at the LHC. Also shown is the region that could be covered by LEP 2 at 192 GeV. Increasing the maximum LEP energy to 200 GeV would improve significantly the coverage for $\tan\beta \sim 3$ to 4, where many different LHC search strategies come into play [9].

LEP 200 would be able to explore completely masses of the lightest neutralino below about 50 GeV [15], where experiments searching for astrophysical dark matter have their greatest sensitivity.

In addition to the more complete searches for supersymmetric Higgs bosons and other supersymmetric particles in models where the lightest neutralino is stable, as reviewed above, LEP 200 could also settle the status of models proposed to explain the CDF $e^+e^- \gamma\gamma$ event [5], and cast light on possible non-standard interpretations of HERA large- Q^2 data [4], as discussed in the next two subsections.

9.4. Search for Supersymmetric Models with a Light Gravitino

Supersymmetric models with a light gravitino have been the object of considerable theoretical interest over the last couple of years, motivated in part by models in which supersymmetry breaking is communicated to the observable sector by gauge interactions [16], rather than by gravity. Efforts on these models have been encouraged [17] by the CDF report of an event containing $e^+e^- \gamma\gamma$ and missing energy [5], that could be due to radiative decays of neutralinos into gravitinos. Searches at LEP 200 for events with photons and missing energy have already excluded a significant fraction of the preferred range of parameters in a favoured model of this type [18], as seen in Fig. 20. Furthermore, as also seen in Fig. 20, searches at LEP 200 should be able to explore essentially the whole of the parameter space of

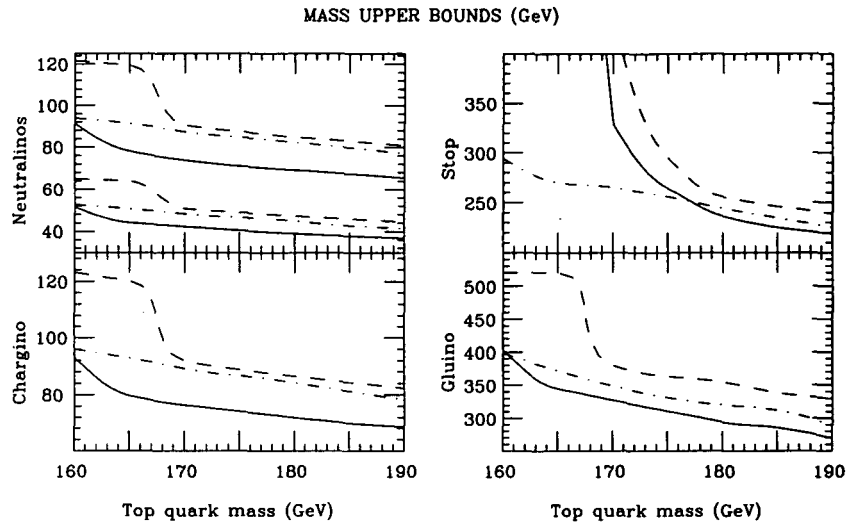


Figure 18. Upper limits on the masses of various supersymmetric particles obtained by requiring that m_Z not vary more than 10 times more rapidly than the input model parameters, under different assumptions on relations between the latter [12].

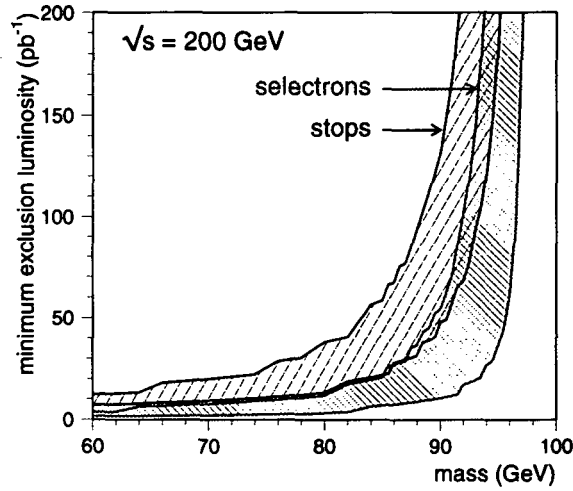


Figure 19. Domains of the masses of the selectron and lighter stop squark that could be explored using LEP 200, as a function of the total luminosity obtained [13]. The spreads in the curves correspond to differing amounts of stop mixing and possible selectron masses.

this model, and the same is true of alternative light-gravitino models. Therefore LEP 200 may be able to deliver a definitive verdict on this generic scenario for supersymmetry breaking.

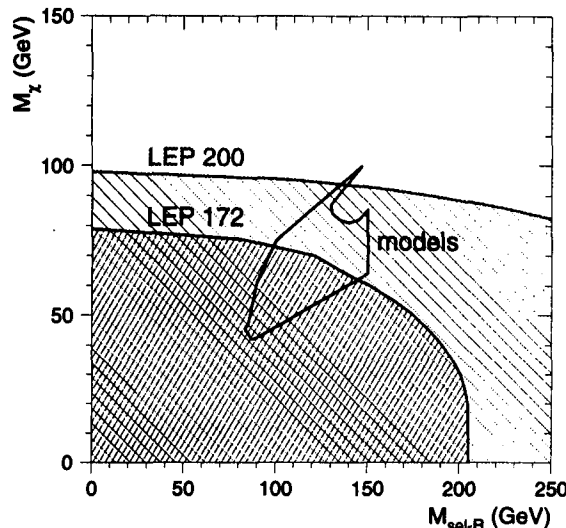


Figure 20. Regions of the electron - lightest neutralino mass plane that have already been explored by LEP and could be explored by LEP 200 [18], compared with the domain of these parameters postulated by explanations of the CDF $e^+e^- \gamma\gamma$ event [5] in terms of selectron-pair production in models with a light gravitino.

9.5. Search for R -Violating Supersymmetry

In the scenarios discussed in the two previous subsections, it was assumed that there is a multiplicatively conserved quantum number, called R parity, which is related to baryon and lepton numbers. Another generic possibility is that although the lightest neutralino is the lightest supersymmetric particle, it is unstable and decays via new interactions that violate baryon and/or lepton number and hence R parity. Models of this type have also attracted renewed attention recently, particularly in connection with possible interpretations of the large- Q^2 events seen at HERA [4] which invoke the production of a squark weighing about 200 GeV by a Yukawa interaction that violates R parity.

Three specific scenarios of this type have been proposed [19]: (a) production of a scharm squark \tilde{c} off a valence d quark in the proton, (b) production of the lighter stop squark \tilde{t}_1 off a valence d quark, and (c) production of the \tilde{t}_1 off an s quark in the sea. One of the important constraints on these scenarios is imposed by the absence of $e^+e^- \rightarrow 2\text{-jet}$ events at the Tevatron collider [20], which requires the e^+q branching ratio of any such squark to be significantly less than unity. This occurs in generic domains of the parameter space for scenario (a), but in only a limited domain of parameters in scenario (b), with scenario (c) being an intermediate case [21].

As was discussed in section 8, the exchange of an R -violating squark could have measurable effects on $e^+e^- \rightarrow \bar{q}q$ cross sections at the highest LEP energies, even if

it cannot be produced directly at LEP. However, at the present time this does not appear to rule out even scenario (c), which requires the largest Yukawa coupling \dagger , and is unlikely ever to challenge scenarios (a) and (b), which require much smaller Yukawa couplings.

As was also mentioned in section 8, there could be an observable cross section for single production of such a quark, via its R -violating interactions, if its mass is below the maximum centre-of-mass energy of LEP. This possibility puts a premium on achieving the highest possible energy at LEP. However, since all of the HERA scenarios require $200 \lesssim m_{\tilde{q}} \lesssim 220$ GeV, this mechanism may lie for ever beyond the reach of LEP.

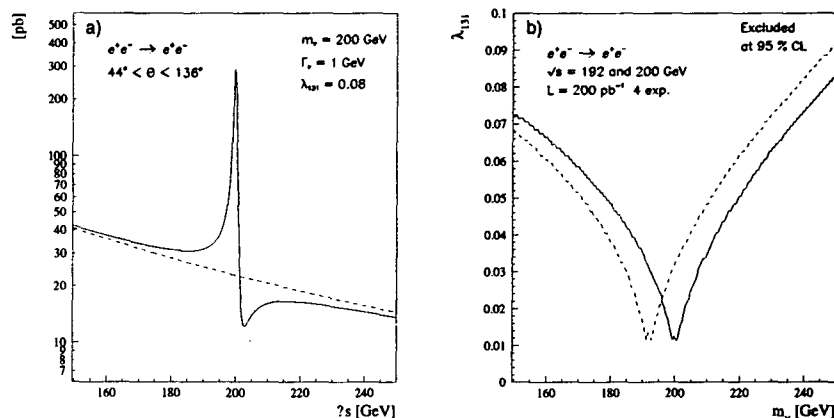


Figure 21. (a) The possible effect on the e^+e^- annihilation cross section of a direct-channel sneutrino resonance [23] with an R -violating coupling, and (b) potential limits on such a coupling, as a function of its mass [24]. It can be seen that LEP 200 would extend significantly the sensitivity to any direct-channel resonance weighing about 200 GeV.

As was discussed in section 7, there could also be R -violating interactions involving just leptons and their supersymmetric partners. In this scenario, sneutrino exchange could have measurable effects on $e^+e^- \rightarrow \ell^+\ell^-$ cross-sections at the highest LEP energies, and single sneutrino production becomes possible. It is even possible that LEP 200 might produce a sneutrino as a direct-channel resonance. Fig. 21 shows the possible shape of such a direct-channel sneutrino resonance [23], as well as the limits that LEP could establish on the coupling of any such sneutrino, as a function of its mass [24]. We see, in particular, the potential impact of additional running of LEP at a centre-of-mass energy of 200 GeV.

9.6. Conclusions

These examples illustrate the rich area of searches to be undertaken at LEP 2, in particular in the Higgs sector and in various supersymmetric scenarios. Other examples could be given in the context of composite models, contact interactions, etc.. However, the capabilities reviewed above suffice to indicate that LEP 2 has every

\dagger Interesting new bounds on R -violating couplings are derived in section 5, on the basis of a renormalization-group analysis of the GUT mass relation $m_b = m_\tau$ [22].

chance to add discovery of new physics beyond the Standard Model to the precision W^+W^- and other measurements discussed by other Working Groups at this meeting.

In several cases, such as searches for Higgs bosons weighing around 100 GeV and supersymmetric particles, there is a premium on running LEP 2 at $E_{CM} = 200$ GeV for a substantial period, preferably both the years 1999 and 2000. We therefore urge in the strongest possible terms that the means to achieve this be made available.

9.7. References

- [1] *Proceedings of the Workshop on Physics at LEP 2*, eds. G. Altarelli, T. Sjöstrand and F. Zwirner, CERN Report 96-01.
- [2] J. Ellis, M.K. Gaillard and D.V. Nanopoulos, *Nucl.Phys.* **B106** (1976) 292;
B.L. Ioffe and V.A. Khoze, *Sov.J.Part.Nucl.* **9** (1978) 50;
B.W. Lee, C. Quigg and H. Thacker, *Phys.Rev.Lett.* **38** (1977) 883 and *Phys.Rev.* **D16** (1977) 1519.
- [3] Y.A. Gol'fand and E.P. Likhtman, *Pis'ma Zh.E.T.F.* **13** (1971) 323;
D. Volkov and V.P. Akulov, *Phys.Lett.* **46B** (1973) 109;
J. Wess and B. Zumino, *Nucl.Phys.* **B70** (1974) 39;
for a review, see P. Fayet and S. Ferrara, *Physics Reports* **32C** (1977) 249.
- [4] H1 Collaboration, *Z.Phys.* **C74** (1997) 191;
ZEUS Collaboration, *Z.Phys.* **C74** (1997) 207.
- [5] S. Park, in *Proceedings of the 10th Topical Workshop on Proton-Antiproton Collider Physics*, Fermilab, 1995, eds. R. Raja and J. Yoh (AIP, New York, 1995), p. 62.
- [6] LEP Electroweak Working Group, CERN preprint PPE/97-183;
J. Ellis, G.L. Fogli and E. Lisi, *Phys.Lett.* **B389** (1996) 321.
- [7] Y. Okada, M. Yamaguchi and T. Yanagida, *Progr.Theor.Phys.* **85** (1991) 1;
J. Ellis, G. Ridolfi and F. Zwirner, *Phys.Lett.* **B257** (1991) 83 and *Phys.Lett.* **B262** (1991) 477;
H.E. Haber and R. Hempfling, *Phys.Rev.Lett.* **66** (1991) 1815;
R. Barbieri, M. Frigeni and F. Caravaglios, *Phys.Lett.* **B258** (1991) 167;
Y. Okada, M. Yamaguchi and T. Yanagida, *Phys.Lett.* **B262** (1991) 54.
- [8] P. Janot, private communication.
- [9] E. Richter-Was, D. Froidevaux, F. Gianotti, L. Poggioli, D. Cavalli and S. Resconi, CERN Preprint TH/96-111 (1996).
- [10] L. Maiani, *Proceedings Summer School on Particle Physics*, Gif-sur-Yvette, 1979 (IN2P3, Paris, 1980), p. 3;
G. 't Hooft, in *Recent Developments in Field Theories*, eds. G. 't Hooft et al. (Plenum Press, New York, 1980);
E. Witten, *Nucl.Phys.* **B188** (1981) 513;
R.K. Kaul, *Phys.Lett.* **109B** (1982) 19.
- [11] S. Dimopoulos, S. Raby and F. Wilczek, *Phys.Rev.* **D24** (1981) 1681;
W.J. Marciano and G. Senjanovic, *Phys.Rev.* **D25** (1982) 3092;
L.E. Ibáñez and G.G. Ross, *Phys.Lett.* **105B** (1982) 439;
M.B. Einhorn and D.R.T. Jones, *Nucl.Phys.* **B196** (1982) 475;
J. Ellis, S. Kelley and D.V. Nanopoulos, *Phys.Lett.* **B249** (1990) 441 and **B260** (1991) 131;
P. Langacker and M. Luo, *Phys.Rev.* **D44** (1991) 817;
U. Amaldi, W. de Boer and H. Furstenau, *Phys.Lett.* **B260** (1991) 447;
F. Anselmo, L. Cifarelli, A. Petermann and A. Zichichi, *Nuovo Cimento* **104A** (1991) 1817.
- [12] J. Ellis, K. Enqvist, D.V. Nanopoulos and F. Zwirner, *Mod.Phys.Lett.* **A1** (1986) 57;
R. Barbieri and G.F. Giudice, *Nucl.Phys.* **B306** (1988) 63;
S. Dimopoulos and G.F. Giudice, *Phys.Lett.* **B357** (1995) 573.
- [13] M. Schmitt, private communication.
- [14] A. Djouadi et al., *Nucl.Phys.* **B349** (1991) 48;
M. Boulware and D. Finell, *Phys.Rev.* **D44** (1991) 2054;
G. Altarelli, R. Barbieri and F. Caravaglios, *Phys.Lett.* **B314** (1993) 357;
D. Garcia and J. Sola, *Phys.Lett.* **B357** (1995) 349;
X. Wang, J. Lopez and D.V. Nanopoulos, *Phys.Rev.* **D52** (1995) 4116;
M. Shifman, *Mod.Phys.Lett.* **A10** (1995) 605;

- G.L. Kane, R.G. Stuart and J.D. Wells, *Phys.Lett.* **B354** (1995) 350;
 J. Erler and P. Langacker, *Phys.Rev.* **D52** (1995) 441;
 P.H. Chankowski and S. Pokorski, *Nucl.Phys.* **B475** (1996) 3;
 J. Ellis, J.J. Lopez and D.V. Nanopoulos, *Phys.Lett.* **B372** (1996) 95 and *Phys.Lett.* **B397** (1997) 88.
- [15] J. Ellis, T. Falk, K.A. Olive and M. Schmitt, CERN preprint TH/97-105, hep-ph/9705444.
- [16] See, e.g., M. Dine and A. Nelson, *Phys.Rev.* **D48** (1993) 1277, **D51** (1995) 1362 and **D53** (1996) 2658.
- [17] D. Stump, M. Wiest and C.-P. Yuan, *Phys.Rev.* **D54** (1996) 1936;
 S. Dimopoulos, M. Dine, A. Raby and S. Thomas, *Phys.Rev.Lett.* **76** (1996) 3494;
 S. Ambrosanio, G. Kane, G. Kribs, S. Martin and S. Mrenna, *Phys.Rev.Lett.* **76** (1996) 3498 and *Phys.Rev.* **D54** (1996) 5395;
 S. Dimopoulos, S. Thomas and J. Wells, *Phys.Rev.* **D54** (1996) 3283;
 K. Babu, C. Kolda and F. Wilczek, *Phys.Rev.Lett.* **77** (1996) 3070;
 J.L. Lopez and D.V. Nanopoulos, *Mod. Phys. Lett.* **A10** (1996) 2473 and *Phys.Rev.* **D55** (1997) 4450;
 J.L. Lopez, D.V. Nanopoulos and A. Zichichi, *Phys.Rev.Lett.* **77** (1996) 5168 and *Phys.Rev.* **D55** (1997) 5813.
- [18] J. Ellis, J.L. Lopez and D.V. Nanopoulos, *Phys.Lett.* **B394** (1997) 354.
- [19] J. Butterworth and H. Dreiner, *Nucl.Phys.* **B397** (1993) 3;
 H. Dreiner and P. Morawitz, *Nucl.Phys.* **B428** (1994) 31;
 E. Perez, Y. Sirois and H. Dreiner, Contribution to Beyond the Standard Model Group, 1995-1996 Workshop on Future Physics at HERA, see also the Summary by H. Dreiner, H.U. Martyn, S. Ritz and D. Wyler, hep-ph/9610232;
 T. Kon and T. Kobayashi, *Phys.Lett.* **B270** (1991) 81;
 T. Kon, T. Kobayashi and S. Kitamura, *Phys.Lett.* **B333** (1994) 263;
 T. Kon, T. Kobayashi, S. Kitamura, K. Nakamura and S. Adachi, *Z.Phys.* **C61** (1994) 239;
 T. Kobayashi, S. Kitamura and T. Kon, *Int.J.Mod.Phys.* **A11** (1996) 1875;
 D. Choudhury and S. Raychaudhuri, *Phys.Lett.* **B401** (1997) 54;
 G. Altarelli, J. Ellis, G.F. Giudice, S. Lola and M.L. Mangano, CERN preprint TH/97-40, hep-ph/9703276.
- [20] H.S. Kambara, for the CDF Collaboration, hep-ex/9706026;
 D0 collaboration, B. Abbott et al., hep-ex/9707033.
- [21] J. Ellis, S. Lola and K. Sridhar, CERN preprint TH/97-109, hep-ph/9705416.
- [22] M.S. Chanowitz, J. Ellis and M.K. Gaillard, *Nucl.Phys.* **B128** (1977) 506.
- [23] J. Kalinowski, R. Rückl, H. Spiesberger and P. Zerwas, hep-ph/9703436.
- [24] D. Bourilkov, private communication.