SEARCHES FOR NEW PARTICLES

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The status of searches for new particles and new physics during the past year at the Fermilab Tevatron, at HERA and at LEP is summarized. A discussion of the hints for the Standard Model Higgs boson from LEP2 data is presented. Searches for non-Standard Model Higgs bosons are also described. Many searches have been carried out for the particles predicted by supersymmetry theories, and a sampling of these is given. There have also been searches for flavor changing neutral currents in the interactions of the top quark. In addition, searches for excited leptons, leptoquarks and technicolor are summarized.

1 Introduction

One of the most tantalizing physics topics of the past year has been the possible evidence for Standard Model Higgs boson production from the LEP experiments. Both the November 2000 combination, which led to a request for an extension of LEP running, and the combination just prepared for the summer conferences are presented here.

Searches for Minimal Supersymmetric Standard Model (MSSM) Higgs bosons and searches in other extensions of the Standard Model have been performed and are summarized. A light Higgs boson with mass near 115 GeV could be the lightest SUSY Higgs $h^0$ with nearly Standard Model couplings.

There have been extensive searches for the supersymmetric partners of the ordinary particles in $p\bar{p}$, $e^+e^-$, and $e^\pm p$ collisions, as well as searches for excited fermions, leptoquarks, and technicolor. In the interests of fitting into the time allowed, I was able to cover only a few of the possible search topics. For example, there were many contributions in various supersymmetry scenarios which I would have liked to discuss in more detail, and I did not discuss the area of large extra dimensions.

I have given references only to the experimental papers, and I refer the reader to them for the theoretical references — otherwise my list of references would have been much longer!

2 Searches for Higgs Bosons

2.1 Standard Model Higgs Search

Preliminary results of searches for the Standard Model Higgs boson at LEP2 were presented at the November 3, 2000, meeting of the LEP Experiments Committee (LEPC) using most of the data collected in 2000. The background probability as a function of the test mass $m_H$ for the combination of all four LEP experiments is shown in Fig. 1. For background only, $(1 - CL_\text{b})$ will be 0.50 on the average. The combination of the four LEP experiments presented at the November 3 LEPC meeting showed an excess of $2.9\sigma$.
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significance, or $(1 - CL_b) = 0.0042$, at $m_H \sim 115$ GeV. The negative log-likelihood ratio $-2 \ln Q$ for the LEP combination is shown in Fig. 2. The value of $m_H = 115.0^{+0.7}_{-0.3}$ GeV is given by the point at which the observed $-2 \ln Q$ versus $m_H$ has its minimum value. The lower limit was $m_H > 113.5$ GeV at 95% confidence level (C.L.) with a median limit of 115.3 GeV expected for background only.

Figure 4. Observed and expected behavior of the likelihood ratio $-2 \ln Q$ as a function of the test mass $m_H$, obtained by combining the data of all four LEP experiments. The solid line represents the observation; the dashed/dash-dotted lines show the median background/signal + background expectations. The dark/light shaded bands around the background expectation represent the $\pm 1/\pm 2$ standard deviation spread of the background expectation obtained from a large number of background experiments. The dotted line is the result of a test where the signal from a 115 GeV Higgs boson has been added to the background and propagated through the likelihood ratio calculation.

Each event is assigned a probability $s_i$ of being a signal event and a probability $b_i$ of being a background event at a test Higgs mass $m_H$. The event weight $w_i$ is given by $w_i = (s_i + b_i)/b_i$. The sample likelihood $L$ is the product of the weights. The logarithm is taken, and then the method is log-likelihood ratio:

$$Q(m_H) = \frac{\mathcal{L}(s + b)}{\mathcal{L}(b)}. \quad (1)$$

Two hypotheses are tested: background only, with compatibility measured by $1 - CL_b$, and signal plus background, with compatibility measured by $CL_{s+b}$ ($CL_s = CL_{s+b}/CL_b$). The event weights in terms of $s/b$ for $m_H = 115$ GeV are given in Table 1 for the current combination and for the November 3 LEP combination for the events with the ten largest weights in the current combination. Apart from the L3 missing energy event (and the OPAL event marked "**", which was

Figure 2. Negative log-likelihood ratio $-2 \ln Q$ as a function of $m_H$ for the four LEP experiments combined for year 2000 data as shown at the November 3, 2000, LEPC meeting.

Figure 3. Higgsstrahlung process for production of the Standard Model Higgs boson in $e^+e^-$ collisions at LEP.

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At LEP the SM Higgs boson is expected to be produced mainly through the Higgsstrahlung process $e^+e^- \rightarrow H^0Z^0$, shown in Fig. 3, with small additional contributions from $t$-channel $W$ and $Z$ boson fusion processes. Searches are performed in the channels $HZ \rightarrow b\bar{b}q\bar{q}$ (four jet), $HZ \rightarrow b\bar{b}\nu\bar{\nu}$ (missing energy), $HZ \rightarrow b\tau^+\tau^-$ or $\tau^+\tau^-q\bar{q}$ (tau), and $HZ \rightarrow bb\tau^+\tau^-$ or $bb\mu^+\mu^-$ (leptonic).
recorded after the deadline for the November 3 combination and was reprocessed with calibrations for that data set, giving it a higher weight), the event weights show only small changes. The L3 event weight changed because the event was unlikely either for signal or background, and higher statistics Monte Carlo simulations resulted in a lower weight. All four LEP experiments have published preliminary results for the 2000 data, and L3 has published their final analysis.

Figure 5. The probability \((1 - CL_b)\) as a function of the test mass \(m_H\). Solid line: observation; dashed/dash-dotted lines: expected probability for the background/signal + background hypotheses.

Figure 6. Probability density functions corresponding to a test mass \(m_H = 115.6\,\text{GeV}\), for the background and signal + background hypotheses. The observed value of \(-2\ln Q\) which corresponds to the data is indicated by the vertical line. The light shaded region is a measure of the compatibility with the background hypothesis, \(1 - CL_b\) \((3.4\%)\), and the dark shaded region is a measure of compatibility with the signal + background hypothesis, \(CL_{s+b}\) \((44\%)\).

Figure 7. Confidence level \(CL_s\) for the signal + background hypothesis. Solid line: observation; dashed line: median background expectation. The dark/light shaded bands around the median expected line correspond to the \(\pm 1/\pm 2\) standard deviation spreads from a large number of background experiments.

Figure 8 shows the negative log-likelihood ratio \(-2\ln Q\) versus \(m_H\) for the current LEP combination of the preliminary results of three LEP experiments and the final result of one experiment. The minimum is observed at \(m_H = 115.6\,\text{GeV}\). The probability \((1 - CL_b)\) versus \(m_H\) is shown in Fig. 8. At \(m_H = 115.6\,\text{GeV}\), \(1 - CL_b = 0.034\), corresponding to a probability of background fluctuation of 2.1 standard deviations.

The probability density functions corresponding to a test mass \(m_H = 115.6\,\text{GeV}\), for the background and signal plus background hypotheses, are shown in Fig. 8. The area under the background curve below the observed value of \(-2\ln Q\) corresponds to 3.4% probability of compatibility with background, and the area under the signal curve above the observed value of \(-2\ln Q\) corresponds to 44% probability of compatibility with signal plus background. Figure 8 shows the the distributions of \(CL_s\) versus \(m_H\), which give the lower limit of \(m_H > 114.1\,\text{GeV}\) at 95% C.L. with a median limit of 115.4 GeV expected for background only.

Figure 9 shows the reconstructed Higgs mass distributions for special non-biasing selections with low (Fig. 8a), medium (Fig. 8b),
Table 1. Comparison of event weights between November 3, 2000, LEPC and current combination.

| Exp. | Channel | \(m_{H}^{REC}\) (GeV) | Nov. 3 s/b | Current s/b |
|------|---------|----------------------|------------|------------|
| 1    | ALEPH   | 114                  | 4.7        | 4.7        |
| 2    | ALEPH   | 113                  | 2.3        | 2.3        |
| 3    | ALEPH   | 110                  | 0.9        | 0.9        |
| 4    | L3      | E-miss               | 115        | 2.1        | 0.7        |
| 5    | OPAL*   | 4-jet                | 111        | 0.4        | 0.7        |
| 6    | DELPHI  | 4-jet                | 114        | 0.5        | 0.6        |
| 7    | ALEPH   | Lept                 | 118        | 0.6        | 0.6        |
| 8    | ALEPH   | Tau                  | 115        | 0.5        | 0.5        |
| 9    | ALEPH   | 4-jet                | 114        | 0.4        | 0.5        |
| 10   | OPAL    | 4-jet                | 113        | 0.5        | 0.5        |

Figure 8. Distributions of the reconstructed Higgs mass, \(m_{H}^{REC}\), from three special, non-biasing, selections with increasing purity of a signal from a 115 GeV Higgs boson.

and high (Fig. 8c) purity.

2.2 MSSM Higgs Search

In the Minimal Supersymmetric Standard Model (MSSM) there are two scalar field doublets resulting in five physical Higgs bosons: two neutral \(CP\)-even scalars, \(h^0\) and \(H^0\) (with \(m_{h^0} < m_{H^0}\)), one \(CP\)-odd scalar, \(A^0\), and two charged scalars, \(H^\pm\). At tree level, \(m_{h^0} \leq m_{Z}, m_{A^0} \leq m_{H^0}, m_{Z} \leq m_{H^0}\), and \(m_{H^\pm} \leq m_{W}\). Loop corrections, predominantly from \(t\) and \(\tilde{t}\), modify these mass relations, unfortunately for LEP2. However, in the MSSM, there must be a lowest mass neutral Higgs boson \(h^0\) with \(m_{h^0} \leq 135\) GeV.

At the current \(e^+e^-\) center-of-mass energies accessible to LEP, the \(h^0\) and \(H^0\) bosons are expected to be produced predominantly via two processes: the Higgsstrahlung process \(e^+e^- \rightarrow h^0Z^0\) (as for \(H^0_{SM}\)) and the pair production process \(e^+e^- \rightarrow h^0A^0\). The cross sections for these two processes, \(\sigma_{hZ}\) and \(\sigma_{hA}\), are related at tree level to the SM cross sections by the following relations:

\[e^+e^- \rightarrow h^0Z^0: \quad \sigma_{hZ} = \sin^2(\beta - \alpha) \sigma_{hZ}^{SM} \quad (2)\]
Figure 9. The MSSM exclusion for the $m_{h^0} - \text{max}$ benchmark scenario. The excluded (hatched) and theoretically disallowed (dark grey) regions are shown as functions of the MSSM parameters in two projections: (left) the ($m_{h^0}, m_{A^0}$) plane and (right) the ($m_{h^0}, \tan \beta$) plane. The dashed lines indicate the boundaries of the regions expected to be excluded at the 95% C.L. if only SM background processes are present.

$$e^+ e^- \rightarrow h^0 A^0 : \sigma_{hA} = \cos^2 (\beta - \alpha) \bar{\lambda} \sigma_{hZ}^{\text{SM}}$$

(3)

where $\sigma_{hZ}^{\text{SM}}$ is the Higgsstrahlung cross section for the SM process $e^+ e^- \rightarrow H_{SM}^{0} Z^0$, and $\bar{\lambda}$ is a factor accounting for the suppression of the $P$-wave cross section near production threshold.

The angle $\beta$ is defined in terms of the vacuum expectation values $v_1$ and $v_2$ of the two Higgs field doublets: $\tan \beta = v_2 / v_1$. The angle $\alpha$ is the mixing angle that relates the physical mass eigenstate $h^0$ with the field doublets.

In addition, the following parameters are needed to specify the MSSM: $M_{\text{SUSY}}$, $\mu$, the Higgs boson mass parameter; $M_1, M_2, M_3$, the gaugino masses at the electroweak scale (gaugino unification gives a common gaugino mass $m_{1/2}$ at the GUT scale and $M_1 = (5/3) \tan^2 \theta_W M_3$); $A_{t}, A_{b}, A_{t}$, the third family trilinear Higgs-sfermion coupling parameters; $m_{l_1}$, the scalar fermion masses (sfermion mass unification gives a common sfermion mass $m_0$ at the GUT scale); and $m_{A_0}$, the running mass of the $CP$-odd scalar $A^0$. In constrained MSSM (CMSSM) the sfermion and gaugino masses are unified. In addition, in minimal supergravity-broken MSSM (MSUGRA) the trilinear couplings are equal ($A_0$), the scalar masses (including Higgs) are unified, and the electroweak symmetry scale determines $\mu$.

The results of the Standard Model Higgs searches are used for the $e^+ e^- \rightarrow h^0 Z^0$ channel, with the cross sections modified as in Eq. (2), and the decay branching ratios determined by the supersymmetry parameters. Dedicated analyses are done for the associated production of a scalar $h^0$ and pseudoscalar ($A^0$) Higgs. The search channels are $hA \rightarrow b \bar{b} b \bar{b}$ (Ah-4b) and $hA \rightarrow \tau^+ \tau^- b \bar{b}$ or $b \bar{b} \tau^+ \tau^-$ (Ah-tau).

The presence of an MSSM Higgs boson signal is tested in a constrained MSSM in which the parameter $A$ is the common trilinear Higgs-squark coupling parameter. Three benchmark scenarios are considered: the “no-mixing” scenario, in which there is no mixing between the scalar partners of the left-handed and right-handed top quarks, $M_{\text{SUSY}} = 1$ TeV, $M_2 = 200$ GeV, $\mu = -200$ GeV, and...
\( X_t(\equiv A - \mu \cot \beta) = 0, \ 0.4 < \tan \beta < 50, \ 4 \text{ GeV} < m_{A^0} < 1 \text{ TeV}, \) and the gluino mass \( m_{\tilde{g}} = 800 \text{ GeV}; \) the “\( m_{h^0} - \text{max} \)” scenario, which is designed to yield the maximal value of \( m_{h^0} \) in the model, corresponds to the most conservative range of excluded \( \tan \beta \) values for fixed values of \( M_{\text{SUSY}} \) and the top quark mass, and has the same values of the parameters as in the no-mixing scenario except for the stop mixing parameter \( X_t = 2M_{\text{SUSY}}; \) and the “large \( \mu \)” scenario, which is designed to illustrate choices of MSSM parameters for which \( h^0 \) does not decay into pairs of \( b \) quarks and uses parameters \( M_{\text{SUSY}} = 400 \) GeV, \( M_2 = 400 \) GeV, \( \mu = 1 \) TeV, \( m_{\tilde{g}} = 200 \) GeV, \( 4 < m_{A^0} < 400 \) GeV, and \( X_t = -300 \) GeV.

Figure 10 shows the MSSM exclusion regions for the \( m_{h^0} - \text{max} \) benchmark scenario for the combination of the preliminary results of the four LEP experiments. In the \( m_{h^0} - \text{max} \) scenario, the limits obtained are \( m_{h^0} > 91.0 \) GeV and \( m_{A^0} > 91.9 \) GeV at 95% C.L., and the range \( 0.5 < \tan \beta < 2.4 \) is excluded for a top quark mass less than or equal to 174.3 GeV.

### 2.3 Non-Standard Model Higgs Searches

Searches for Higgs bosons decaying into photons have been carried out by the four LEP collaborations, and the combination of preliminary results is shown in Fig. 10. A lower bound of 108.2 GeV is set at 95% C.L. for Higgs bosons produced with the Standard Model cross section \( \sigma_{\text{SM}} hZ \) and not decaying into fermion pairs.

Searches for Higgs bosons produced with the Standard Model \( hZ \) cross section and decaying hadronically but not necessarily into \( b \) quarks have been combined for the four LEP experiments for the first time. The combination of preliminary results in shown in Fig. 11. A lower limit of 112.9 GeV at 95% C.L. was obtained for \( h \) decaying 100% hadronically.

Two Higgs Doublet Models (2HDMs) are extensions of the Standard Model in which two scalar doublets and five physical Higgs
Figure 12. Excluded \((m_{A^0}, m_{h^0})\) region independent of \(\alpha\), together with the expected exclusion limit. A particular \((m_{A^0}, m_{h^0})\) point is excluded at 95% C.L. if it is excluded for \(0.4 \leq \tan \beta \leq 58.0\) (darker grey region), \(0.4 \leq \tan \beta \leq 1.0\) (lighter grey region) and \(1.0 \leq \tan \beta \leq 58.0\) (hatched region) for \(-\pi/2 \leq \alpha \leq \pi/2\). The cross-hatched region is excluded using constraints from \(\Gamma_Z\) only. Expected exclusion limits are shown as a dashed line.

### 3 Searches for Supersymmetry

In supersymmetric (SUSY) models each of the “normal” particles (leptons, quarks, and gauge bosons) has a supersymmetric partner (scalar leptons, scalar quarks, and gauginos) with spin differing by half a unit. Most of the searches for these supersymmetric particles are performed within the MSSM assuming \(R\)-parity conservation. \(R\)-parity is a multiplicative quantum number defined as 

\[
R_p = (-1)^{3B+L+2S},
\]

where \(B\), \(L\), and \(S\) are the baryon number, lepton number, and spin of the particle, respectively. \(R\)-parity discriminates between ordinary and supersymmetric particles: \(R_p = +1\) for the ordinary SM particles and \(-1\) for their supersymmetric partners. If \(R\)-parity is conserved, supersymmetric particles are always produced in pairs and always decay through cascade decays to ordinary particles and the lightest supersymmetric particle (LSP), which must be stable.

In gravity mediated SUSY breaking, the LSP is the lightest neutralino \(\tilde{\chi}_1^0\), and the gravitino \(\tilde{G}\) is heavy. In gauge mediated
SUSY breaking, the G is very light (LSP) and $\tilde{\chi}^0_1 \to \tilde{G} \gamma$, for example.

### 3.1 Searches for Scalar Leptons

Scalar leptons (sleptons, $\tilde{\ell}^\pm$) can be produced in pairs in $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$. They decay, for example, to the LSP $\tilde{\chi}^0_1$ and a lepton of the same flavor: $\tilde{\ell}^- \to \tilde{\chi}^0_1 \ell^-$. The topology is acoplanar leptons $\ell^+\ell^-$, and observation depends on $\Delta M = M_{\ell^+\ell^-} - M_{\tilde{\chi}^0_1}$ since the $\tilde{\chi}^0_1$ is undetectable.

Preliminary searches for sleptons from the four LEP experiments have been combined and the excluded regions are shown in Fig. 13. The combined LEP 95% C.L. lower limits for $\Delta M > 10$ GeV are: $M_{\tilde{\ell}_R} > 99$ GeV, $M_{\tilde{\ell}_L} > 95$ GeV, and $M_{\tilde{\chi}^0_1} > 80$ GeV. [Note: $\tilde{\ell}^+_R, \tilde{\ell}^-_L$ are the scalar partners of the right-handed, left-handed $\ell^-$, and $\sigma(e^+e^- \to \tilde{\ell}^+_R\tilde{\ell}^-_R)$ is smaller than $\sigma(e^+e^- \to \tilde{\ell}^+_L\tilde{\ell}^-_L)$,].

### 3.2 Searches for Squarks and Gluinos

The SUSY partners of top and bottom quarks (stop, $\tilde{t}$, and sbottom, $\tilde{b}$) have been searched for in the LEP experiments. Stop and sbottom are mixtures of the SUSY partners of the left- and right-handed quarks, with the lowest mass squarks denoted by $\tilde{t}_1 = \tilde{t}_L \cos \theta_t + \tilde{t}_R \sin \theta_t$ and $\tilde{b}_1 = \tilde{b}_L \cos \theta_b + \tilde{b}_R \sin \theta_b$, where $\theta_t$ and $\theta_b$ are the mixing angles. Searches for no mixing and for the mixing angles for which the $\tilde{t}_1$ and $\tilde{b}_1$ decouple from the $Z^0$. Exclusion regions for combinations of preliminary data from the four LEP experiments are shown in Fig. 14 for no mixing and for the mixing angles for which the $\tilde{t}_1$ and $\tilde{b}_1$ decouple from the $Z^0$. The 95% C.L. lower limits are shown in Table 2.

Experiments at hadron colliders are sensitive to searches for scalar quarks ($\tilde{q}$) and gluinos ($\tilde{g}$). An example is shown in Fig. 13 of a recent search by CDF based on the signature of large missing energy from the two LSPs and three or more hadronic jets resulting from the decays of the $\tilde{q}$ and/or $\tilde{g}$. They obtain 95% C.L. limits of $m_{\tilde{q}} > 195$ GeV independent of $m_{\tilde{g}}$, and $m_{\tilde{g}} > 300$ GeV for the case $m_{\tilde{q}} \approx m_{\tilde{g}}$. 

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Figure 14. 95% C.L. lower limits for combined data from the LEP experiments for the masses of scalar top and scalar bottom quarks versus the mass of the supersymmetric decay product. Limits are shown for zero mixing angle and for the mixing angle at which the $\tilde{t}_1$ ($\tilde{b}_1$) decouples from the $Z^0$. 

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ADLO Preliminary

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ALO Preliminary

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Table 2. The excluded $M_{\tilde{t}_1}$ and $M_{\tilde{b}_1}$ regions at 95% C.L. for $\Delta M > 10$ GeV.

| Lower limit for $\tilde{t}_1$ (GeV) | Lower limit for $\tilde{b}_1$ (GeV) |
|----------------------------------|----------------------------------|
| $\theta_1$                      | $\theta_2$                      |
| $\tilde{t}_1 \rightarrow \tilde{t}_1$ | $\tilde{b}_1 \rightarrow \tilde{b}_1$ |
| $c\chi^0_1$                     | $b\ell\nu$                      |
| 0                               | 97                              |
| 97                              | 97                              |
| 68                              | 92                              |

Figure 15. The 95% C.L. region in the $m_q - m_{\tilde{q}}$ plane newly excluded by CDF. Results from some previous searches by CDF, D0, LEP, UA1 and UA2 are also shown.

3.3 Searches for Charginos and Neutralinos

Charginos ($\tilde{\chi}^\pm$) can be produced in pairs in $e^+e^-$ collisions: $e^+e^- \rightarrow \tilde{\chi}^+_1\tilde{\chi}^-_1$. They can then typically decay as $\tilde{\chi}^+_1 \rightarrow \tilde{\chi}^0_1 W^* \rightarrow \chi^0_1 \ell^+\nu$ or $\tilde{\chi}^+_1 q\bar{q}'$. The signature is large missing energy and large missing transverse momentum, and detection depends on $\Delta M = M_{\tilde{\chi}^+_1} - M_{\tilde{\chi}^0_1}$. There are several topologies: hadronic with large multiplicity, large multiplicity with isolated lepton, and low multiplicity (acoplanar leptons). At large $m_0$ (heavy scalar leptons) the cross section is the largest. The lower limit for $M_{\tilde{\chi}^+_1}$ is nearly at the kinematical limit. The exclusion region from the combination of preliminary searches from the four LEP experiments is shown in Fig. [14]. The 95% C.L. lower limit is $M_{\tilde{\chi}^+_1} > 103.5$ GeV for $M_{\tilde{\chi}^0} > 300$ GeV.

Limits on the $\chi^0_1$ LSP mass are obtained from combined searches for charginos, sleptons, and MSSM Higgs bosons. The exclusion regions for MSUGRA constraints and for CMSSM constraints for the combined preliminary LEP searches are shown in Fig. [17]. The 95% C.L. lower limits are $M_{\tilde{\chi}^0_1} > 60$ GeV for MSUGRA and $M_{\tilde{\chi}^0_1} > 45.6$ GeV for CMSSM, both for 175 GeV top quark mass.

3.4 Searches for R-parity Violating SUSY

In R-parity violating SUSY decays, the lightest supersymmetric particle is expected to be unstable. Many searches have been performed for R-parity violating SUSY. One example from H1 is shown in Fig. [18]. In this case the squarks are assumed to be produced through an R-parity violating $\lambda'_{ijk}$ coupling. They decay either through the same coupling or through an R-parity conserving gauge decay into a $\tilde{\chi}^\pm$, a $\tilde{\chi}^0$, or a $\tilde{g}$.
4 Single Top Quark Production

Searches for flavor-changing neutral currents (FCNC) have been performed at the Fermilab Tevatron in rare decays of the top quark and at LEP and HERA in single top quark production. FCNC are suppressed at tree level in the Standard Model (GIM mechanism). Small contributions occur at the one-loop level. In $e^+ e^-$ the SM cross section is $\sim 10^{-9}$ fb. Extensions to the Standard Model, such as SUSY and multiple Higgs
doublet models, can allow FCNC at the tree level.

\[ e^- (u,c) \rightarrow \gamma, Z \]

LEP $e^+e^- \rightarrow t\bar{q} \rightarrow bWq$

\[ e^- (u,c) \rightarrow \gamma, Z \]

HERA $e^-p \rightarrow e^-bWX$

Figure 19. Single top quark production at LEP and HERA.

Figure 20. The light grey region shows the combined LEP exclusion region at 95% C.L. in the $\kappa_Z - \kappa_\gamma$ plane for $m_t = 174$ GeV with QCD and ISR corrections. The exclusion curves for different values of $m_t$ are also shown. The hatched area shows the CDF exclusion region, and the two vertical lines with arrows show the ZEUS and H1 $\kappa_{\gamma\nu}^b$ exclusion regions.

CDF performed a search in the top decays $t \rightarrow \gamma c(u)$ and $t \rightarrow Z^0 c(u)$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. Searches for single top production at LEP and HERA can be described by the processes shown in Fig. 19. The FCNC transition can be described using the anomalous coupling parameters $\kappa_\gamma$ and $\kappa_Z$, which represent the tree-level $\gamma$ and $Z^0$ exchange contributions. The 95% C.L. exclusion regions in the $\kappa_\gamma - \kappa_Z$ plane are shown in Fig. 21 for CDF, ZEUS, H1, and the combination of preliminary LEP data. QCD and ISR corrections to the Born-level cross sections are used for the LEP combination.

5 Events with Isolated Leptons and Large Missing $p_T$

The H1 experiment at HERA observes an excess of events with isolated leptons and large missing transverse momentum ($p_T$). The primary Standard Model process is single $W$ production. The presence of these excess events increases the lower limit on $\kappa_\gamma$ in the single top quark search. Figure 21 shows a comparison of the events with the predictions for single $W$ production for electrons and muons separately. The excess above the SM expectation is mainly due to events with transverse momentum of the hadronic system ($P_T^X$) greater than 25 GeV where 10
events are found compared to 2.8 ± 0.7 expected. The numbers of events in the electron and muon channels for $P_T^X < 25 \text{ GeV}$ and $P_T^X > 25 \text{ GeV}$ are shown in Table 3. The ZEUS experiment does not observe an excess; the numbers of events for $P_T^X > 25 \text{ GeV}$ for ZEUS are also shown in Table 3.

Table 3. Comparison of numbers of events with isolated leptons and large missing $p_T$ with the predictions of Standard Model single $W$ production for H1 and ZEUS. $P_T^X$ is the transverse momentum of the hadronic system.

|        | $P_T^X < 25 \text{ GeV}$ | $P_T^X > 25 \text{ GeV}$ |
|--------|--------------------------|--------------------------|
| H1     |                         |                          |
| electron | 6 | 6.6 | 2 | 1.0 |
| muon    | 4 | 1.3 | 6 | 1.5 |
| ZEUS    |                         |                          |
| electron | 1 | 1.1 | 1 | 1.3 |

6 Searches for Leptoquarks

Leptoquarks are resonant states carrying both baryon number and lepton number. Searches for them have been performed at the Tevatron and at LEP, and especially at HERA, where they may be produced directly through $e^\pm$-quark fusion, and decay into $e^\pm$-quark or $\nu(\bar{\nu})$-quark. Leptoquarks can be scalar or vector states. $F = L + 3B$ is preserved. Figure 22 shows ZEUS and H1 limits on the Yukawa coupling constant $\lambda$ versus the leptoquark mass for first generation leptoquarks.

7 Searches for Excited Fermions

Excited fermions arise naturally in models that predict a substructure in the fermion sector. Searches for pair production of excited leptons and singly produced excited leptons have been carried out at LEP. The effective electroweak Lagrangian describing chiral magnetic transitions from excited to ordinary leptons can be written

$$\mathcal{L}_{\ell\ell'} = \frac{1}{2\Lambda} \tilde{\ell}^a \sigma^{\mu\nu} \left[ gf \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] \ell_L + h.c., \quad (4)$$

where $\Lambda$ corresponds to the compositeness scale, the subscript L stands for left-handed, $g$ and $g'$ are the SM gauge coupling constants, and the factors $f$ and $f'$ are weight factors associated with the two gauge groups SU(2).
Figure 24. 95% C.L. upper limits on the ratio of the coupling to the compositeness scale for combined LEP search for excited leptons at $\sqrt{s} = 189 - 209$ GeV (left), for ZEUS, H1 and combined LEP searches for excited electrons (center), and for H1 search for excited neutrinos (right).

Typical decays of excited leptons are the following: $\ell^*\pm \rightarrow \ell^\pm \gamma$, $\ell^*\pm \rightarrow \nu W^\pm$, $\ell^*\pm \rightarrow \ell^\pm Z^0$, $\nu^* \rightarrow \nu \gamma$, $\nu^* \rightarrow \ell^\mp W^\pm$, and $\nu^* \rightarrow \nu Z^0$.

Excited fermion production and decay at HERA can occur through the processes shown in Fig. 23. Figure 24 shows the 95% C.L. upper limits on the ratio of the coupling to the compositeness scale for the combined LEP searches for excited leptons $e^*$, $\mu^*$, and $\tau^*$ at $\sqrt{s} = 189 - 209$ GeV, for ZEUS, H1, and combined LEP searches for excited electrons, and for the H1 search for excited neutrinos.

8 Technicolor Searches

Technicolor represents an alternative to the Higgs mechanism for generating electroweak symmetry breaking. In this model the longitudinal degrees of freedom of the massive SM gauge bosons are the Goldstone bosons associated with the breaking of global chiral symmetry of a new kind of fermions, the technifermions, which besides the SM quantum numbers carry the charge of a new QCD-like interaction called Technicolor. In walking technicolor, the lightest technicolor mesons may be light enough to be observable at LEP2. DELPHI and OPAL have carried out searches for such technimesons: $\pi_T$ and $\rho_T/\omega_T$. Figure 24 shows the 95% C.L. excluded regions for these searches. OPAL obtains $m_{\rho_T} > 77$ (62) GeV for $N_D = 9$ (2), where $N_D$ is the number of technifermion doublets (2 is the minimum number). DELPHI obtains $m_{\rho_T} > 89.1$ (79.8) GeV for $N_D = 9$ (2).

9 Summary and Conclusions

There is a “hint” at the two standard deviation level of a signal for a Standard Model Higgs boson from the combined search results of the four LEP experiments. The hint is weaker than it was at the November 3, 2000, LEPC presentation, but the number of events was not enough to establish a signal in any case. An extension of the LEP2 run was requested but unfortunately was not granted. Now we will have to wait until $\sim 2007$ to find out whether there is a light Higgs boson with $m_H \sim 115$ GeV. The 95% confidence level lower limit from the LEP searches is $m_H > 114.1$ GeV with a median limit of 115.4 GeV expected for background only.

Many searches for new particles have been performed, but there have been only negative results and new limits established, so we are still left with only questions: Is there another mechanism for electroweak symmetry breaking? Supersymmetry? Tech-
nicolor? Something we have not even thought of yet? In ten years’ time we should have some answers.

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