The Status of MSSM Higgs Boson Searches at LEP

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The most recently available results from searches conducted by the four LEP experiments at 189 GeV center-of-mass energy for Higgs bosons of the Minimal Supersymmetric Standard Model (MSSM) are presented. No evidence for a signal has been observed, and the null result is used by the experiments, both individually and collectively, to exclude regions of the MSSM parameter space and to set lower limits on Higgs boson masses at 95% confidence level in constrained MSSM scenarios.

I. INTRODUCTION

The problem of the origin of electroweak symmetry breaking in fundamental theories of particle physics is often solved by invoking a Higgs mechanism, where the symmetry is broken by the introduction of one or more scalar field doublets, which in turn give rise to the existence of physical neutral scalar particles called Higgs bosons. Unfortunately the Higgs masses are left as free parameters of the theory. Current fits to precision electroweak data, for example, can allow a Standard Model Higgs boson ($\mathrm{H}^0_{\mathrm{SM}}$) mass of up to 262 GeV/$c^2$ [1].

A common feature of supersymmetric extensions to the SM, however, is the prediction of the existence of a relatively light Higgs boson. In particular, the Minimal Supersymmetric Standard Model (MSSM) predicts the existence of five Higgs bosons: two neutral and CP-even (h^0 and H^0, with $m_{\mathrm{h}^0} < m_{\mathrm{H}^0}$ by definition), one neutral and CP-odd (A^0), and two charged ($\mathrm{H}^{\pm}$). At tree level, m_{h^0} is predicted to be less than m_{Z^0}; however, radiative corrections depending strongly on the top quark mass and mixing in the MSSM's stop sector significantly alter this relation. The stop-mixing terms in turn depend on a number of unknown MSSM parameters, but an upper bound on m_{h^0} can still be set at around 130 GeV/c^2 [2] independent of the choice of these parameters. A substantial fraction of this mass range can be explored at LEP2.

In 1998, the four LEP experiments (ALEPH, DELPHI, L3, and OPAL) each collected over 150 pb^{-1} of $\mathrm{e}^+\mathrm{e}^-$ collision data at $\sqrt{s} \approx 189$ GeV. The individual experimental results presented here are those most recently available, and are in most cases based on only a partial sample of the 1998 data. Therefore they should be regarded as very preliminary.

II. PRODUCTION AND DECAY OF HIGGS BOSONS AT LEP2

Figure 1 shows the two dominant MSSM Higgs production mechanisms at LEP2 ("Higgsstrahlung" and "pair-production"). Their cross-sections are given by

$$\sigma_{\mathrm{hZ}} = \sin^2(\beta - \alpha)\sigma^{\mathrm{HZ}}_{\mathrm{SM}} \tag{1}$$

$$\sigma_{\mathrm{hA}} = \cos^2(\beta - \alpha)\bar{\lambda}\sigma^{\nu\bar{\nu}}_{\mathrm{SM}} \tag{2}$$

where $\tan\beta$ is the ratio of the VEV's of the two neutral CP-even Higgs fields, α is the mixing angle between them, and $\bar{\lambda}$ is a kinematic factor. A complementarity between the two processes can be seen in the appearance of the $\cos^2$ and $\sin^2$ terms.

The Higgsstrahlung process is the radiation of a Higgs by a virtual Z^0 that subsequently goes on-shell. This process is favored in the low $\tan\beta$ ($\approx 1-2$) regime, where it is almost indistinguishable from SM Higgs production and decay. Hence, the SM Higgs searches are "recycled;" we look for a pair of b-jets or τ leptons recoiling from a fermion-antifermion pair with the mass of the Z^0 (the Higgs couples preferentially to high-mass particles; at LEP2 the b and τ are the most massive kinematically-allowed decay products).

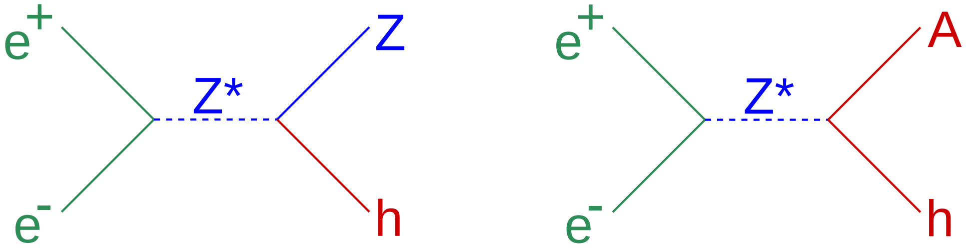

FIG. 1. Feynman diagrams for the h^0Z^0 Higgsstrahlung and h^0A^0 pair-production processes.

The second process is the pair-production of the h^0 and A^0 from the decay of a virtual Z^0. This is the favored process for large $\tan\beta$ (> 15) and gives rise to final states with four heavy fermions. Therefore dedicated searches for the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ final states have been developed.

A third set of topologies can exist in a small subset of the MSSM parameter space where $m_{h^0} > 2m_{A^0}$. In this case $h^0 \to A^0A^0$ may be the dominant decay. The SM Higgs searches still retain a respectable efficiency for this decay when it occurs within the Higgsstrahlung process; in the pair-production process, OPAL performs a dedicated search for the $b\bar{b}b\bar{b}b\bar{b}$ final state.

III. EXPERIMENTAL APPROACH

The predominance of b quarks in the Higgs final states makes b-tagging one of the most important tools in Higgs searching. To that end, all the LEP detectors were equipped with silicon microvertex detectors for precision secondary vertexing of the charged tracks produced in long-lived B hadron decays. The lifetime information is combined with other discriminating variables to yield high-efficiency b identification. As an example of the performance of these algorithms, Figure 2 shows the DELPHI b-tagging efficiency with respect to the dominant Higgs backgrounds as a function of the efficiency for $e^+e^- \to h^0A^0$. For a signal efficiency of 70%, the background from Z^0-pairs and QCD is reduced by an order of magnitude, and in the case of the b-less W-pair decays, several orders of magnitude.

Since the b-tagging is so crucial to the analyses, it is important that its performance is well-understood. For example, OPAL cross-checks Monte Carlo efficiency/fake-rate predictions with high-energy data samples such as radiative returns to the Z^0 pole and semileptonic W-pair decays. Checks like these ensure the robustness of the analyses performed in the channels described below.

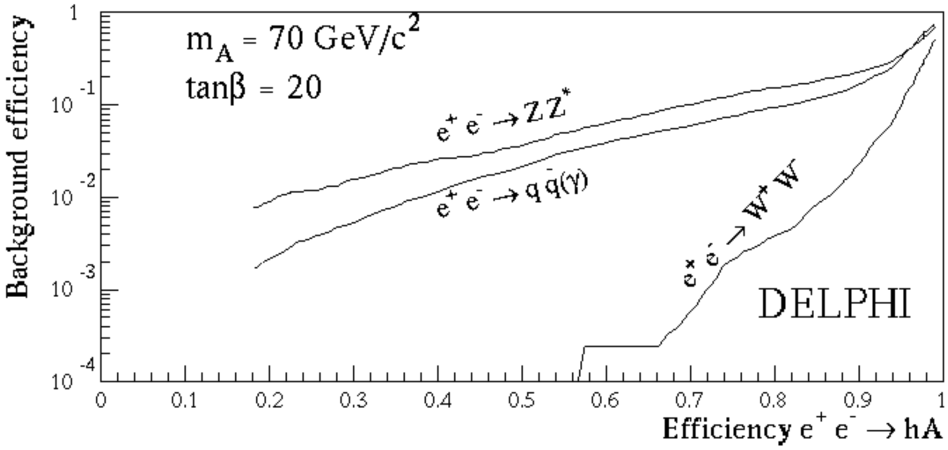

FIG. 2. DELPHI b-tagging efficiency for Higgs background processes versus signal efficiency.

TABLE I. Performance summary of the LEP 4b analyses.

	analyzed $\mathcal{L}(\mathrm{pb}^{-1})$ at 189 GeV	number of events expected	number of events observed	typical efficiency
ALEPH	35.7	1.9	3	60%
DELPHI	158.0	11.1	11	65%
L3[a]	32.9			
OPAL	151.0	7.0	12	50%

[a] Specific numbers from L3 were not available at conference time. This is also the case in Table II.

TABLE II. Performance summary of the LEP tau analyses.

	analyzed $\mathcal{L}(\mathrm{pb}^{-1})$ at 189 GeV	number of events expected	number of events observed	typical efficiency
ALEPH	35.7	0.1	0	30%
DELPHI	158.0	0.6	0	20%
L3	32.9			
OPAL	149.4	4.8	5	40%

A. The 4b Channel

B-tagging information and kinematic quantities are combined to discriminate signal-like $\mathrm{b\bar{b}b\bar{b}}$ events from background, usually via sophisticated algorithms such as multivariate relative likelihoods or artificial neural networks. A summary of the individual experiments' performance in this channel is given in Table I. The signal efficiency typically ranges from 50-65% (the exact number depends on what Higgs masses are under consideration), while the accepted background cross-section is reduced to tens of femtobarns. No significant excess is seen in the data.

B. The Tau Channel

To search for $\mathrm{b\bar{b}}\tau^+\tau^-$ events, b-tagging and kinematic quantities are again combined, this time in addition to tau-tagging schemes of varying complexities. Table II summarizes the performance of the experiments' analyses in this channel. Efficiencies are somewhat lower than in the 4b channel, yet the accepted background cross-section can be reduced to a few femtobarns. Again, no excess is observed in the data.

C. The 6b channel

The presence of 6 b-flavored jets in the $\mathrm{b\bar{b}b\bar{b}b\bar{b}}$ final state is a striking enough topology that a simple analysis can be afforded. Cuts on the charged multiplicity of the event, jet-finding resolution parameters, and b-tags are sufficient to achieve good efficiency with a manageable background. OPAL expects 7.3 background events and observes eight in 151 pb^{-1} of analyzed 189 GeV data while retaining signal efficiencies around 60%. It is worth noting that no explicit mass reconstruction is done in this channel due to the combinatorics involved in reconstructing the six jets to two bosons.

IV. INTERPRETATION AND RESULTS

The non-observation of Higgs production allows us to rule out[1] MSSM scenarios and Higgs masses yielding observable cross-sections. In its most general form the MSSM has more than one hundred free parameters, but many of them have no impact on Higgs phenomenology. Bearing that in mind, results are interpreted within a constrained MSSM where unification of the sfermion masses at the GUT scale is assumed, as well as unification of the sfermion tri-linear couplings and gaugino masses at the electroweak scale.

A. Benchmark Scan

Following a prescription for a benchmark set of MSSM parameters set forth in [3], a large number of possible values of $\tan\beta$ and the running A^0 mass are scanned while keeping the soft SUSY-breaking masses, the top quark mass[2], and the supersymmetric Higgs mass parameter μ fixed. In addition two possible mixings in the stop sector are considered (minimal and maximal). Figure 3 shows an example of the results of this scan in the $m_{\mathrm{h}^0} - m_{\mathrm{A}^0}$ plane for $\tan\beta > 1$. The white area shows the only region that is not excluded by either theory or experiment. Lower limits on m_{h^0} and m_{A^0} can then be read off from the lower left corner of this region; these limits are summarized in Table III. Another projection of this scan, this time in the $m_{\mathrm{h}^0} - \tan\beta$ plane (Figure 4), shows that a range of low $\tan\beta$ can be excluded even with maximal stop-mixing. This exclusion has only become available with the 189 GeV data. It should be noted, however, that this exclusion vanishes using a top mass 2σ larger than its measured central value.

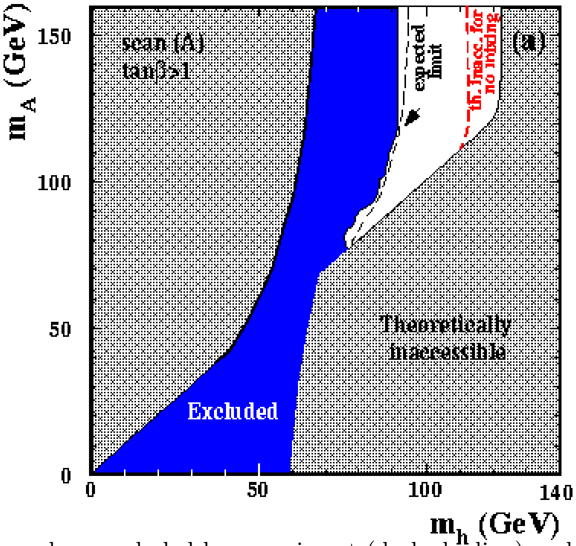

FIG. 3. Regions of the $m_{\mathrm{h}^0} - m_{\mathrm{A}^0}$ plane excluded by experiment (dark shading) and theory (light shading) for $\tan\beta > 1$ (preliminary OPAL 189 GeV benchmark scan).

B. General Scan

A more general interpretation is obtained by ALEPH, DELPHI, and OPAL by releasing all the parameters fixed in the benchmark scan. However, large areas of this enormous parameter space can be excluded on physical grounds,

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[1] All exclusions and mass limits presented here are at 95% confidence level.

[2] The experimental uncertainty on m_t combined with the Higgs sector's strong sensitivity to this parameter makes m_t "quasi-free."

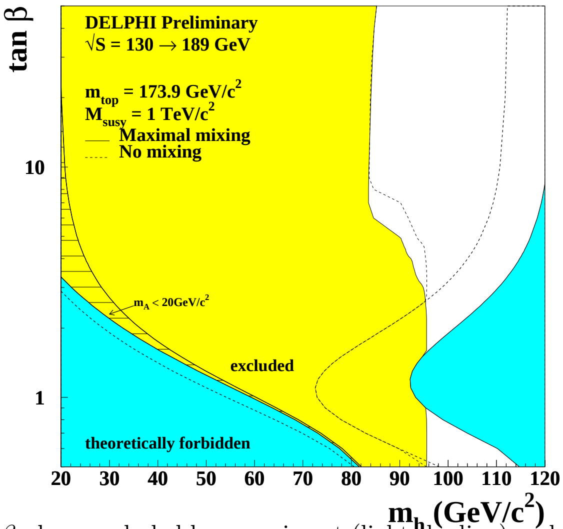

FIG. 4. Regions of the $m_{\mathrm{h}^0} - \tan\beta$ plane excluded by experiment (light shading) and "maximal stop-mixing" theory (dark shading) in the benchmark scan. The long dotted line shows the larger excluded area if only minimal stop-mixing is considered.

TABLE III. Lower mass limits for $\tan\beta > 1$, based on varying amounts of analyzed data at 189 GeV.

	ALEPH[a]	DELPHI	L3	OPAL
m_{h^0} (GeV/c^2)	79.7	83.5	74	76
m_{A^0} (GeV/c^2)	79.7	84.5	74	77

[a] Results based on hA search only

such as requiring the absence of charge and color-breaking minima in the MSSM Lagrangian and requiring neutralino and stop masses that are unexcluded by direct searches. An example of this scan in the $m_{\mathrm{h}^0} - m_{\mathrm{A}^0}$ plane is shown in Figure 5 (this scan only uses data taken up to and including 1997's 183 GeV run). Some conclusions drawn from these scans are that absolute mass limits are generally 5-10 GeV/c^2 worse than those derived from the benchmark scan, and that the limit-weakening parameter sets constitute 0.01-0.1% of those scanned. These sets are usually characterized by a small $\sin^2(\beta - \alpha)$ (such that $\mathrm{h}^0\mathrm{Z}^0$ production is heavily suppressed) and an A^0 out of LEP2's kinematic reach.

C. LEP-wide Combinations

It can be seen that the individual experiments' mass limits are well below the kinematic limit; therefore substantial gains can be made by pooling the luminosities of the four experiments. This is not a straightforward procedure; the LEP Higgs Working Group has investigated four statistical procedures for combining the individual results, described in [4]. This combination has been done within the context of the benchmark scan for all data up to and including 1997's 183 GeV run. Quantitative results from this combination include an exclusion of $\tan\beta$ in the range 0.8-2.1 for minimal stop-mixing and $m_t = 175$ GeV/c^2, and lower mass limits on m_{h^0} and m_{A^0} of 78.8 and 79.1 GeV/c^2, respectively. These mass limits represent a gain of about 10 GeV/c^2 with respect to the experiments' individual 183 GeV results.

V. CHARGED HIGGS BOSONS

Charged Higgs bosons could be produced at LEP2 from the decay of a virtual Z^0 into a $\mathrm{H}^+\mathrm{H}^-$ pair. Most MSSM scenarios predict a charged Higgs mass that puts it out of reach of LEP2; however, light charged Higgses can exist in some more general two-Higgs-doublet models. Searches for $\mathrm{H}^+\mathrm{H}^-$ have been performed at LEP2 in the hadronic

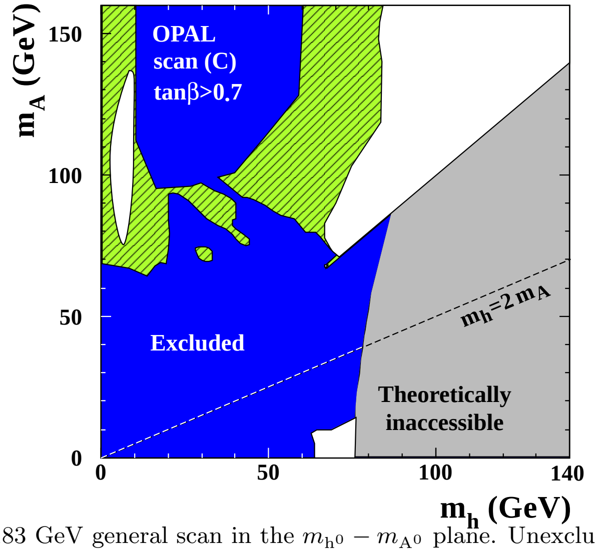

FIG. 5. Results of the OPAL 183 GeV general scan in the $m_{\mathrm{h}^0} - m_{\mathrm{A}^0}$ plane. Unexcluded regions are shown in white.

(c$\bar{\mathrm{s}}\bar{\mathrm{c}}$s), semileptonic (cs$\tau\nu_\tau$) and leptonic ($\tau^+\nu_\tau\tau^-\bar{\nu_\tau}$) channels. This search is experimentally quite challenging due to the large background from W-pair decays with topologies nearly identical to the signal. No evidence for a signal has been observed in the data, and lower limits are placed on $m_{\mathrm{H}^\pm}$ as a function of the branching ratio to $\tau\nu_\tau$ and assuming $\mathrm{BR}(\tau\nu_\tau) + \mathrm{BR}(\mathrm{q}\bar{\mathrm{q}}') = 1$. The charged Higgs LEP-wide combination is a project that is still in its infancy, but the result of one preliminary combination (again only up to 183 GeV) is shown in Figure 6, which gives a lower limit of 68 GeV/c^2, representing a gain of about 10 GeV/c^2 with respect to the experiments' individual 183 GeV limits.

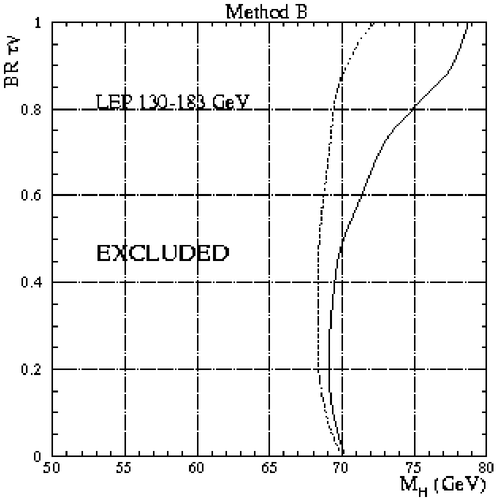

FIG. 6. LEP-wide charged Higgs lower mass limit as a function of $\mathrm{BR}(\mathrm{H}^\pm \to \tau\nu_\tau)$. The dotted line represents the observed limit; the solid line is the average expected limit obtained from a large number of background-only experiments.

VI. CONCLUSION

Despite active searching, the LEP experiments have yet to find any evidence for MSSM Higgs boson production. They have combined their results from data taken at center-of-mass energies from 91 to 183 GeV to place lower benchmark limits on m_{h^0} and m_{A^0} of 78.8 and 79.1 GeV/c^2, respectively. In addition, they exclude the range

$0.8 < \tan\beta < 2.1$ for minimal stop-mixing and $m_t = 175$ GeV/c^2. However, the experiments' individual results from 189 GeV have already begun to supersede the combined results; for example, DELPHI's lower limits on m_{h^0} and m_{A^0} are 83.5 and 84.5 GeV/c^2, respectively. In addition, exclusions of $\tan\beta$ with $m_t = 175$ GeV/c^2 are becoming available for *any* stop-mixing scenario.

The final years of LEP2 running promise to be exciting ones as the center-of-mass energy is pushed up to 200 GeV and possibly beyond. Either the Higgs boson will be discovered, or we will be able to severely constrain the numerous possible manifestations of the MSSM.

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[4] ALEPH, DELPHI, L3, and OPAL Collaborations, the LEP working group for Higgs boson searches, *Lower bound for the Standard Model Higgs boson mass from combining the results of the four LEP experiments*, CERN-EP/98-046 (1998).