Consistency of LEP $Z + b$-jets excess with an $h \to aa$ Decay Scenario and Low-Fine-Tuning NMSSM Models

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We examine the LEP limits for the $Zh \to Z + b$'s final state and find that the excess of observed events for $m_h \sim 100$ GeV correlates well with there being an $m_h \sim 100$ GeV Higgs boson with SM-like $ZZh$ coupling that decays partly via $h \to b\bar{b} + \tau^+\tau^-$ [with $B(h \to b\bar{b}) \sim 0.08$] but dominantly via $h \to aa$ [with $B(h \to aa) \sim 0.9$], where $m_a < 2m_h$ so that $a \to \tau^+\tau^-$ (or light quarks and gluons) decays are dominant. Scenarios of precisely this type arise in the Next-to-Minimal Supersymmetric Model for parameter choices yielding the lowest possible fine-tuning.

LEP has placed strong constraints on $Zh$ production where $h$ decays primarily to $b$-quarks. The limits on $C_{eff}^{2b} = \left| g_{ZZh}^2 / g_{ZZh_{SM}}^2 \right| B(h \to b\bar{b})$ are shown in Fig. 1. These limits rule out a Standard Model (SM) Higgs boson with $m_h \leq 114$ GeV at 95% CL. However, the plot also exhibits the well-known excess of observed vs. expected $C_{eff}^{2b}$ limits for a test Higgs mass of $m_h \sim 100$ GeV. This excess is particularly apparent in the $1 - CL_b$ result (Fig. 7 of [1]) obtained after combining all four LEP experiments. Various interpretations of this excess in terms of a non-SM Higgs sector have been suggested [2, 3]. In this letter, we point out that this excess is consistent with a scenario in which the Higgs boson has SM-like $ZZh$ coupling, but has reduced $B(h \to b\bar{b})$ by virtue of the presence of $h$ decays to a pair of lighter Higgs bosons, $h \to aa$, where we use the notation $a$ appropriate to the NMSSM cases of interest where $a$ is a CP-odd Higgs boson. (For a generic two-Higgs doublet model with or without extra singlets, the light Higgs could alternatively be CP-even, or if CP-violation is present, of mixed CP-nature.) As we shall discuss, the $a$ must not have significant $B(a \to b\bar{b})$. The most naturally consistent possibility is $m_a < 2m_h$ so that $a \to \tau^+\tau^-$ or light quarks and gluons. We then emphasize that parameter choices for the Next to Minimal Supersymmetric Model (NMSSM) that yield the smallest possible fine-tuning typically predict precisely this kind of scenario.

The limits on $C_{eff}^{2b}$ apply when the only decays of the $h$ to $b$-quarks are direct, $h \to b\bar{b}$. If the only decays of $h$ to $b$'s were via $Zh \to Zaa \to Zb\bar{b}a\bar{b}$, alternative constraints [2] on $C_{eff}^{4b} = \left| g_{ZZh}^2 / g_{ZZh_{SM}}^2 \right| B(h \to Zaa)a[B(a \to b\bar{b})]^2$ would apply. Again, $C_{eff}^{4b}$ is above the background Monte Carlo predictions, in particular for $m_h \geq 105$ GeV and $m_a \sim 30 \div 45$ GeV. However, since in the LEP analyzes for the $Z2b$ and $Z4b$ final states the selected candidates are correlated, the $Z2b$ and $Z4b$ excesses cannot be treated as being independent if the Higgs boson decays to both kinds of final state. In particular, a model for which the predictions for $C_{eff}^{2b}$ and $C_{eff}^{4b}$ are individually allowed but both are close to their respective

![FIG. 1: Expected and observed 95% CL limits on $C_{eff}^{2b} = \left| g_{ZZh}^2 / g_{ZZh_{SM}}^2 \right| B(h \to b\bar{b})$ from Ref. [1] are shown vs. $m_h$. Also plotted are the predictions for NMSSM parameter choices in our fixed $\tan\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV scan that give fine-tuning measure $F < 25$ and $m_{a_b} < 2m_h$ and that are consistent with the preliminary LHWW analysis code.](image-url)
matching the requirements described above. In contrast, in the CP-conserving Minimal Supersymmetric Model (MSSM), $h \to b\bar{b}$ decays are dominant and all parameter choices consistent with LEP limits on $m_h$ are such that the fine-tuning and hierarchy problems are severe.

The NMSSM is an extremely attractive model. First, it provides a very elegant solution to the $\mu$ problem of the MSSM via the introduction of a singlet superfield $\tilde{S}$. For the simplest possible scale invariant form of the superpotential, the scalar component of $\tilde{S}$ naturally acquires a vacuum expectation value of the order of the SUSY breaking scale, giving rise to a value of $\mu$ of order the electroweak scale. The NMSSM is the simplest supersymmetric extension of the standard model in which the electroweak scale originates from the SUSY breaking scale only. Hence, the NMSSM deserves very serious consideration.

Apart from the usual quark and lepton Yukawa couplings, the scale invariant superpotential of the NMSSM is $W = \lambda \tilde{S} H_u H_d + \frac{\kappa}{2} \tilde{S}^3$ depending on two dimensionless couplings $\lambda$, $\kappa$ beyond the MSSM. [Hatted (unhatted) capital letters denote superfields (scalar superfield components).] The associated trilinear soft terms are $\lambda A_{\tilde{S}} H_u H_d + \frac{\kappa}{2} A_{\tilde{S}} S^3$. The final two input parameters are $\tan \beta = h_u/h_d$ and $\mu_{\text{eff}} = \lambda s$, where $h_u \equiv \langle H_u \rangle$, $h_d \equiv \langle H_d \rangle$ and $s \equiv \langle S \rangle$. The Higgs sector of the NMSSM is thus described by the six parameters $\lambda$, $\kappa$, $A_\lambda$, $A_{\tilde{S}}$, $\tan \beta$, $\mu_{\text{eff}}$. In addition, values must be input for the gaugino masses and for the soft terms related to the (third generation) squarks and sleptons that contribute to the radiative corrections in the Higgs sector and to the Higgs decay widths.

The particle content of the NMSSM differs from the MSSM by the addition of one CP-even and one CP-odd state in the neutral Higgs sector (assuming CP conservation), and one additional neutralino. The result is three CP-even Higgs bosons ($h_1, h_2, h_3$) two CP-odd Higgs bosons ($a_1, a_2$) and a total of five neutralinos $\tilde{\chi}_1^{0,\ldots,4,5}$. The NMHDECAY program, which includes most LEP constraints, allows easy exploration of Higgs phenomenology in the NMSSM.

In Fig. 1, we found that the Next to Minimal Supersymmetric Model (NMSSM) can avoid the fine-tuning and hierarchy problems of the MSSM for parameter choices that were consistent with all LEP constraints available at the time. Defining the fine-tuning measure to be

$$F = \text{Max}_p F_p \equiv \text{Max}_p \left| \frac{d \log m_Z}{d \log p} \right|, \quad (1)$$

where the parameters $p$ comprise all GUT-scale soft-SUSY-breaking parameters, we found that $F < 10$ could be achieved. Further, at moderate $\tan \beta$, the parameter choices with such $F$ are always such that the lightest CP-even Higgs boson, $h_1$, is SM-like as regards its gauge and fermionic couplings, but decays primarily into a pair of the lightest CP-odd Higgs bosons of the model, $h_1 \to a_1 a_1$. The importance of such decays was first emphasized in Ref. 3, and later in Ref. 4, followed by extensive work in Refs. 11,12.

We note that a light $a_1$ is natural in the NMSSM in the $\kappa A_\lambda, \lambda A_\lambda \to 0$ limit. This can be understood as a consequence of a global $U(1)_R$ symmetry of the scalar potential (in the limit $\kappa A_\lambda, \lambda A_\lambda \to 0$) which is spontaneously broken by the vevs, resulting in a Nambu-Goldstone boson in the spectrum $\tilde{S}$. This symmetry is explicitly broken by the trilinear soft terms so that for small $\kappa A_\lambda, \lambda A_\lambda$ the lightest CP odd Higgs boson is naturally much lighter than other Higgs bosons. For the $F < 10$ scenarios, $\lambda(m_Z) \sim 0.15 \div 0.25$, $\kappa(m_Z) \sim 0.15 \div 0.3$, $|A_\lambda(m_Z)| < 4$ GeV and $|A_{\tilde{S}}(m_Z)| < 200$ GeV, implying small $\kappa A_\lambda$ and moderate $\lambda A_\lambda$. The effect of $\lambda A_\lambda$ on $m_{a_1}$ is further suppressed when the $a_1$ is largely singlet in nature, as is the case for low-$F$ scenarios. Therefore, we always obtain small $m_{a_1}$. We note that small soft SUSY-breaking trilinear couplings at the unification scale are generic in SUSY breaking scenarios where SUSY breaking is mediated by the gauge sector, as, for instance, in gauge or gaugino mediation. Although the value $A_\lambda(m_Z)$ might be sizable due to contributions from gaugino masses after renormalization group running between the unification scale and the weak scale, $A_\lambda$ receives only a small correction from the running (such corrections being one loop suppressed compared to those for $A_{\tilde{S}}$). Altogether, a light, singlet $a_1$ is very natural in models with small soft SUSY-breaking trilinear couplings at the unification scale. Finally, we note that the above $\lambda(m_Z)$ values are such that $\lambda$ will remain perturbative when evolved up to the unification scale, implying that the resulting unification-scale $\lambda$ values are natural in the context of model structures that might yield the NMSSM as an effective theory below the unification scale.

We will now discuss in more detail results for the NMSSM using the representative fixed values of $\tan \beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV while varying all other model parameters. Similar results are obtained for other choices of $\tan \beta$ and $M_{1,2,3}(m_Z)$. The points plotted for the NMSSM in Fig. 1 show the $C_{eff}^{28}$ predictions for all parameter choices in our scan that had $F < 25$ and $m_{a_1} < 2 m_h$ and that are consistent with the experimental and theoretical constraints built into NMHDECAY as well as with limits from the preliminary LHWW full analysis code. The eight $F < 10$ points are singled out. From Fig. 1 we see that these latter points cluster near $m_{h_1} \sim 98 \pm 105$ GeV (see also Fig. 3 of Ref. 4). We will see that most are such that $m_{h_1}$ and $B(h_1 \to b\bar{b})$ are appropriate for explaining the $C_{eff}^{28}$ excess. The other primary $h_1$ decay mode for all the plotted points is $h_1 \to a_1 a_1$ with $a_1 \to \tau^+ \tau^-$ or light quarks and gluons (when $m_{a_1} < 2 m_h$). In Table 1 we give the precise masses and branching ratios of the $h_1$ and $a_1$ for all the $F < 10$ points. We also give the number of standard deviations, $n_{abs}(n_{exp})$, by which the observed rate (expected
TABLE I: Some properties of the $h_1$ and $a_1$ for the eight allowed points with $F < 10$ and $m_{a_1} < 2m_b$ from our tan $\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV NMSSM scan. The $n_{\text{obs}}, n_{\text{exp}}$ and $s_{95}$ values are obtained after full processing of all Zf final states using the preliminary LHWG analysis code (thanks to P. Bechtle). See text for details. $N_{\text{LHC}}^{\text{SD}}$ is the statistical significance of the best “standard” LHC Higgs detection channel for integrated luminosity of $L = 300$ fb$^{-1}$.

| $m_{a_1}/m_{a_1}$ (GeV) | Branching Ratios | $n_{\text{obs}}/n_{\text{exp}}$ | $s_{95}$ | $N_{\text{LHC}}^{\text{SD}}$ |
|-----------------------|-------------------|----------------------|--------|-------------------------|
| 98.0/2.6              | 0.062             | 0.926                | 0.000  | 2.25/1.72               | 2.79  |
| 100.0/9.3             | 0.075             | 0.910                | 0.852  | 1.98/1.88               | 2.40  |
| 100.2/3.1             | 0.141             | 0.832                | 0.000  | 2.26/2.78               | 1.31  |
| 102.0/7.3             | 0.095             | 0.887                | 0.923  | 1.44/2.08               | 1.58  |
| 102.2/3.6             | 0.177             | 0.789                | 0.814  | 1.80/3.12               | 1.03  |
| 102.4/9.0             | 0.173             | 0.793                | 0.875  | 1.79/3.03               | 1.07  |
| 102.5/5.4             | 0.128             | 0.848                | 0.938  | 1.64/2.46               | 1.24  |
| 105.0/5.3             | 0.062             | 0.926                | 0.938  | 1.11/1.52               | 2.74  |

We wish to emphasize that in our scan there are many, many points that satisfy all constraints and have $m_{a_1} < 2m_b$. The remarkable result is that those with $F < 10$ have a substantial probability that they predict the Higgs boson properties that would imply a LEP Zh $\rightarrow Z + b\bar{b}$ excess of the sort seen. The smaller number of $F < 10$ points with $m_{a_1}$ substantially above $2m_b$ all predict a net Z + b’s signal that is ruled out at better than 99% CL by LEP data. Indeed, all $F < 25$ points have a net $h \rightarrow b\bar{b}$ branching ratio, $B(h \rightarrow b\bar{b}) > 0.85$, which is too large for LEP consistency if $m_{a_1}$ is substantial. Analysis of points with $m_{a_1}$ very near $b\bar{b}$ is dominant, is very subtle. Such points arise for $F < 10$ and require further analysis in cooperation with the LHWG.

An important question is the extent to which the type of $h \rightarrow aa$ Higgs scenario (whether NMSSM or other) described here can be explored at the Tevatron, the LHC and a future $e^+e^-$ linear collider. This has been examined in the case of the NMSSM in [2,14,17], with the conclusion that observation of any of the NMSSM Higgs bosons may be difficult at hadron colliders. At a naive level, the $h_1 \rightarrow a_1a_1$ decay mode renders inadequate the usual Higgs search modes that might allow $h_1$ discovery at the LHC. Since the other NMSSM Higgs bosons are rather heavy and have couplings to $b$ quarks that are not greatly enhanced, they too cannot be detected at the LHC. The last column of Table I shows the statistical significance of the most significant signal for any of the NMSSM Higgs bosons in the “standard” SM/MSSM search channels for the eight $F < 10$ NMSSM parameter choices. For the $h_1$ and $a_1$, the most important detection channels are $h_1 \rightarrow \gamma\gamma, W h_1 + \tilde{t}h_1 \rightarrow \gamma\gamma+X, \tilde{t}h_1/a_1 \rightarrow \tilde{b}\tilde{b}, \tilde{b}h_1/a_1 \rightarrow b\tau\tau\tau\tau$ and $WW \rightarrow h_1 \rightarrow \tau^+\tau^-\tau^+\tau^-$ see [12]. Even after $L = 300$ fb$^{-1}$ of accumulated luminosity, the typical maximal signal strength is at best 3.5$\sigma$. For the eight points of Table I this largest signal derives from the $W h_1 + \tilde{t}h_1 \rightarrow \gamma\gamma+X$ channel. There is a clear need to develop detection modes sensitive to the dominant $h_1 \rightarrow a_1a_1 \rightarrow \tau^+\tau^-\tau^+\tau^-$ decay channel.

Let us consider the possibilities. One detection mode that can be considered is $WW \rightarrow h_1 \rightarrow a_1a_1 \rightarrow 4\tau$. Second, recall that the $\tilde{t}\tilde{t} \rightarrow h_1\tilde{b}\tilde{b}$ channel provides a signal in the MSSM when $h_1 \rightarrow bb$ decays are dominant. See, for example, [13]. It has not been studied for $h_1 \rightarrow a_1a_1 \rightarrow 4\tau$ decays. If a light $\chi_1^0$ provides the dark matter of the universe (as possible because of the $\chi_{1,2}^0 \rightarrow a_1 \rightarrow X$ annihilation channels for a light $a_1$, see [14,15] and references therein), the $m_{\tau\tau} - m_{\chi_1^0}$ mass difference might be large enough to allow such decays. Diffractive production [16], $pp \rightarrow pp h_1 \rightarrow ppX$, where the mass $M_X$ can be reconstructed with roughly a 1–2 GeV resolution, can potentially reveal a Higgs peak, independent of the decay of the Higgs. A study [17] is underway to see if this discovery mode works for the $h_1 \rightarrow a_1a_1 \rightarrow 4\tau$ decay mode as well as it appears to work for the simpler SM $h_{SM} \rightarrow bb$ case. The main issue may be whether events can be triggered despite the soft nature of the decay products of the $\tau$’s present in X when $h_1 \rightarrow a_1a_1 \rightarrow 4\tau$ as compared to $h_{SM} \rightarrow bb$.

At the Tevatron it is possible that $Zh_1$ and $Wh_1$ production, with $h_1 \rightarrow a_1a_1 \rightarrow 4\tau$, will provide the most favorable channels. If backgrounds are small, one must simply accumulate enough events. However, efficiencies for triggering on and isolating the $4\tau$ final state will not be large. Perhaps one could also consider $gg \rightarrow h_1 \rightarrow a_1a_1 \rightarrow 4\tau$ which would have substantially larger rate. Studies are needed. If supersymmetry is detected at the
Tevatron, but no Higgs is seen, and if LHC discovery of the $h_1$ remains uncertain, Tevatron studies of the 4r final state might be essential. However, rates imply that the $h_1$ signal could only be seen if Tevatron running is extended until $L > 10$ fb$^{-1}$ has been accumulated. Of course, the LHC would observe numerous supersymmetry signals and would confirm that $WW \to WW$ scattering is perturbative, implying that something like a light Higgs boson must be present, but direct detection of the $h_1$ might have to rely on an extended Tevatron run.

Of course, discovery of the $h_1$ will be straightforward at an $e^+e^-$ linear collider via the inclusive $Z\ell\ell$ method, which allows Higgs discovery independent of the Higgs decay mode. Direct detection in the $Zh\gamma\gamma$ mode will also be possible. At a $\gamma\gamma$ collider, the $\gamma\gamma \to h \to 4\tau$ signal will be easily seen.

In contrast, since (as already noted) the $a_1$ in these low-F NMSSM scenarios is less singletlike in nature, its direct (i.e., not in $h_1$ decays) detection will be very challenging even at the ILC. Further, the low-F points are all such that the other Higgs bosons are fairly heavy, typically above 400 GeV in mass, and essentially inaccessible at both the LHC and all but a $1 \sim 1$ TeV ILC.

We should note that much of the discussion above regarding Higgs discovery is quite generic. Whether the $a$ is truly the NMSSM CP-odd $a_1$ or just a lighter Higgs boson into which the SM-like $h$ pair-decays, hadron collision detection of the $h$ in its $h \to aa$ decay mode will be very challenging — only an $e^+e^-$ linear collider can currently guarantee its discovery.

In conclusion, we reemphasize that the prominent LEP event excess in the $Z+b$'s channel for reconstructed Higgs mass of $m_h \sim 100$ GeV is consistent with a scenario in which the $Zhh$ coupling is SM-like but the $h$ decays mainly via $h \to aa \to \tau^+\tau^-\tau^+\tau^-$ (requiring $m_a < 2m_h$) leaving an appropriately reduced rate for $h \to bb$. We strongly encourage the LEP groups to push the analysis of the $Z\chi\chi$ channel in the hope of either ruling out the $h \to aa \to 4\tau$ scenario, or finding a small excess consistent with it. Either a positive or negative result would have very important implications for Higgs searches at the Tevatron and LHC. Further, we have emphasized that the NMSSM models with the smallest fine-tuning typically predict precisely the above scenario with $h = h_1$ and $a = a_1$. We speculate that similar results will emerge in other supersymmetric models with a Higgs sector that is more complicated than that of the CP-conserving MSSM.

This work was supported by the U.S. Department of Energy under grants DE-FG02-90ER40542 and DE-FG03-91ER40674. JFG thanks the Aspen Center for Physics where part of this work was performed. We are very grateful to P. Bechtle for processing our low-$F$ points through the full preliminary LHWG machinery and for a careful reading of and useful comments on the paper. We thank A. Sopczak for help in obtaining the $Z4b$ data files. R.D. thanks K. Agashe and N. Weiner for discussions.

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