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The 115 GeV Higgs Odyssey

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Abstract

On his way home from Troy, Odysseus had arrived within reach of Ithaca when a great storm blew up. He was swept away, and only several years later was he able to return to reclaim his rights from the rapacious suitors, with the aid of his son Telemachus. Some wonder whether this epic is repeating itself, if the Higgs weighs 115 GeV. If so, are CMS and ATLAS cast in the role of Telemachus? In this paper, I first discuss how close to Ithaca LEP may have been, the fact that a 115 GeV Higgs boson would disfavour technicolour, its potential implications for supersymmetry, and finally the prospects for completing the Higgs Odyssey.

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1 How far from Ithaca?

For several years now, the precision electroweak data have been suggesting [1] that the Higgs boson is very close to the present experimental limit of 113.5 GeV [2]. Fig. 1 shows a recent combination of the likelihood information from one precision electroweak fit with the lower limit from direct searches at LEP [3]. The central value of m_H indicated by the precision electroweak data increases by about 30 GeV if the new BES data on $\sigma(e^+e^- \rightarrow \text{hadrons})$ are used to re-evaluate $\alpha_{em}(m_Z)$ [1], but the message remains clear: Ithaca cannot be far away.

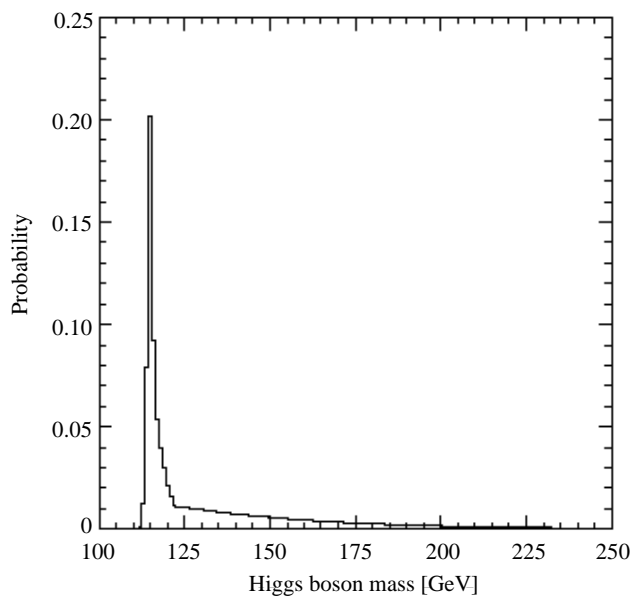


Figure 1: *Probability distribution for the Higgs mass, obtained by combining the LEP lower limit [2] with a precision electroweak fit [3].*

As is well known, in the minimal supersymmetric extension of the Standard Model (MSSM), the Higgs mass may be calculated, is unlikely to exceed 130 GeV [4], and may well be considerably lighter, depending on the ratio of Higgs v.e.v.'s and on the mass of the stop squark. Later we use this linkage to estimate the sparticle spectrum. For the moment, we just note that this is an independent argument for thinking that LEP might have arrived within sight of Ithaca.

Much excitement has been generated by the 'signal' for a Higgs boson with $m_H = 115.0^{+1.3}_{-0.7}$ GeV (90% confidence range), produced in association with a Z^0 [5], reported by the LEP collaborations [6] and the LEP Working Group on Higgs boson searches this Autumn.

The overall significance on Nov. 3rd [2] was higher than on Oct. 10th [7], which was in turn higher than on Sept. 5th [8]: $2.2\sigma \rightarrow 2.5\sigma \rightarrow 2.9\sigma$. Moreover, the overall significances on all three dates were in (improving) agreement with the estimated sensitivity for $m_H \sim 115$ GeV: see Fig. 2 [9]. The probability that the data sample be compatible with background only was found by the LEP Higgs working group to be 1.2% on Sept. 5th, 0.6% on Oct. 10th, and 0.4% on Nov. 3rd, respectively.

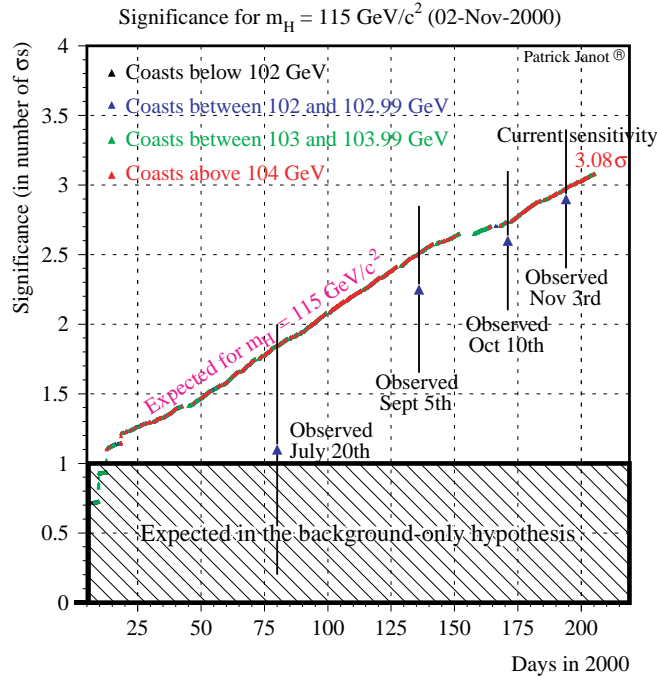


Figure 2: *Expected LEP 2 sensitivity to a Higgs weighing 115 GeV, as a function of the number of days running at high energy in 2000. Also shown as triangles with error bars are the magnitudes of the observed ‘signals’ on Sept. 5th, Oct. 10th and Nov. 3rd.*

The overall significance of the LEP 2 Higgs ‘signal’ did not decrease as would have been expected if there was only background, but instead grew just as would be expected if there was also a real Higgs weighing 115 GeV [2].

The growth in significance between September 5th and November 3 was mainly a result of the accumulation of interesting candidates by L3 and OPAL. The DELPHI ‘signal’ reported on September 5th weakened after re-analysis, and the ALEPH ‘signal’ did not grow. The present situation is that ALEPH still has the largest ‘signal’, the next largest is in L3, then OPAL, and DELPHI is more compatible with pure background, as seen in Fig. 3. The distribution of log-likelihood across the four experiments is quite consistent with common sampling of the same ‘signal’.

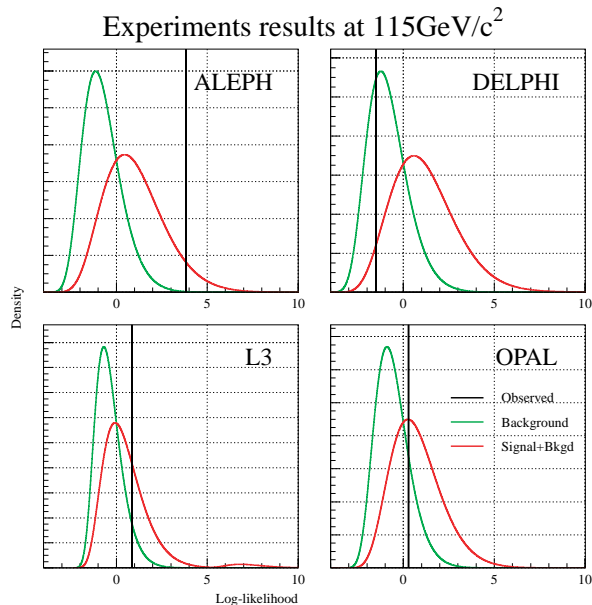


Figure 3: *The distributions of log-likelihood expected in the background and signal + background hypotheses in the four LEP experiments, compared with their observations (vertical lines) [2, 9].*

Moreover, the ‘signal’ spread from the original $\bar{b}b\bar{q}q$ channel to the $\bar{b}b\bar{\nu}\nu$ channel, where it is now almost as significant, as seen in Fig. 4. This metastasis is largely due to an interesting $\bar{b}b\bar{\nu}\nu$ event from L3. They see a pair of $\bar{b}b$ jets with relatively low net p_T that emerge almost back to back. This would be surprising if their invariant mass were much less than 114 GeV, but is just what one might expect if $H \rightarrow \bar{b}b$ with $m_H > 114$ GeV [10], as confirmed by an ALEPH Monte Carlo simulation [11].

Thus the LEP Higgs ‘signal’ did all that it could with the increase in the statistics analyzed on Nov. 3rd - increased in significance, spread to other detectors and to another channel. It would have been nice to have a ‘gold-plated’ event, e.g., in the $\bar{b}b\ell^+\ell^-$ channel, but the truth is that no channels are background-free at LEP ¹.

2 Meanwhile on Mount Olympus

What would be the significance of a Higgs weighing 115 GeV [12]? It would not just be the crowning confirmation of the Standard Model, but would also be evidence for new physics

¹The same is even more true at the Tevatron and the LHC.

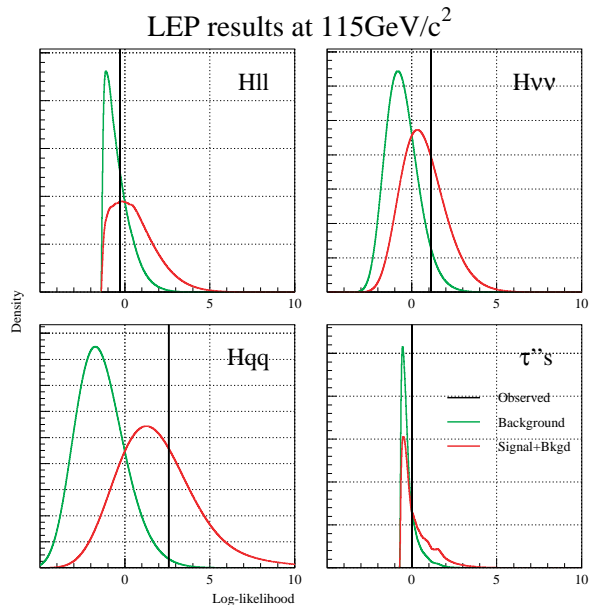


Figure 4: *The distributions of log-likelihood expected in the background and signal + background hypotheses in the four possible Higgs detection channels, compared with their observations (vertical lines) [2, 9].*

beyond it, at a relatively low scale, potentially accessible to the LHC. The reason for this is the shape of the effective Higgs potential, determined by the quartic Higgs coupling λ_H . This is subject to renormalization by the top-quark Yukawa coupling λ_t , as well as by the quartic Higgs coupling λ_H itself. With $m_t \sim 175$ GeV and $m_H \sim 115$ GeV, the renormalization by λ_t is stronger. Moreover, it tends to decrease λ_H , eventually turning it negative at a scale $\lesssim 10^6$ GeV [13]. This causes the effective Higgs potential to become unbounded below, implying that our present electroweak vacuum is unstable - *unless some new physics is introduced at an energy below 10^6 GeV*.

Could this new physics be a new non-perturbative set of strong interactions, as in technicolour or topcolour models? These generally predict large effective scalar masses, e.g., about 1 TeV in the technicolour case [14]. In order to generate fermion masses, one needs to extend technicolour, and such models predict additional pseudoscalar bosons weighing ~ 100 GeV. However, these would not be produced at LEP in association with the Z [15]. Therefore, *technicolour has no obvious candidate for a 115 GeV ‘Higgs’*, and the same seems to be true of other strongly-interacting models of electroweak symmetry breaking [12].

On the other hand, such a *light Higgs boson cries out for supersymmetry*, and vice versa.

In any perturbative framework, one can argue that the new low-energy physics should be *bosonic*, so that it may help λ_H counterbalance the destabilizing effects of λ_t . In MSSM, the task of stabilization is undertaken by the stop squarks.

As already mentioned, in the MSSM the lightest neutral Higgs boson is predicted to weigh $\lesssim 130$ GeV. Since its mass is sensitive, via radiative corrections, to sparticle masses, one can try to use the ‘measurement’ $m_H = 115$ GeV to guess how heavy squarks and other sparticles might be. To do this requires some assumption on the nature of the sparticle spectrum. For example, if all the spin-0 sparticles are assumed to be degenerate at some high (GUT) energy scale with a mass m_0 and likewise for the spin-1/2 gauginos with a common mass $m_{1/2}$, we found that m_H is most sensitive to $m_{1/2}$ [12]. Indeed, as seen in Fig. 5, we found the lower limit $m_{1/2} \gtrsim 240$ GeV if $m_H \gtrsim 113$ GeV and $m_t \leq 180$ GeV. The gluino and squark masses would then be 2 or 3 times heavier: $m_{\tilde{g}} \gtrsim 600$ GeV and $m_{\tilde{q}} \gtrsim 700$ GeV, beyond the reach of the Tevatron ². However, masses up to a factor three above these lower limits are within reach of the LHC, which should be able to cover all of the $(m_0, m_{1/2})$ parameter region where the lightest supersymmetric particle is likely to constitute the cold dark matter posited by astrophysicists and cosmologists [12].

3 Return to Ithaca

We now turn to the jealous suitors and Telemachus. What is the sensitivity of the Tevatron experiments to a Higgs weighing 115 GeV? As seen in Fig. 6, in order to attain 3 (5) σ , it is estimated that they would need 5 (15) fb^{-1} [17]. As for the prospective Tevatron luminosity, at the moment, 2 fb^{-1} is ‘promised’ by 2003. However, a roadmap for reaching 15 fb^{-1} by 2007 has been proposed. If this is achieved, the Tevatron may have a chance if the Higgs weighs 115 GeV, but does not seem likely to detect any heavier Higgs boson.

What of Telemachus? According to CMS and ATLAS studies, as seen in Fig. 7 [18], the minimum luminosity required to start seeing a 115 GeV Higgs at 5 σ is $\sim 10 \text{fb}^{-1}$, which may be achieved after two years of LHC running. Since at most a few weeks of very low luminosity collisions can be envisaged in 2005, and only 1 or 2 fb^{-1} is anticipated in 2006, this presumably means that the LHC could hope to discover a 115 GeV Higgs boson after the 2007 run.

²These lower bounds remain valid even if the LEP Higgs ‘signal’ eventually turns out to be a chimera. Other groups have repeated this analysis using alternative assumptions, obtaining analogous results [16].

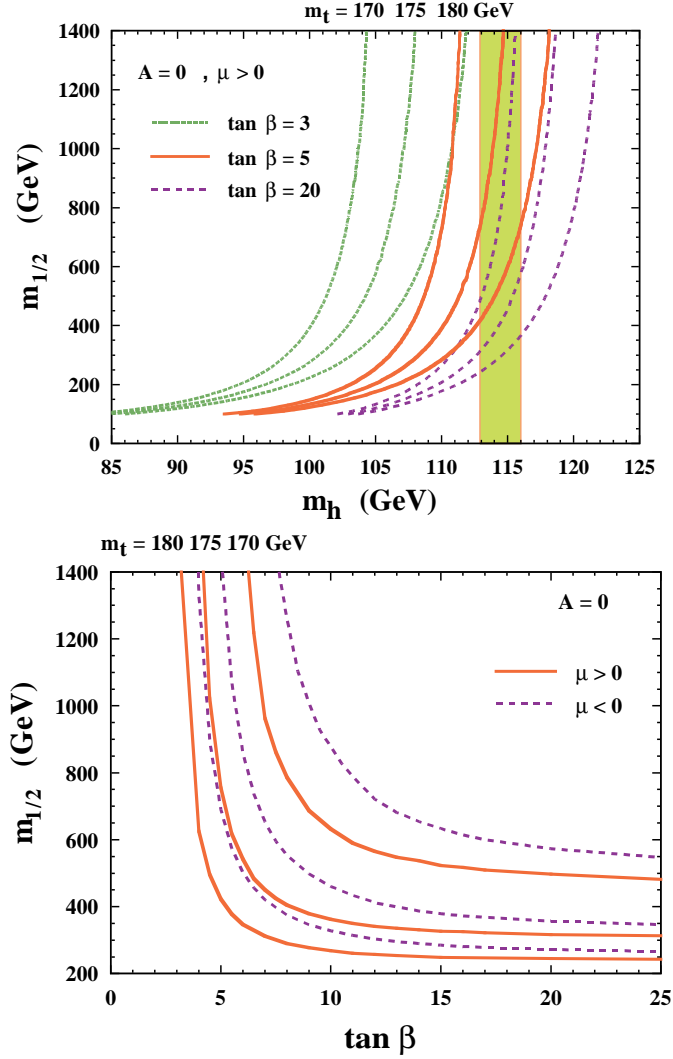


Figure 5: (a) The value of the sparticle mass scale $m_{1/2}$ required in the minimal supersymmetric extension of the Standard Model, assuming universal input sparticle masses, to obtain $m_H \sim 115$ GeV for different values of $\tan \beta$ and m_t , and (b) the corresponding lower bound on $m_{1/2}$ [12].

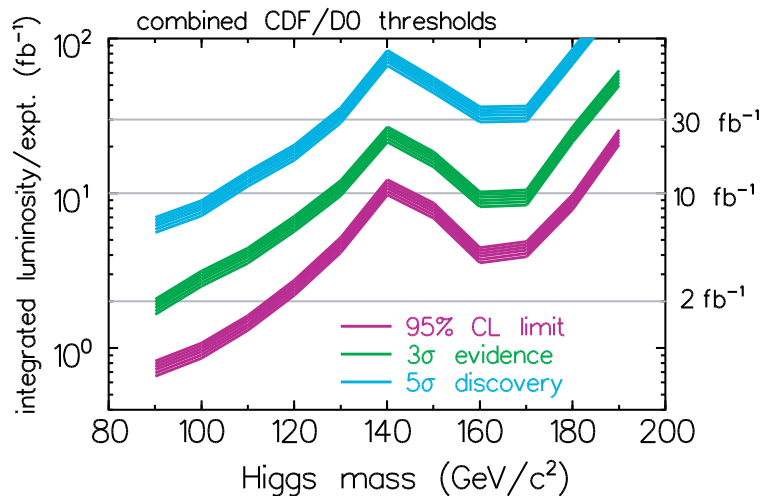


Figure 6: *The sensitivity of the FNAL Tevatron experiments to a light Higgs, as a function of its mass [17].*

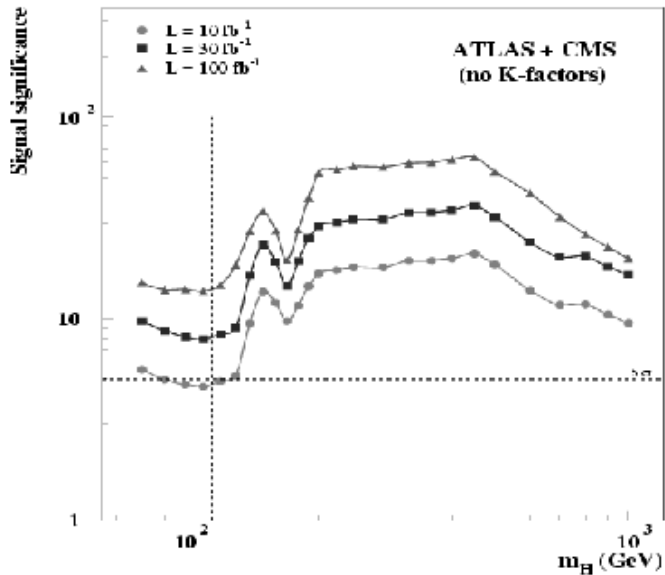


Figure 7: *The sensitivity of the LHC experiments to a Higgs, as a function of its mass, for different accumulated luminosities [18].*

There is, however, an important proviso. The LEP production mechanism, $e^+e^- \rightarrow Z + H$ [5], measures a different coupling - ZZH - from those to which the LHC is sensitive - $\bar{t}tH$ and $\gamma\gamma H$, with the latter being quite model-dependent. The $\gamma\gamma H$ coupling is controlled by loop diagrams sensitive to virtual particles and the $\bar{t}tH$ coupling is sensitive to the ratio of v.e.v.'s and Higgs mixing in the MSSM. Therefore the information obtained at the Tevatron and the LHC will be complementary to that obtained by LEP, and both sets of information will be helpful in determining whether the candidate Higgs boson has all the expected couplings.

The long-term plans for high-energy physics at all major laboratories around the world (NLC, JLC, TESLA, Muon Collider) depend very much whether or not there is a light Higgs. All the indications from LEP precision data are that it must weigh $\lesssim 200$ GeV [1]. A Higgs in the hand would be worth two in the bush to the NLC, JLC, TESLA and Muon Collider communities, when they approach their funding agencies. For this they may have to wait until 2007. Until then, they and the rest of the particle physics community may be left in suspense while the Higgs Odyssey continues across the wine-dark seas of LHC construction.

In the mean time - even if we are cast in subordinate roles analogous to the swineherd Eumaeus, old Laertes, faithful Penelope, the observant nurse Eurycleia, or the dying dog Argos - we all support CMS and ATLAS in their definitive search for the Higgs boson.

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