PERSPECTIVES: PARTICLE PHYSICS

The Search for the Higgs Boson

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A critical requirement of the Standard Model, today's dominant theory of elementary particles and their interactions, is a means to endow these entities with the property of mass. According to the Higgs mechanism (*1–4*), particle masses are the result of an invisible energy field that permeates space and confers inertia upon most of these particles. Without such an all-pervasive, ethereal medium, the particles would remain forever massless like the photon—racing about at light speed and never coalescing into galaxies, stars, planets, or people.

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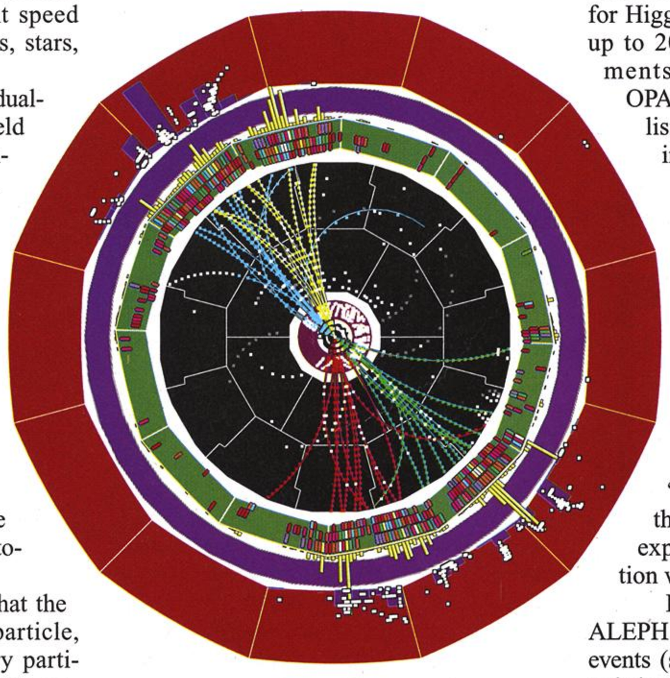
According to the wave-particle duality of quantum mechanics, this field should become manifest as a spinless particle called the Higgs boson (H), which corresponds to disturbances in the field (*5*). Searches for this intriguing object have occurred at ever higher energies since the late 1970s (*6*). Possible evidence for its existence recently turned up on the Large Electron-Positron (LEP) collider at the European Center for Particle Physics (CERN). New searches are about to begin on the recently upgraded Tevatron collider at the Fermi National Accelerator Laboratory (in Illinois).

The evidence so far indicates that the Higgs boson is a very massive particle, heavier than all known elementary particles except possibly the top quark. To create such a heavy particle in the laboratory, physicists must concentrate enough energy to produce it. Early LEP experiments at a lower energy searched for distinctive events that might produce an H in tandem with a pair of ghostly particles called neutrinos. No such events were detected, and it was concluded that Higgs bosons had to have a mass-energy greater than 65 gigaelectron volts (GeV), or 69 times the proton mass (*7*).

Thanks to quantum-mechanical effects, however, important information about Higgs bosons can be obtained from experiments that are unable to produce them directly. Because of the Heisenberg uncertainty principle, which allows elementary particles to appear and disappear spontaneously, physicists are able to constrain the masses of as-yet-unobserved particles. Known as virtual effects, these fleeting apparitions may nevertheless have profound physical consequences. A Higgs boson should induce such effects, with magnitudes that depend on its mass. But because the effects are small, only high-precision experiments can elucidate them.



One of the candidate four-jet Higgs events recorded by ALEPH. In this computer reconstruction, all four jets of subatomic particles originated from *b* quarks and antiquarks. The blue and green jets are believed to have come from the decay of a Higgs boson.

Prominent among such experiments are measurements at CERN, Fermilab, and the Stanford Linear Accelerator Center (SLAC) of the properties of the W and Z particles, which have masses of 80 GeV and 91 GeV, respectively. Discovered at CERN in the early 1980s, these heavy particles act as carriers of the unified "electroweak" force that is the centerpiece of the Standard Model. The first hints that a Standard Model Higgs boson might have a mass in the range accessible to the second round of LEP or Tevatron experiments came in the mid-1990s after Fermilab's top quark discovery. Precision electroweak data obtained on LEP and the Stanford Linear Collider (SLC), an electron-positron collider at SLAC, subsequently permitted limits to be set on the Higgs mass (*8*). Interpretation of all the precision electroweak data now available—including recent accurate measurements of the W mass at CERN and Fermilab—suggests that the mass of the Higgs boson is less than 170 GeV (*9*). The SLC measurements indicate it is less than 147 GeV (*10–12*).

The LEP collider was originally designed for a maximum electron-positron collision energy of 200 GeV. No evidence for Higgs bosons was obtained at energies up to 202 GeV on all four LEP experiments (ALEPH, DELPHI, L3, and OPAL). In mid-2000, however, the collision energy exceeded 206 GeV, and intriguing results began to appear.

The LEP experiments have searched for the process

$$e^{+} + e^{-} \rightarrow Z + H$$

with the Z and H identified by their decay products. The dominant decay mode for both particles is a quark-antiquark pair, with H decaying into a bottom (*b*) quark and its antiquark. Because quarks and antiquarks appear in detectors as sprays or "jets" of other subatomic particles, the most common event signature is expected to be a four-jet configuration with two jets identified as *b* jets.

In early September 2000, the ALEPH experiment reported three four-jet events (see the first figure) whose characteristics are consistent with production of a 114-GeV Higgs boson—and incompatible with known backgrounds at greater than three standard deviations (*13*). Similar events would not have appeared at lower collision energies because too little energy was then available to create both a Z particle and another particle at 114 GeV. Because of this intriguing observation, CERN extended the LEP run to the beginning of November. In mid-October, the L3 experiment recorded a candidate event with two *b* jets and a Z particle decaying into a pair of neutrinos; this event had essentially the same Higgs boson mass as the earlier ALEPH events (*14*). The two remaining experiments, DELPHI and OPAL, observed small excesses of events in the same mass region but did not find any clear Higgs candidates. The combined result, based on all

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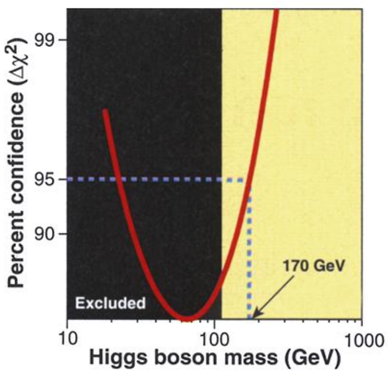
four experiments, is consistent with production of a Standard Model Higgs boson at a mass of 115 ± 1 GeV and incompatible with backgrounds at 2.9 standard deviations (*15*). This result excludes masses less than 113 GeV (see the second figure).

These intriguing indications of the direct production of a Higgs boson near 115 GeV are thus in agreement with recent indirect evidence that such a particle should have a mass less than about twice that of the Z particle. This range of masses is accessible at Fermilab's Tevatron (which resumes operation in March 2001) provided that it generates enough proton-antiproton collisions. Because of the rarity of Higgs boson events expected at Tevatron energies, however, it will take at least a few years before solid evidence for its existence can emerge. If experiments on this collider do not discover the Higgs boson, the Large Hadron Collider—a proton-proton collider now under construction at CERN that is scheduled to begin experiments in 2006 with up to seven times the Tevatron's energy—should be able to resolve this crucial question. In addition, the advanced linear electron-positron colliders now being designed in Germany, Japan, and the United States are ideally suited for detailed studies of such a relatively light Higgs boson.



Exclusion plot for the mass of a Standard Model Higgs boson. The shaded region indicates that a mass of less than 113 GeV is excluded by the direct search experiments at LEP. Precision electroweak data indicate that its mass should be less than 170 GeV (at 95% confidence level).

References and Notes

1. P. W. Higgs, *Phys. Lett.* **12**, 132 (1964).
2. F. Englert, R. Brout, *Phys. Rev. Lett.* **13**, 321 (1964).
3. G. S. Guralnik, C. R. Hagen, T. W. B. Kibble, *Phys. Rev. Lett.* **13**, 585 (1964).
4. L. Hoddeson *et al.*, *The Rise of the Standard Model* (Cambridge Univ. Press, New York, 1997).
5. In extensions of the Standard Model, two or more fields are expected to occur, with corresponding multiple Higgs bosons.
6. J. F. Gunion *et al.*, *The Higgs Hunter's Guide* (Addison-Wesley, Reading, MA, 1990).
7. G. Mikenberg, in *17th International Symposium on Lepton-Photon Interactions* (World Scientific, Singapore, 1996), p. 595.
8. LEP Electroweak Working Group, Report No. CERN-PPE/95-172 (November 1995) (available at preprints.cern.ch/cgi-bin/setlink?base=preprint&categ=cern&id=ppe-95-172).
9. A. Gurta, paper presented at the XXX International Conference on High Energy Physics, Osaka, Japan, 26 to 31 July 2000 (available at ichep2000.hep.sci.osaka-u.ac.jp/plenary.html#plenary_July31).
10. SLD Collaboration, K. Abe *et al.*, *Phys. Rev. Lett.* **84**, 5945 (2000).
11. K. Abe *et al.*, *Phys. Rev. Lett.*, in press; preprint available at xxx.lanl.gov/abs/hep-ex/0010015.
12. The LEP and SLC calculations differ; if the LEP procedure is used on the SLC data, this limit falls to 116 GeV. All limits are given at 95% confidence level.
13. ALEPH Collaboration, R. Barate *et al.*, *Phys. Lett. B* **495**, 1 (2000).
14. L3 Collaboration, N. Acciari *et al.*, *Phys. Lett. B* **495**, 18 (2000).
15. P. Igo-Kemenes, presentation of LEP Higgs working group, CERN, Geneva, 3 November 2000 (PDF file available at lephiggs.web.cern.ch/LEPHIGGS/talks/pik_lepc_nov3_2000.pdf).

PERSPECTIVES: NEUROSCIENCE

Seeking Categories in the Brain

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Perceptual categorization is a fascinating cognitive operation in which the mammalian brain groups together objects that share common properties, regardless of their physical differences. For example, we naturally group together cats, fish, birds, insects, and snakes into the category "animal," even though visually they are very diverse. Understanding categorization is a major challenge facing cognitive neuroscientists, a challenge that Freedman and co-workers (*1*) take on in their study on page 312 of this issue.

These authors examined the responses of neurons in the prefrontal cortex (PFC) of monkeys trained to categorize animal forms (generated by computer) as either "doglike" or "catlike." By continuously "morphing" the basic form of one animal into the other, the authors were able to test (with single-cell recording electrodes) how monkey PFC neurons responded to forms that could be either cat or dog (that is, shapes that were somewhere between the two animals). They report that many PFC neurons responded selectively to the different types of visual stimuli belonging to either the cat or the dog category and with the same strength, regardless of how morphologically close the images were to the other category. The firing of impulses by PFC neurons thus reflects category membership rather than simple processing of the physical characteristics of the images.

The neurons that Freedman *et al.* recorded from almost certainly receive their visual inputs from the inferior temporal cortex (ITC), a part of the brain that lies at the end of the chain of visual processing stages of the so-called ventral visual pathway (see the figure). It has been known for many years that some ITC cells can be highly selective to particular visual stimuli such as faces (*2*, *3*) and can even respond to a range of two-dimensional views of the same object (*4*). More recently, Vogels examined the responses of ITC cells in monkeys trained to categorize pictures of trees and fish. He reported a number of cells that were only activated by certain stimuli belonging to a given category (*5*), although none of them responded to all exemplars of the category. In a particularly impressive recent study, Sheinberg and Logothetis recorded the activity of ITC neurons in monkeys trained to search a large color photograph for small hidden figures—very much like the "Where's Waldo" game familiar to children (*6*). A wide range of different objects was artificially divided into two sets. To get a reward, the monkey had to pull a lever on the left for one set and on the right for the other set. The monkeys were extremely good at the task, and many ITC neurons showed a strong burst of firing when the monkey's eyes landed on (or close to) particular targets, remaining silent while the monkey was exploring the rest of the natural scene. However, there was no obvious relation between the set of targets to which the neuron responded and the artificial object categories as defined by the two response sets. It thus appears that the cognitive task of the ITC cells may be different from that of the PFC neurons described by Freedman *et al.*—activity patterns in the Freedman monkey neurons changed when the same set of images needed to be categorized in a different way. Clearly we need experiments that directly compare ITC and PFC responses using the same behavioral tests. Nevertheless, it looks like ITC and PFC may have different parts to play in these higher order visual tasks: ITC may provide highly processed visual information concerning the visual objects that are present, but PFC may be required to decide how these objects should be categorized.

In a way, this distinction between the visual representations seen in ITC and the more behaviorally relevant activity in PFC

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