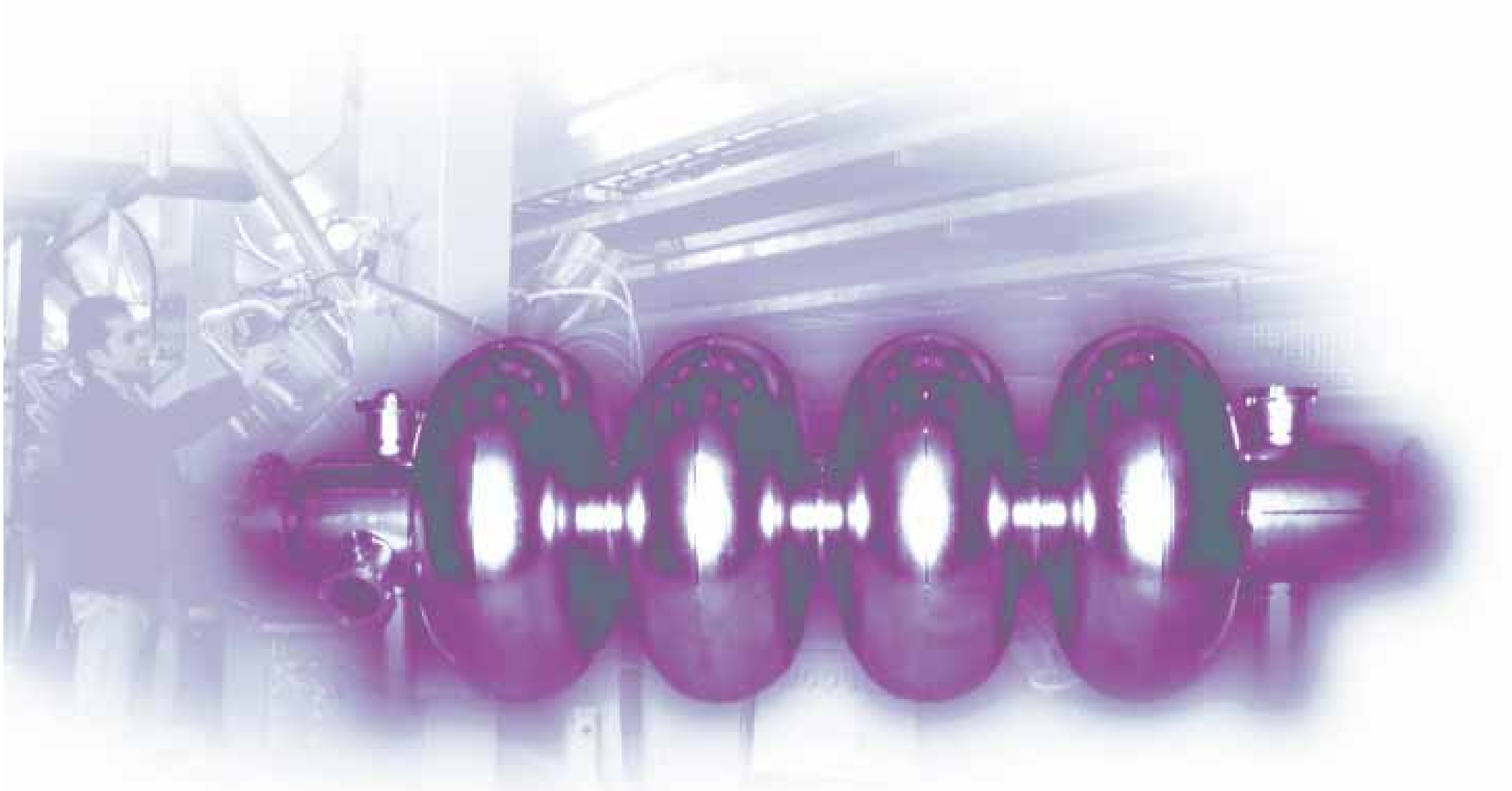
PHYSICS AT LEP 2

by MICHAEL SCHMITT

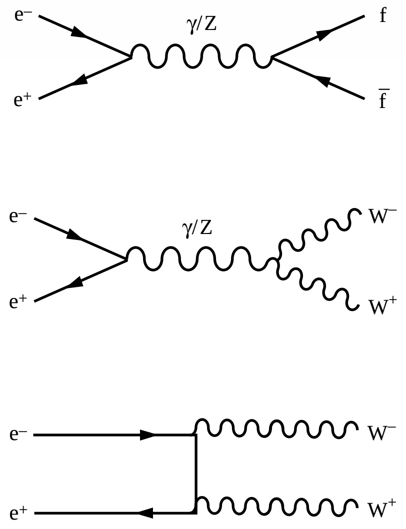
Particles colliding at CERN with a center-of-mass energy close to 200 GeV are changing the character of electron-positron physics. Here's what it means for new particle searches and precision measurements.

A NEW ERA IN ELECTRON-POSITRON collisions began four years ago at CERN. The center-of-mass energy of the Large Electron-Positron Collider (LEP) increased by half to 135 GeV—well above the peak of the *Z* boson resonance around 91 GeV, where LEP and its American cousin, the Stanford Linear Collider, have been taking data for years. Since then the energy has risen gradually to 189 GeV, making this collider, now called LEP 2, a unique high energy physics machine (see the article by Daniel Treille in the Fall 1992 issue of the *Beam Line*, Vol. 22, No. 3).

The first era of LEP physics began with the detailed study of the *Z* boson. When early hopes of discovering new phenomena were not realized, the four LEP collaborations—ALEPH, DELPHI, L3, and OPAL—concentrated on precision measurements and rare particle decays, leading to important results far beyond initial expectations. Perhaps the best examples are the measurement of the *Z* boson mass—now one of the best known quantities in all of particle physics—and the isolation of a small sample of $B^0 \rightarrow J/\Psi K^0_S$ decays with which to examine CP-violation. The main areas of study included electroweak processes, tau physics, the physics of "beauty" mesons and baryons, and quantum chromodynamics. Searches for new particles such as the Higgs boson or supersymmetric particles found nothing new within the limits imposed by kinematics, namely, that the sum of the masses of the particles produced is less than the total beam energy.



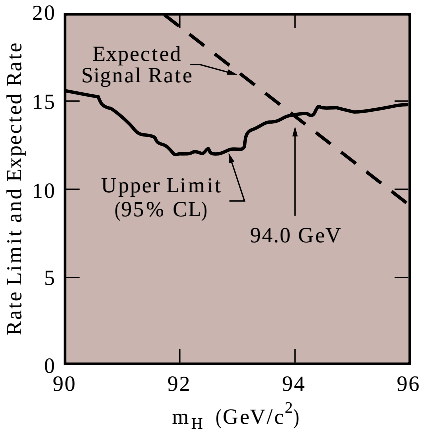
At LEP 2 the *Z* boson resonance is gone, and the previously huge production of two-fermion final states (pairs of leptons or quarks) is now accompanied by the appearance of four-fermion final states made large by the production of pairs of *W* bosons (see diagrams at right). The careful measurement of two-fermion cross sections and asymmetries continues, as tests of Standard Model predictions could well turn up deviations suggesting *new* physics. In addition, LEP 2 presents a wonderful opportunity to study the *W* boson, which previously had been produced in large numbers only at Fermilab. Most important, however, is the *direct* search for new particles—for should any such thing be discovered, particle physics would enter a new age.



Feynman diagrams of processes which dominated at LEP 1 (top), and those that are relatively more important at LEP 2.

SEARCHES FOR NEW PARTICLES

Theorists have proposed many new particles that might be discovered at LEP 2. Paramount among them is the Higgs boson, which in the Standard Model and its variants is the principal agent responsible for the masses of the known particles. This unique particle is not democratic with regard to the three generations of quarks and leptons: it couples more strongly to the heavy than to the light. Consequently, it prefers to decay into a pair of heavy particles that together are lighter than it. Unless the Higgs boson is



The expected rate of Higgs events as a function of the Higgs mass, compared to the upper limit derived from the direct search. These preliminary data from the OPAL Collaboration exclude a Higgs boson lighter than 94 GeV.

particularly heavy itself, this means mostly a pair of *b* quarks, with *c* quarks and tau leptons showing up 10 times less frequently.

A Higgs boson is thus expected to materialize most often as a pair of high energy "*b* jets"—a bundle of ordinary hadrons originating from a *b* quark. It would be produced when an electron and positron annihilate to create a supermassive *Z*, which would immediately "decay" into an ordinary *Z* and a Higgs boson. Although this would be a very rare process, it has advantageous properties: the *Z* decays to a pair of charged leptons, quarks, or neutrinos, all of which help physicists distinguish Higgs events from standard processes. The two *b*-quark jets emerging from the Higgs boson decay can be used to measure its mass; if Higgs bosons are produced at LEP 2, a peak should appear in plots of the two-jet mass.

Standard searches for Higgs bosons have been developed and perfected by all four collaborations, with each group competing for even modest improvements in their analyses. Unfortunately, no hint of any telltale excess of *b*-quark jets has appeared yet, and the researchers have had to be content with excluding ranges of possible Higgs boson mass. The combined data of all four experiments currently indicates that if the Higgs boson exists at all, its mass must be greater than 94 GeV (see figure on the left). With an ultimate LEP 2 collision energy of 200 GeV, these experiments can search for Higgs bosons up to a mass of about 109 GeV.

Supersymmetry (SUSY) is a collection of theories with many undetermined parameters and so far only *indirect* supporting evidence. Its basic premise can be stated easily: for every quark or lepton there are two new bosons, or scalar particles, and for every Standard Model boson there is a new fermion—including a partner for the as-yet unobserved Higgs boson! All these new particles must be very heavy, otherwise we should have discovered one by now.

The supersymmetric partner of the *W* boson, a charged particle called the "chargino," will be produced copiously if it is light enough. In the simplest scenario, the chargino decays the same way as a *W*, so one is looking for a second *W*-like particle that decays into pairs of quarks or leptons. In other scenarios chargino decays into leptons may be enhanced, but generally that poses no particular problem for experimenters. Charginos with masses less than 94 GeV have essentially been excluded by now.

Neutral sisters of the charginos, called "neutralinos," could enhance the signal for supersymmetry; if charginos are produced, one might expect also to observe neutralinos. The lightest neutralino plays a special role as the lightest of all supersymmetric particles. If it is stable, as usually assumed, then neutralinos left over from the Big Bang probably comprise a large fraction of the mysterious cold dark matter of the Universe (see article by Michael Turner in the Fall 1997 issue of the *Beam Line*, Vo. 27, No. 3) which is thought to clump together with the visible galaxies. Indirect limits on such a particle require its mass to be larger than about 28 GeV.

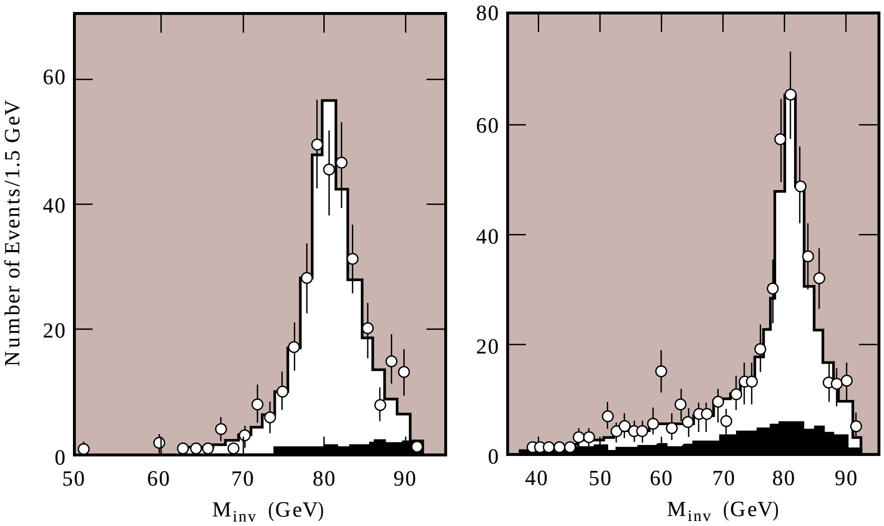
Other supersymmetric particles might be produced at LEP 2, including scalar leptons and quarks, which would show up as ordinary leptons and jets of hadrons plus missing energy. Ironically, the scalar top quark is the most promising of the scalar quarks; due to possible mixing of the two SUSY partners of the top quark, one light and one heavy mass eigenstate could result.

At the present time there is no whiff of supersymmetry in the data. Does this mean that this theory will soon be discarded? Probably not, as it does not specify precisely the masses of all the new particles—which might all be too heavy for LEP to produce. Their masses *should* come in largely below 1000 GeV, however, and the Large Hadron Collider will have a mass reach nearly that high. Supersymmetry, however, does place one important restriction on the mass of the lightest Higgs boson: it must weigh in at less than about 135 GeV, which is not far above the reach of LEP 2. And, judging from the indications gleaned from all the precision electroweak measurements, the Higgs boson may well fall within its reach.

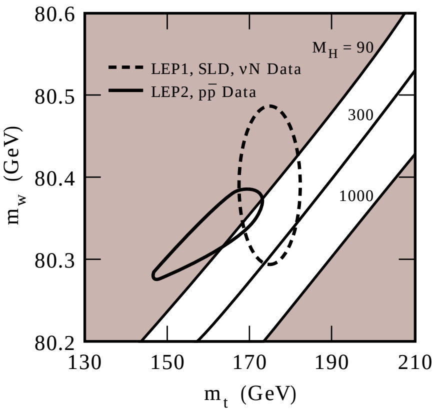
PRECISION MEASUREMENTS

The triumph of the precision measurements at LEP 1 is the mass of the *Z* boson, known now to one part in 30,000: $M_Z = 91.188 \pm 0.003$ GeV. As the mediator of the neutral weak force, the *Z* is produced naturally in electron-positron collisions. The mediator of the charged weak current is the *W* boson, which in electron-positron collisions is usually produced in pairs. Since a higher energy—more than 160 GeV—is required to produce a pair of *W*'s than a single *Z*, the study of the *W* has only become possible in the LEP 2 era.

The extraction of the *Z* mass was a question of measuring the event rate as the center-of-mass energy swept across the *Z* resonance, but *W*'s are another story. Since each event contains a pair of *W*'s, the resonance shape appears directly in the reconstruction of their masses. For example, if two *W*'s each decay to two jets, then in principle the masses of those two *W*'s can be reconstructed directly from the jet momenta. In reality there is a problem with jet confusion (How do you know which jets come from which *W* boson?) and the reconstruction of the jets themselves, so events that have a single charged lepton and two jets are easier to analyze. From fits to the resonance peaks measured so far (see graph below), the best *W* mass value is 80.37±0.09 GeV. When the data taken in 1998 have been fully analyzed, the



Reconstructed W mass peaks. On the left, one W decays to a charged lepton and a neutrino while the other decays into a pair of quarks. On the right, both W's decay into quark pairs. These data come from the L3 Collaboration; the solid lines are fits to the data and the black areas represent background events.



Bounds on the Higgs mass from precision electroweak measurements from combined data presented at the 1998 Vancouver conference. The two round curves indicate the (68% confidence) constraints from indirect measurements of M_W and M_t (solid curve) and direct measurements (dashed curve). The white band shows the theoretical calculation. The data seem to favor low Higgs masses, which are, however, gradually being excluded by direct searches at LEP.

error will shrink substantially, so that the mass of the *W* will be known to one part in a thousand. By the end of LEP 2 running, this will be improved by another factor of two.

Of what use are very accurate values for the *W* and Z masses? Isn't it enough to know that they exist? Not in particle physics. We do not yet have a theory of everything; we have the Standard Model—which is not fully validated until we find the Higgs boson—and speculative extensions of it. In order to pick out the more worthy speculations, we need to "peer" from the energy scale of the experimental phenomena we observe (roughly 100 GeV) to much higher scales (such as 10^{16} GeV), where new phenomena would dominate. This procedure works because the new particles that are active at those high energy scales have indirect effects at these low-energy scales; we can see their impact in very subtle shifts of the interactions and masses of the known particles like the *W* and *Z*.

This procedure may seem rather speculative, but we know that it works. The top quark was found at the Tevatron in 1995 (see the article by Bill Carrithers and Paul Grannis in the Fall 1995 issue of the *Beam Line*, Vol. 25, No. 3), but before that no one knew for sure what its mass was. We could make a serious estimate, however, because it impacts the measurement of the mass of the *Z* boson and its decays. As it turns out, the value obtained indirectly agrees with the actual Tevatron measurement.

Now that we know the top quark mass, we can use the precision measurements to try to deduce an indirect value for the Higgs boson mass. This turns out to be much harder than for the top quark, because the Higgs boson has a weaker impact on things like the mass of the *Z* and the mass of the *W*. Consequently, improving the accuracy of the *W* mass measurement is vitally important. The bounds placed on the Higgs mass by the current measurements of the top quark and *W* masses (see graph on the left) are beginning to be significant. If the total error on the the *W* mass shrinks to 0.04 GeV, as anticipated, then the constraints on the Higgs boson mass will become much more stringent. If, for example, we find the mass of the *W* equals 80.48±0.04 GeV while the mass of the top equals 174±5 GeV—and still no Higgs boson is found with a mass less than 109 GeV— then the Standard Model will be in jeopardy.

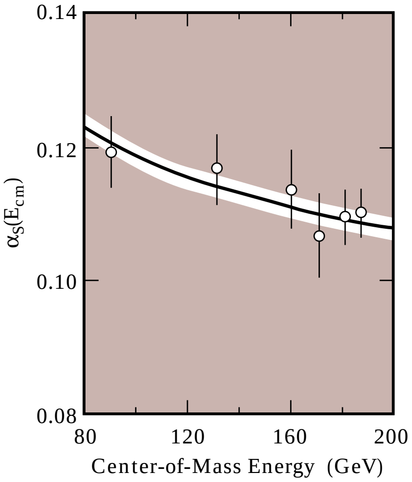
The calculation of these indirect "virtual" effects relies on field theory methods that predict that the strength of an interaction depends on its energy. In the parlance of particle physics, the "coupling constants run." In fact they run at different rates: the coupling constant for electromagnetism increases gradually with energy, the coupling for the weak force hardly changes at all, and the coupling constant for the strong force, α_s, actually decreases. One would like to know whether, at some high energy scale, all three have the same value. If they do, then they may be viewed as three aspects of a single, universal force, that is, they will be "unified." In the unaltered Standard Model, we already know that they do not unify, but in SUSY models, it looks like they do. To make a more stringent test, we need more precise measurements of the coupling constants, which in the case of α_S is experimentally challenging.

Fortunately, physicists have identified many indirect ways to measure α_S. For example, the emission of gluons, which shows up as “extra” hadronic jets, depends directly on α_S. A related feature is the overall “shape” of these hadronic events. They may be long and thin, indicating only two energetic quarks in the final state; broad and flat, indicating an additional gluon; or spherical, indicating two or more energetic gluons. It is impossible to make an absolute prediction for the shape of events or the number of jets, due to experimental and theoretical ambiguities. Fortunately, how these quantities *change* as a function of energy is well defined and easily measured. The doubling of LEP energy allows exceptionally clean observations of the running of α_S—better than 3 percent (see graph on the right).

There is a middle ground between direct searches for new particles and ultra-precise measurements of masses and couplings, and that is the measurement of cross sections and angular distributions for which the Standard Model makes clear and definite predictions. For example, we can easily calculate and cleanly measure the total cross section for hadronic events with center-of-mass energy well above the mass of the Z. If the measured value comes in larger than predicted, it might be due to the production of new particles somehow missed in the direct searches, or perhaps a deviation of the coupling constants that would point to new virtual effects. Of particular interest in this regard is the number of b-quark pairs produced, since this is the heaviest fermion produced at LEP. Thus far no deviation has been spotted, although the measurements have turned out to be more challenging than anticipated.

A more exotic corner of cross-section measurements actually tests the interactions among W’s, Z’s, and photons, rather than just their couplings to quarks and leptons. For example, a W boson can turn the incoming electron and positron into a pair of neutrinos—which escape detection—at the same time emitting a photon that generates a large signal in the electromagnetic calorimeter. A contribution due to this W-W-γ vertex can be isolated on a statistical basis, affording a direct test of the Standard Model in this important aspect. Other kinds of events test the W-W-Z vertex that contributes to W-pair production, and the Z-Z-γ vertex that should vanish to lowest order. These vertices lie at the very heart of electroweak symmetry.

The LEP collider will run through the year 2000, when its energy will reach 200 GeV. By the end of the program each experiment should have recorded more than enough data to complete searches for Higgs bosons and supersymmetric particles, and measure very precisely the properties of the W boson. Perhaps a genuine discovery will be made, or a new virtual effect uncovered. In either case the elucidation of any new phenomena would be carried out at future programs, such as future runs at the Tevatron, or at the LHC, or perhaps best of all, at the next generation of electron-positron colliders now in the design stages.



Variation of α_S with collision energy. This plot shows preliminary results from the ALEPH Collaboration.