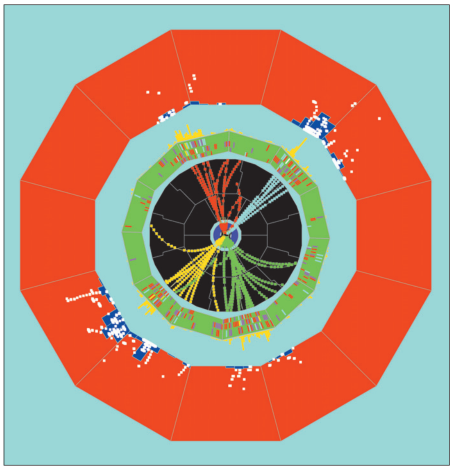
Particle physicists caught their first glimpse of the W boson in January 1983. Now they have measured its mass so precisely that the Standard Model is under threat

The W boson weighs in

Peter Renton

"THEY look like W's, they feel like W's, they smell like W's, they must be W's!" So Carlo Rubbia is said to have remarked as he pondered evidence for the existence of the W boson in January 1983. The discovery, made by the rival UA1 and UA2 experiments at CERN's Super Proton Synchrotron (SPS), was a historic moment in particle physics – with Rubbia and the UA1 collaboration narrowly beating the UA2 experiment to the prize (see "Carlo Rubbia and the discovery of the W and the Z" on pages 23–28). The discovery of the Z boson followed hot on the heels of the W in June and together they put the Standard Model of particle physics on a solid footing.



CERN

Heavy hitters – W bosons leave their mark on the ALEPH detector at the LEP collider at CERN.

The W boson is the key to our understanding of the weak force, which in turn can tell us how stars, radioactivity and other nuclear processes work. Physicists now have 20 years of W production behind them. So what has happened during this time? Well, quite a lot actually. Crucially, two new colliders have been built: the Tevatron proton–antiproton collider at Fermilab near Chicago and the large electron–positron (LEP) collider at CERN. So, instead of the handful of events that were accumulated in the discovery of the W, thousands more have now been produced and studied. This has enabled particle physicists to pin down the fundamental properties of the W very precisely. Indeed, we now know the mass of the W to an accuracy of four parts in 10 000.

The mass of the W is important because it is set by the boson's interactions with other particles through subtle quantum corrections. Some of these particles are already known to exist while others, such as the elusive Higgs boson, have yet to be discovered. Therefore, the more precisely we can pin down the mass of the W, the more we can learn about the basic properties of the fundamental particles of nature. It is still too early to say, but the most accurate measurements of the W mass to date suggest that cracks might just be starting to appear in the Standard Model.

The Standard Model

In the Standard Model "spin 1" bosons, such as the W, mediate the interactions between "spin $\frac{1}{2}$" fermions. Spin is a particle's internal angular momentum, measured in multiples of Planck's constant. Each of nature's four fundamental forces is carried by a particular boson: the photon for the electromagnetic force, the W and Z for the weak force, and gluons for the strong force. So far there is no corresponding "quantum field theory" for gravity, and formulating such a theory remains one of the major goals in physics.

Fermions come in two types – quarks and leptons – which fall naturally into three generations of increasing mass. Everyday matter is made of fermions from the lightest generation, namely the up and down quarks and the electron. The second generation includes the charm and strange quarks, along with the muon, while the third generation contains the top and bottom quarks along with the tau lepton. Each generation also includes a neutrino and every fermion has an antifermion partner.

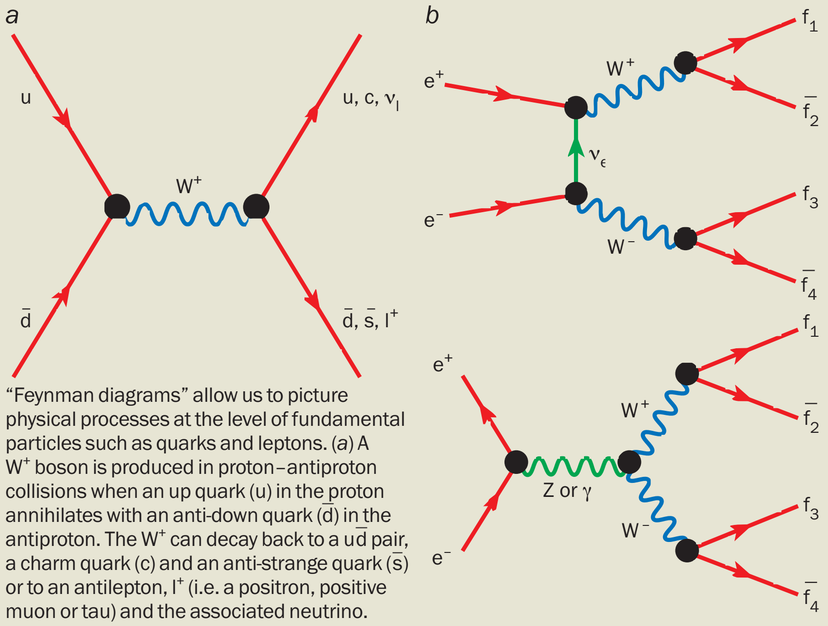
The final ingredient of the Standard Model is the Higgs boson, a neutral spin-zero particle. The Higgs boson interacts with other particles, including the W and Z bosons, to give them mass. It is a vital part of the model because without it all particles would be strictly massless.

Indeed, the W and Z bosons are very massive, which means the weak force has a short range (unlike the massless photon that gives rise to the infinite range of the electromagnetic force). The two bosons are about the same mass as the heavy nuclei rubidium and molybdenum, about 80.4 and 91.2 GeV, but they are over 1000 times smaller. In addition, while the nuclei are "bags" of protons and neutrons made of fundamental quarks and gluons, the W and Z do not appear to be composed of other particles.

There are, in fact, two different W bosons: one with positive charge and the other with negative charge. We believe, based on theory, that these two states have the same mass, although this is still rather poorly tested.

The first experimental evidence for the weak force was the observation of nuclear beta decay, in which one nucleus disintegrates into a second, lighter nucleus plus either an electron and an antineutrino, or a positron and a neutrino. In 1933 Enrico Fermi developed a theory in which beta decay was described as the interaction of four fermions – for example a proton, neutron, positron and neutrino – at the same space–time point. But Fermi's theory was problematic because the interaction probability became infinite as the collision energy increased.

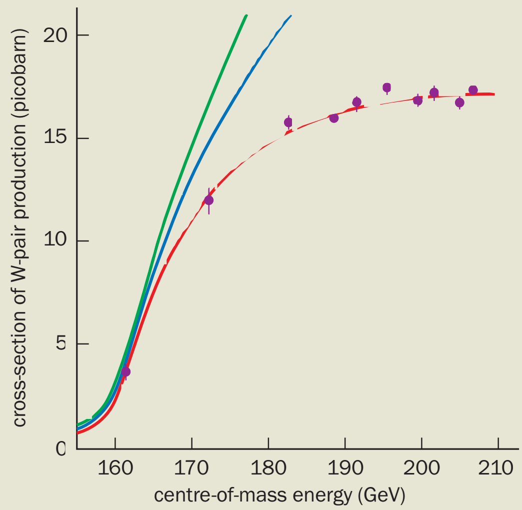
1 W-pair production and decay



"Feynman diagrams" allow us to picture physical processes at the level of fundamental particles such as quarks and leptons. (*a*) A W$^+$ boson is produced in proton–antiproton collisions when an up quark (u) in the proton annihilates with an anti-down quark ($\bar{d}$) in the antiproton. The W$^+$ can decay back to a u$\bar{d}$ pair, a charm quark (c) and an anti-strange quark ($\bar{s}$) or to an antilepton, l^+ (i.e. a positron, positive muon or tau) and the associated neutrino.

W$^-$ bosons are created in collisions between down and anti-up quarks, and decay into a d$\bar{u}$ pair, a s$\bar{c}$ pair or to a lepton, l, and its associated antineutrino, ν_l. At each vertex in the diagram, electric charge must be conserved. (*b*) In the electron–positron collisions at LEP, pairs of W bosons are produced and these subsequently decay into four fermions, f (quarks or leptons). The W pairs can be produced in one of three processes: the exchange of an electron neutrino between the electron and positron (top) or the annihilation of the electron and positron into a

2 Triumph of the Standard Model



The cross-section for the production of pairs of W bosons in electron–positron collisions varies with the centre-of-mass energy in the collisions (purple circles). The predictions of the Standard Model (red line) are in good agreement with experiment when three processes – the exchange of a neutrino, a photon and a Z boson – are included in the calculations. The agreement breaks down if we only include neutrino exchange (green line) or just neutrino and photon exchange (blue line). The data correspond to the increasing energies achieved during the LEP2 phase of the LEP collider, from 161 GeV in 1996 to 209 GeV in 2000.

Five years later in 1938, Oscar Klein suggested that the weak interaction was not point-like, rather it was propagated by a massive charged particle with a role analogous to that of the photon in quantum electrodynamics. Since this particle must be electrically charged, this leads to what is called a weak "charged current". In the 1960s Sheldon Glashow, Abdus Salam and Steven Weinberg developed a model in which the weak force is united with electromagnetism into a single electroweak theory. This theory also contained weak "neutral currents" mediated by the photon and Z boson. The strong interaction, felt only by quarks and gluons, and involving the exchange of the "colour" quantum number, is described by quantum chromodynamics. Together with electroweak theory this comprises the Standard Model of particle physics. Gravity is not yet included, but there is considerable effort going into the unification of all the forces.

The first and most crucial test of electroweak theory was the production of W bosons in a controlled way. But this was no easy task because it involved colliding specific particles at very high energies with extraordinary precision. At CERN's SPS the production and storage of the proton beam was relatively straightforward, but the antiprotons presented more of a challenge. Being antimatter, antiprotons are not available off-the-shelf and have to be created by smashing a proton beam into a metal target. But only about one in a million collisions produces an antiproton, and the few that are produced fly out of the target with a wide range of energies and directions.

To be useful, the antiprotons must be made almost mono-energetic and must also follow the same orbit. The crucial breakthrough that led to the 1984 Nobel Prize in Physics for Carlo Rubbia and Simon van der Meer was the development of a novel "cooling" system. This ensured that the antiprotons could be contained within the circular accelerator.

Once the SPS was up and running, large magnets were used to focus the counter-rotating proton and antiproton beams at two points. Around these sat the giant UA1 and UA2 detectors, which recorded the debris from the 540 GeV collisions (270 GeV per beam).

By 1990 the SPS was reaching the end of its programme and the Tevatron proton–antiproton collider was taking shape at Fermilab near Chicago. This new machine had several advantages. The collision energy was a factor of three higher than the SPS and higher-intensity beams increased the W production rate considerably. The Tevatron came into its own in 1994 when it embarked on a long data-taking run that was to last into 1996 (dubbed "Run 1"), involving the experimental detectors CDF and D0. Out of this came not only the discovery of the top quark, but a fivefold improvement in the precision of the W mass.

Brief encounter

The key to understanding the W is its interactions with other fundamental particles, which describe how the bosons are produced and how they decay (figure 1). The W only exists for about 10^{-25} s before it decays into either lepton and antilepton or quark and antiquark pairs. Conversely, W bosons can be created by effectively running the decay process back in time and colliding pairs of leptons or pairs of quarks.

At both the SPS and Tevatron, W bosons are created by the collisions between up and down quarks and antiquarks in the proton–antiproton beams (figure 1*a*). However, individual quarks only carry a fraction of the energy of their parent protons and antiprotons. Therefore, the energy of the colliding beams needs to be very high in order to produce the heavy W and even then the probability of actually producing the particle is tiny. For example, in making the W discovery the UA1 detector recorded about 1 million potentially interesting events on magnetic tape, from which only five W candidates were found after a complete analysis.

The situation can be improved if we collide beams of fundamental particles, such as electrons and positrons, rather than composite particles such as protons and antiprotons. However, electron–positron colliders such as LEP can only produce pairs of W particles, which means the centre-of-mass energy must be at least twice the W mass. It is also possible to produce W bosons by colliding electrons and protons, as happens at the HERA accelerator at the DESY laboratory in Hamburg.

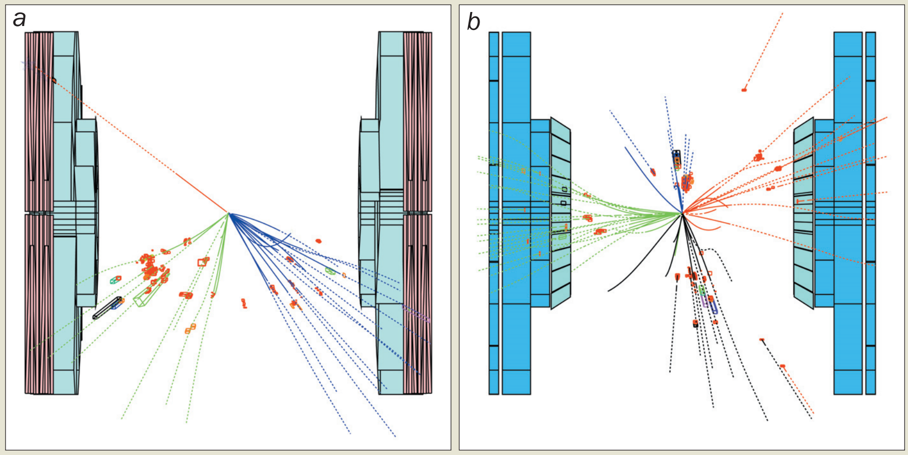
The machine that really put electroweak physics to the test, and allowed the most precise measurements of the W mass to date, was LEP. This collider operated in two energy regimes in the period between 1989 and 2000 in order to study both the W and Z bosons. The LEP1 phase produced single Z bosons by colliding beams at centre-of-mass energies of about 92 GeV, the Z mass. (Note that mass is expressed in terms of energy units because the speed of light is taken to equal 1.) In the LEP2 phase, energies between 161 GeV –the threshold to produce W^+W^- pairs – and 209 GeV were achieved. The machine has now been dismantled to make way for the Large Hadron Collider.

Thanks to the sterling work of the LEP machine experts, more than 30 000 pairs of W bosons were recorded in the four experimental detectors (ALEPH, DELPHI, L3 and OPAL). The analysis of these events gives the most precise measurements of the properties of the W so far. For example, the Standard Model assumes that the three lepton species couple to the W with the same strength. This "lepton universality" is the simplest theoretical assumption, but that does not mean it is true. At LEP the number of times a W decays to each of the three possible lepton generations (electron, muon or tau) has been found to be equal to within 3%. The deeper question as to why there are three generations of leptons and why their couplings are equal still awaits a satisfactory answer.

There are three processes in the Standard Model by which a pair of W bosons can be produced at LEP, the relative importance of which changes as the collision energy increases (figure 1*b*). In the first, a neutrino is "exchanged" between the electron and positron, and this process dominates when the collision energy is just above the threshold for production of W pairs. In the second process, a Z boson is created by the incident electron and positron, and decays into a pair of W bosons that subsequently decay into fermions (in the LEP1 phase the Z boson did not have enough energy to produce W pairs). In the third process, a photon is produced and then decays into a pair of W bosons.

At LEP the probability of producing a pair of W bosons has been measured at a series of increasing centre-of-mass energies from the threshold at 161 GeV up to 209 GeV. The relative production probability, or cross-section, increases rapidly just above threshold then starts to flatten off, in excellent agreement with the Standard Model prediction (figure 2).

3 W-pair events at LEP



Examples of W-pair events recorded by the DELPHI detector. These particle tracks and energy deposits (red boxes) are the starting point for measuring the W mass. (*a*) This shows a semi-leptonic event in which one W has decayed into quarks, resulting in two jets of particles (with the tracks shown in green and blue), and the other into a muon (shown in red) and a missing neutrino. (*b*) This event is fully hadronic where both W bosons have decayed into quark pairs producing four jets.

Reconstructing the W mass

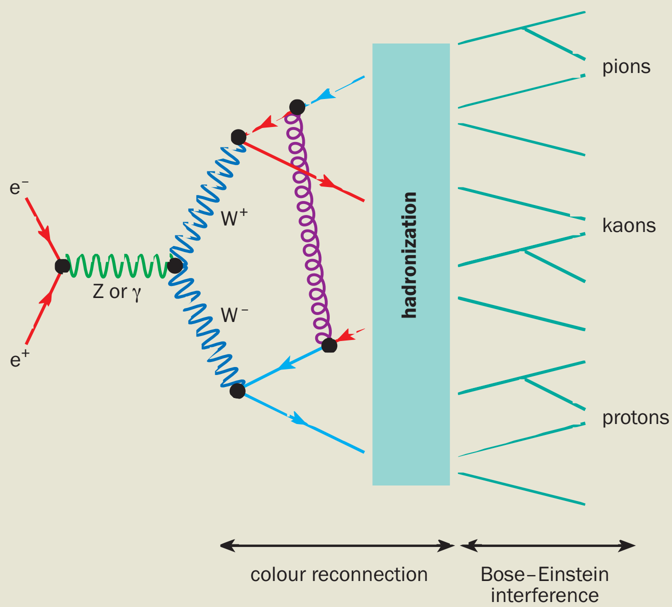
In the fraction of a moment that a W exists, the distance it travels is much less than the diameter of a nucleus, making it impossible to track and measure with detectors. To calculate the mass of the W we must therefore begin with measurements of the energy and momentum of all its decay products in each event. A large sample of W events is needed to reduce the eventual statistical uncertainty of the mass measurement, while systematic uncertainties due to biases in the energy and momentum scales, for example, must be kept to a minimum.

The extraction of the W mass proceeds through a number of analysis stages, amounting to hundreds of thousands of lines of computer code developed by many people over several years. The analysis essentially works backwards to reconstruct the original W from the multi-particle final states recorded by the detectors (figure 3).

The first task is to select a sample of W events from the many "background" events that leave similar signatures. If the W decays into leptons, it leaves a clear experimental signature in the detector. The electrons or muons produced are energetic and are therefore relatively easy to identify by their straight tracks (the tracks produced by slower particles are curved due to the high magnetic field in the detector) and other characteristics. The neutrinos, on the other hand, pass through the detector as if it were not there. But they do not go unnoticed because they carry away energy and momentum from the event. This means that their presence can be inferred by calculating the missing energy and momentum. The tau-lepton decay is more difficult to detect because the particle has a short lifetime, so it decays rather close to the point where the W was produced. Furthermore, it has many possible decay modes, all of which include an additional undetected neutrino.

If the W bosons decay to quarks and antiquarks, then a completely different signature is produced. As the energetic quarks and antiquarks fly away from the W decay, they create narrow collimated "jets" of hadrons – particles made of quarks, such as pions and protons. This is due to the nature of the strong force, which, unlike the other basic forces in nature, *increases* with the distance between the quarks, resulting in the

4 Cross-talk between W bosons



Different phases in the production and decay of W pairs. First, a photon or a Z boson decays into a pair of W bosons that each decay to quark–antiquark pairs. Gluons can then be exchanged between the quarks and antiquarks coming from the same W, or from quarks and antiquarks from different W bosons. This is the colour-reconnection phase. The quarks, antiquarks and gluons then produce hadrons (pions, kaons, etc) in the hadronization process, depicted by the turquoise box. After hadrons have been produced, Bose–Einstein interference between identical pions and kaons from different W bosons can take place. Both the colour-reconnection and Bose–Einstein effects make the overall measurement of the W mass more difficult.

quarks being "confined" within hadrons. These hadronic jets, which comprise a dozen or so particles such as π and K mesons, leave clear signatures in the detectors (figure 3). However, there are many processes other than W decay that can also produce jets of particles, particularly at proton–antiproton colliders. When selecting hadronic W decays, it is therefore more difficult to end up with a high-purity sample of W bosons compared with the selection of leptonic ones.

At LEP there are two W bosons per event to consider, which means that there are three possible final states depending on how each W decays: fully leptonic, semi-leptonic and fully hadronic. Each requires a different analysis to reconstruct the W mass. In the fully leptonic decay route, or channel, there are two missing neutrinos, which means that there are not enough kinematic constraints to use such events to measure the W mass directly. In the semi-leptonic channel the energy and momentum of the missing neutrino can be computed if the centre-of-mass energy is known (figure 3*a*). If both W bosons decay hadronically then four jets of hadrons are produced. The difficulty with this channel is that the jets have to be matched to the correct parent particles and there is a possible threefold ambiguity in this assignment (figure 3*b*).

Once selected, each event is constrained to conserve energy and momentum since we know this holds at the point where the electron and positron annihilate. A "kinematic fit" adjusts the measured momenta of the final-state particles within their uncertainties until the whole event satisfies the constraint. This improves the precision of the eventual mass measurement, particularly for the hadronic channel. The success of this analysis stage relies on how well the centre-of-mass collision energy is known: at LEP this energy is known to 2 parts in 10 000.

At proton–antiproton colliders, things are not quite as straightforward. The quark and antiquark that produce the W are analogous to the electron and positron, in that they give the fundamental collision of interest. But the rest of the quarks and antiquarks in the proton and antiproton do not participate in this process and end up as hadrons travelling at very small angles with respect to the incident beams, often disappearing back down the beam pipe itself. These particles are outside the instrumented region of the detectors and so are not recorded.

Since we do not detect and measure all the final-state particles in proton–antiproton collisions, we cannot use energy–momentum conservation to compute the neutrino energy and momentum for a leptonic W decay. But all is not lost. The escaped particles are mostly in the longitudinal (beam) direction, so we can safely use the constraint in the plane transverse to the beam direction. The W-decay events are selected by first detecting an energetic electron or muon. The momentum of the missing neutrino in the transverse plane is then calculated from the apparent imbalance in the momenta of all the detected particles in this plane. A mass value called the transverse mass is calculated using just two dimensions, rather than three. This mass is not the true W mass, but it is rather sensitive to it and the true mass can therefore be deduced. Although information is lost when just two dimensions are used, compared with LEP where all three are used, the larger statistical samples collected partly compensate for this loss in the final accuracy of the measurement.

W bosons talk to each other

In semi-leptonic events at LEP, the two W bosons decay independently of each other. This means the mass of the W is just the mass of the decay products of either the lepton and its neutrino from one W, or of the hadrons produced by the quark–antiquark pair from the other. But for fully hadronic events this is not necessarily the case, and there is a significant problem to be overcome when extracting the W mass. Quarks and antiquarks interact by exchanging gluons, and because the W pairs are in such close proximity when they decay into quarks, the gluons can get mixed up between different W bosons (figure 4). As a result, the energy and momentum of the quarks and antiquarks, and thus the hadrons produced, is different to the situation where the bosons decay independently, and this directly affects the apparent W mass.

When the gluon momenta are large, this "colour reconnection" process is well described by quantum chromodynamics and the apparent shift in the mass due to this effect is small. However, the effect is strongest for gluons with low momentum, for which there is no precise theory. Physicists have to rely on models of the process whereby quarks form jets of hadrons ("hadronization"), which introduce a sizeable systematic uncertainty to the mass measurement.

And if this were not enough, the fully hadronic channel has further problems. The production rates for identical π or K mesons in the hadronization process should be symmetric under the interchange of these particles because they obey Bose–Einstein statistics. These identical bosons can come from either the same or different W bosons, so again there can be cross-talk between the decay products of the different particles. The Bose–Einstein correlations between decay particles from different W bosons are found to be smaller than those between particles from the same boson. Estimating the possible shift in the W mass from these effects again relies on hadronization models, which introduces a further systematic error.

Colour reconnection seems to have the greater impact of these two effects. Work is still under way to understand it, but according to Nigel Watson of Birmingham University, who leads a LEP team exploring the effect, many of the models currently used are perfectly consistent with all aspects of the data. In other words, we cannot use the data to discriminate among the models. But these models predict large apparent changes in the measured W mass from the fully hadronic channel – up to 90 MeV. There is no comparable uncertainty for the semi-leptonic channel because there is no gluon cross-talk between the hadronic and leptonic W decays.

This uncertainty becomes important when we combine the values of the W mass calculated using the fully hadronic and semi-leptonic channels to get the best value from LEP. Both measurements have similar statistical uncertainties from the limited event samples collected, plus further uncertainties from other effects. However, while in the semi-leptonic channel the statistical and systematic uncertainties are similar (about 30 MeV), the colour-reconnection uncertainty in the hadronic channel is much larger. The upshot is that the hadronic decay channel contributes very little (only about 9%) to the combined mass value. The Tevatron experiments do not suffer from this problem because the W bosons are produced singly.

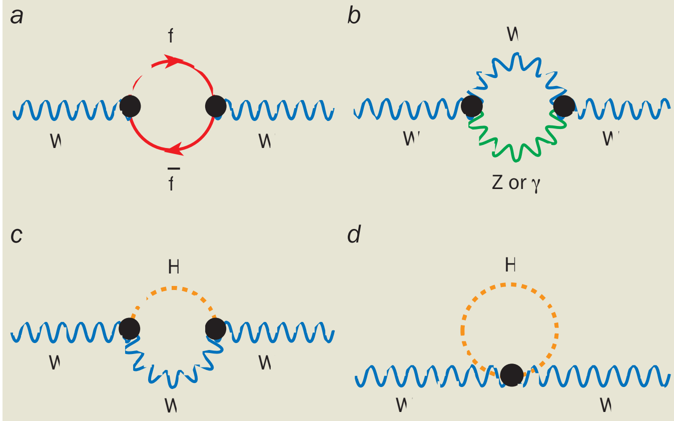
The current uncertainty in the W mass measured using LEP is 42 MeV, a relative uncertainty of 5 parts in 10 000. The value from the Tevatron is compatible with the LEP value, but has the somewhat larger uncertainty of 59 MeV. When these measurements are combined we get a value for the W mass of 80 449 MeV with an uncertainty of only 34 MeV. This is a very impressive achievement, particularly when compared with the uncertainty of about 2000 MeV that Carlo Rubbia reported in his Nobel-prize lecture.

W bosons are not always W bosons

Having measured the W mass precisely we can start really testing the Standard Model because we can compare the direct measurement with the value predicted by the theory. These calculations are performed as a series expansion, where each term gets progressively smaller. The terms correspond to higher complexity in the "Feynman diagrams" describing the physical processes. The basic (lowest order) processes are those shown in figure 1, where the W "propagates" the weak interaction between two fermions. More complicated diagrams represent corrections to this basic process (figure 5). For example, the W can momentarily dissociate into a fermion–antifermion pair such as a top and anti-bottom quark. Normally this is kinematically forbidden because the top quark is much heavier than the W. However, energy conservation can be violated for short periods of time according to the uncertainty principle, and such diagrams can be rigorously evaluated using quantum-field-theory techniques. In this way all the fundamental particles contribute to the mass of the W boson but to varying degrees.

In the Standard Model the top quark has the largest effect on the W mass because the correction appears as the difference in mass squared between the top and bottom quarks, which is very large. Using the measured value of the W mass and fixing the Higgs mass at 115 GeV (physicists know that the Higgs is at least this heavy) we get an indirect estimate of the mass of the top quark as 186 GeV. This is reasonably compatible with the directly measured value of 174 GeV, given that the uncertainties in both measurements are about 5 GeV.

5 Quantum corrections to the W mass



The W boson can temporarily dissociate into other particles, violating energy conservation in accordance with the uncertainty principle. The examples shown are (*a*) the dissociation into a fermion–antifermion pair (of which top–anti-bottom is the dominant contribution), (*b*) a W plus either a photon or Z boson, (*c*) a W plus a Higgs boson (H) and (*d*) a loop diagram involving only a Higgs boson. These loop corrections, along with higher-order diagrams containing two or more loops, affect the mass of the W.

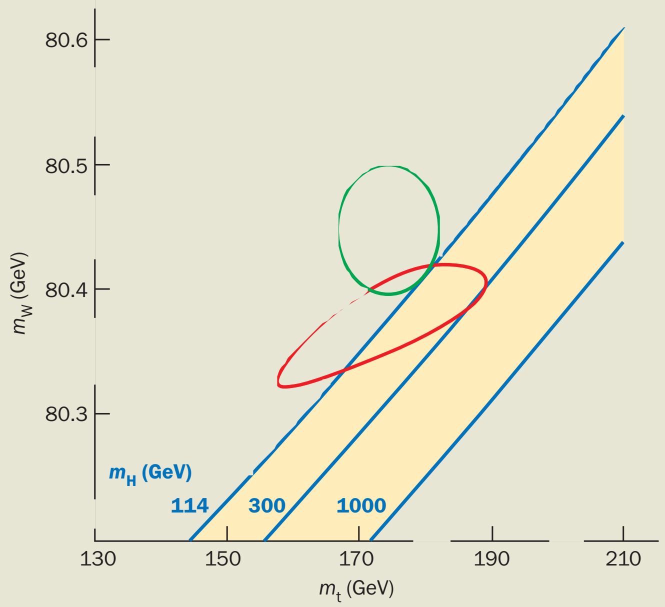
The dependence of the W mass on the mass of the Higgs boson is logarithmic, and is therefore much weaker than that of the top quark. There were tantalising hints of the Higgs at LEP towards the end of 2000, but we have no direct measurement of the Higgs mass. However, physicists do know, at a confidence level of 95%, that it must be above 114 GeV because otherwise the Higgs would already have been detected. If we input the experimentally measured W and top-quark masses in the Standard Model, then the data are now precise enough to predict a Higgs mass of 26 GeV. Despite a sizeable uncertainty in this value, there is only a 3% chance that the Higgs mass extracted using the W-mass measurement and the lower limit of the Higgs mass from LEP are compatible (figure 6).

The next 20 years?

Assuming the measurement of the W mass is reliable, this could be the first long-awaited sign of physics beyond the Standard Model. Indeed, the measured value is just in the region predicted by supersymmetry (SUSY), in which the Standard Model is extended by the addition of a new symmetry between bosons and fermions. For each boson in the Standard Model there is a supersymmetric fermion, and vice versa. Most of these SUSY particles are expected to be heavier than their ordinary-matter counterparts but less than about 1000 GeV. They will add new loop diagrams in the calculation of the W mass and will thus modify its value.

Progress requires yet further improvement in the experimental precision of the W mass. Whereas the LEP analysis is nearing completion, the data that are being collected in "Run 2" at the Tevatron will enable significant improvement in precision over the old data. The programme will continue until about 2008 and an improvement in the statistics of a factor of at least 20 is expected. If all goes well, then the uncertainty in the W mass from Run 2 could eventually be reduced to

6 Direct versus indirect W-mass measurements



From the directly measured values and uncertainties of the masses of the top quark (m_t) and W boson (m_W) a contour can be defined in the $m_t - m_W$ plane, inside which the true values should lie at the 68% confidence level (green line). From measurements of the electroweak properties of the Z boson we can predict the contour of the 68% confidence level, shown as a red line, inside which m_t and m_W should be found, if the Standard Model is correct. The indirect measurements are only in marginal agreement with the direct ones. In the Standard Model the Higgs mass (m_H) can be calculated if we specify the values of m_t and m_W. The blue lines shown are for m_H = 114, 300 and 1000 GeV. The area between 114 and 1000 GeV is shaded yellow. It can be seen that both the direct and indirect measurements favour a value of m_H at, or below, the lower limit on m_H of 114 GeV coming from direct measurements at LEP.

15 MeV. However, this will be very challenging experimentally. The Large Hadron Collider at CERN, due to start colliding proton beams in 2007, and any future electron–positron linear collider, will also help beat down this uncertainty. The direct observation of the Higgs boson and the measurement of its mass are also major goals for these colliders. We will then be able to compare the direct and indirect Higgs measurements.

All this will take is some time and considerable ingenuity. But if the central value of the W mass stays at its current value, and if we can reduce the uncertainty by a factor of two or more, then there will be a clear breakdown of the Standard Model (figure 6). There is therefore strong motivation to continue the work pioneered 20 years ago at CERN, and it is every bit as exciting.

Further reading

D H Perkins 2000 *Introduction to High Energy Physics* (Cambridge University Press) 4th edn

P Renton 1990 *Electroweak Interactions* (Cambridge University Press)

P M Watkins 1986 *Story of the W and Z* (Cambridge University Press)

Links

LEP electroweak working group: lepewwg.web.cern.ch/LEPEWWG/lepww/mw

DELPHI experiment at LEP: delphiwww.cern.ch/Welcome.html

CDF experiment at Fermilab: www-cdf.fnal.gov

Peter Renton is at the Department of Physics, Denys Wilkinson Building, University of Oxford, Keble Road, Oxford OX1 3RH, UK, email p.renton1@physics.ox.ac.uk