Heavy quarks and leptons in particle physics

The study of quarks and leptons provides an essential part of the standard model of modern particle physics.

Brian Foster

The concept of quarks and leptons as the basis for the understanding of the fundamental structure of matter and forces was established in the late sixties and early seventies, culminating in the discovery of the J/ψ particle in the so-called „November revolution“ of 1974. This particle was subsequently interpreted as the bound state of a new heavy quark, the charm quark, and its antiparticle. The subsequent discovery of the heavy lepton, the τ, and the even heavier bottom and top quarks completed the picture of the fermion content of the Standard Model of particle physics.

The standard model of particle physics represents the best current description of the fundamental particles and interactions of nature (excluding gravity). This is illustrated in Figure 1, which shows the twelve fermions subdivided both horizontally and vertically. The horizontal division is into quarks, which feel all three of the fundamental forces, strong, electroweak and gravitation, and leptons, which do not feel the strong force. Vertically the division is into three „families“; the first family, containing the up and down quarks, the electron and the electron neutrino, are sufficient to make up all of the matter that exists in the universe under anything but the most extreme and/or ephemeral conditions. The remaining two families appear to be „carbon copies“ of the first generation, whose properties are identical except that their masses are larger. While it is unclear why such copies exist, at least three generations are required to give the possibility of a slight difference between the behaviour of matter and antimatter to the electroweak force. This is believed to be related to the observed enormous preponderance of matter over antimatter that is observed in the universe. The rightmost column in Fig. 1 shows the four bosons that act as „force carriers“. There are eight different types of massless gluons which mediate the strong force; the massless photon carries the familiar electromagnetic force; the massive W and Z bosons carry the weak force. Not contained at all in the Standard Model is the gravitational force, which so far has only been described by Einstein’s general theory of relativity and not by a quantum field theory as have all the other forces.

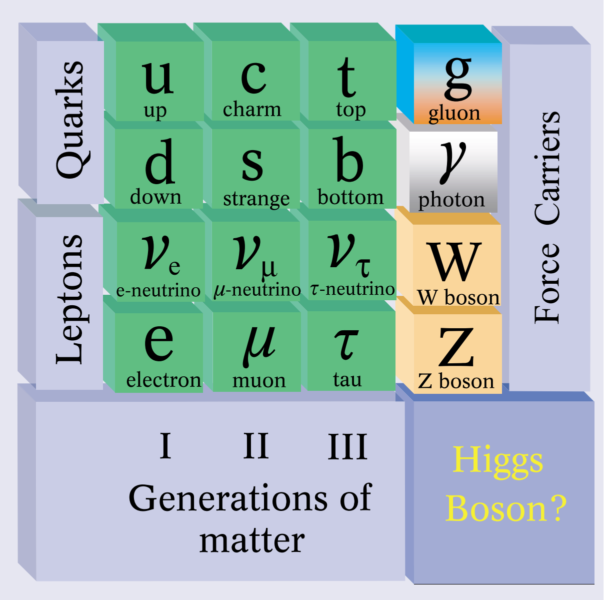

Fig. 1:
Diagrammatic representation of the Standard Model of particle physics. Each cube represents one of the „fundamental“ particles in the standard model. The first three columns represent the three „generations“, which contain related fermions. The second and third generations appear to be differentiated from the first only by the increasingly heavier mass of the fermions. Each column is split into two halves, the top of which contain quarks, which fell all of the forces, and leptons, which do not feel the strong force. The final column represents the force carriers: the top one represents the massless photon, the second the eight massless gluons and the final two the charged W and the neutral Z bosons, which are very massive and which convey the weak force, which is weak precisely because of their large mass. The lowest right-hand block represents the Higgs boson, thought to be the mechanism by which these particle acquire mass, but not as yet discovered.

Although not shown in Fig. 1 explicitly, the mass of the particles in each of the three families increases from left to right in the picture. This may not be true for the neutrinos, whose non-zero mass is one of the most exciting discoveries of recent years; however, at the moment we only have measurements of the mass differences between neutrino types rather than the actual mass values themselves. One of the most remarkable facts in particle physics is the enormous differences in mass among the particles in the standard model; the ratio of the typical neutrino mass to that of the top quark is more than 10^{11}. Not only do we have no understanding of the size of such ratios, but as yet we do not know how mass is acquired by particles. The

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key to this in the standard model, the Higgs boson shown in Fig. 1, has not yet been discovered, the presumption being that it is too massive to be seen at the energies until now available.

The picture described above could never have been achieved without the careful study of quarks and leptons, particularly the heavier ones. The discovery of the J/ψ marked a sea change between quarks being considered as a mathematical abstraction which was useful to describe very energetic lepton scattering from nucleons to being considered as indispensable for the understanding of all aspects of particle physics. The discovery of the τ lepton and the bottom and top quarks produced further laboratories for the study of the strong and electroweak interactions. The reason why the study of these objects is so important for the strong interaction is that it rapidly becomes stronger as the distance scale being probed increases, i.e. as the energy drops. For energies less than around 1 GeV, the strong coupling constant approaches unity, so that the only mechanism we have to calculate in quantum field theories, namely perturbation theory, fails, since terms of higher order in the coupling constant become of size comparable to the lowest-order terms. The mass even of the charm quark is large enough so that there is always a scale in any process involving heavy quarks that allows a sensible perturbative expansion of the theory of the strong force, Quantum Chromodynamics (QCD). This allows calculations to be made and confronted with experimental data. In fact, possible discrepancies between QCD and data on heavy quark production are currently particularly interesting. The top quark is so massive that its weak decay to the bottom quark takes place so quickly that it cannot form a bound state analogous to the J/ψ; it also decays before it can „hadronise“ into less massive bound states by plucking quarks from the vacuum.

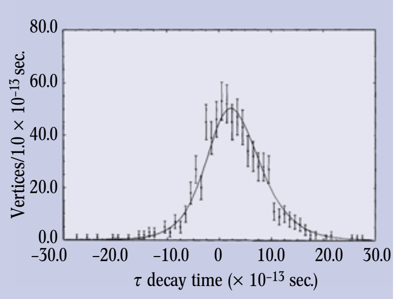

Fig. 2:
The distribution of decay times for τ leptons produced in electron-positron annihilation as measured by the vertex detector and tracking system of the TASSO experiment. The distribution is a convolution of a Gaussian resolution function with the exponential decay of the tau lepton. The resolution function gives rise to the apparently negative decay times; the exponential decay leads to the clear tail of positive decay times.

Heavy quarks and leptons are even more important in studying the properties of the electroweak interaction. The τ lepton is the only lepton massive enough to decay into strongly interacting particles, and the patters of its decay into the many possible final states open to it give important information on the systematics of the weak interaction. The weak decays of heavy quarks are also of the first importance; since we do not understand the mechanism by which particles acquire mass, there is no reason to believe that the mass eigenstates will be identical to the weak eigenstates. The relationship between these two bases is normally parameterised in terms of elements of the Kobayashi-Maskawa matrix, which are fundamental parameters of nature and which cannot be predicted within the standard model.

The properties of the τ lepton

My involvement with the study of heavy quarks and leptons began in 1978 when I joined the TASSO experiment at the PETRA ring under construction at DESY in Hamburg. The pioneering work of SPEAR at Stanford and DORIS at DESY in understanding the spectroscopy of charmed particles was still being digested and the bottom quark had only just been discovered. The main hope of the new machine was to discover the even heavier partner of the bottom quark in the third family, the top quark, for whose existence there was strong indirect evidence. As we now know, the maximum energy of PETRA, which was eventually painstakingly coaxed to 45.2 GeV, was almost a factor of three too small to see top. The major discovery of TASSO was in fact the gluon, the carrier of the strong interaction. My own work concentrated on the properties of the τ lepton and the measurement of the lifetimes of particles containing the bottom quark. The relatively long lifetime of these particles (of order 10^{-12} secs.) had not been measured when TASSO was designed, so although we were able to make a very crude measurement with the original apparatus in 1980, it was necessary to redesign the experiment immediately surrounding the e^+e^- interaction point by building a high-precision gaseous drift chamber with point accuracy around 100 μm. By going much closer radially to the interaction point than we had previously dared, we were able to utilise this drift chamber to resolve the typical decay lengths of a few mm before the τs decay. This can be seen in Fig. 2, where the exponential decay time of the τ, convoluted with the resolution function, can be clearly seen. A similarly precise measurement was carried out for particles containing the bottom quark, for which the average lifetime is of order 3 – 4 times longer than that of the τ. These drift chambers, together with similar ones at Stanford at the PEP-II machine, were precursors for the much more precise vertex detectors in modern particle physics experiments which are now usually constructed from silicon strip detectors or charge-coupled devices.

Lifetimes of heavy quarks and leptons

The high-precision measurement of the lifetimes of heavy quarks and leptons and the use of sophisticated vertex detectors now lies at the heart of modern particle physics experiments. The use of separated vertices for tagging heavy quark production is an integral part of the search for Higgs boson production (which because it produces mass, couples proportionately stronger the more massive the particle) at the LEP electron-positron collider at CERN and at the Tevatron experiments in Fermilab, USA. They are also particularly important at the so-called „B factories“ PEP-II at the Stanford Linear Accelerator Centre (SLAC) and KEK-B in Japan. I was a member of the BaBar experiment at PEP-II from the design stage. The detector has the usual „onion-like“ construction, with various cylindrical layers completely enclosing the interaction point; in particular, it has a highly sophisticated silicon strip detector close to the interaction point which has superb resolution to tag the decays of B particles. The energy of the electron beam is three times larger than that of the positron beam, so that the produced particles are boosted in the electron direction. This boost together with the intrinsically long lifetime of the b quark, means that the decays of the heavy quarks can be detected with high efficiency. Indeed, BaBar and its sister experiment taking data at KEK-B, Belle, have now made the most precise measurements of heavy quark and lepton lifetimes. The production of a neutral B meson (which consists of a bottom quark plus an anti-down quark) is always accompanied by an anti-B meson in a pure quantum superposition of states. Thus it makes no sense to ask which is the B or which the anti-B; until one decays, each contains equal elements of both particle and anti-particle. Once the first decays, say into a particle, the other immediately becomes an anti-particle. It is possible to use some unique decay signatures to determine whether one decay corresponds to a particle or an antiparticle, known as „tagging“. The decay of the other into a single well-defined final state can then be examined to measure the small difference between the decay of particle and antiparticle, which is known as „CP violation“. The asymmetry depends on time since the probability for the particle to oscillate into the antiparticle (and vice-versa) before it decays depends on time. Figure 3 shows the difference between the decay rates of particle and antiparticle into a given final state as a function of the difference in time between the two decays. A clear asymmetry can be observed, which can be used to deduce one of the three parameters that are used to describe CP violation. This parameter has now been measured to a precision of better than 10 %. The measurement of the other two parameters is much more difficult and is currently the subject of extensive study in both BaBar and Belle.

The ZEUS experiment

The production of heavy quarks is also of great interest in deep inelastic electron/positron-proton scattering. In January I stepped down after four years as Spokesman of the ZEUS experiment, which began operation ten years ago at the unique HERA electron-proton collider at DESY. The breadth of physics that can be investigated at HERA is enormous, encompassing almost all aspects of the strong interaction and also electroweak interactions in a kinematic region not explored either at LEP or at the Tevatron. One of the most interesting results is the explicit demonstration of the unity of the electromagnetic and weak forces which is an integral part of the standard model. This unification is demonstrated if the intrinsic coupling is identical for both interactions, their enormous apparent difference in strength arising purely from the difference in mass between the massless photon and the W and Z particles, whose masses are approximately 80 and 90 GeV, respectively. That this is indeed the case can be seen from Fig. 4, which shows the cross section, or equivalently the relative probability, for reactions involving exchange of these three particles as measured by ZEUS and its sister experiment, H1. The blue experimental points and the standard model fit to them are dominated at low four-momentum-transfer squared (Q^2, proportional to the inverse square of the wavelength of the photon) by photon exchange. The red points and curve can only take place by W exchange (which leads to a neutrino rather than an electron or positron in the final state), and therefore represent a purely weak interaction. At small Q^2, the probability for a weak interaction is some three orders of magnitude smaller than the electromagnetic interaction, whereas when the Q^2 approaches the W mass, the two types of interaction have similar probability. The small differences between the electron and positron cross sections relate to the quark content in the proton; the largest difference is caused by the fact that, at the highest Q^2, the proton consists of two up and one down „valence“ quarks. Whereas both up quarks can couple to the W^- emitted from electrons, being converted into a down quark in the process, only the down quark can couple to the W^+ from the positron, giving a factor of two in the relative probability. The detailed differences between electron and positron cross sections, as well as between different lepton-polarisation states, allow aspects of the electroweak couplings of the quarks to be measured; this will become much more important as the HERA II upgrade programme comes online. This

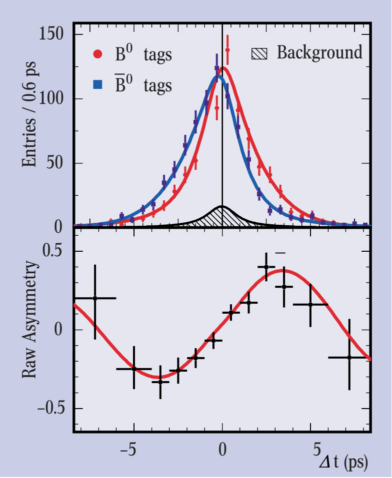

Fig. 3:
The distribution of decays into a particular final state as a function of the time difference between the two decays for two samples, in one of which one of the particles has been tagged as a particle („B^0 tags“) and the other in which one of the particles is tagged as an antiparticle („$\bar{B}^0$“). The frequency of decays as a function of the time difference is shown for the two samples. The upper plot shows the separate distributions, while the lower plot shows the difference between the two samples, illustrating the CP asymmetry. The shaded area shows the small contamination from background processes.

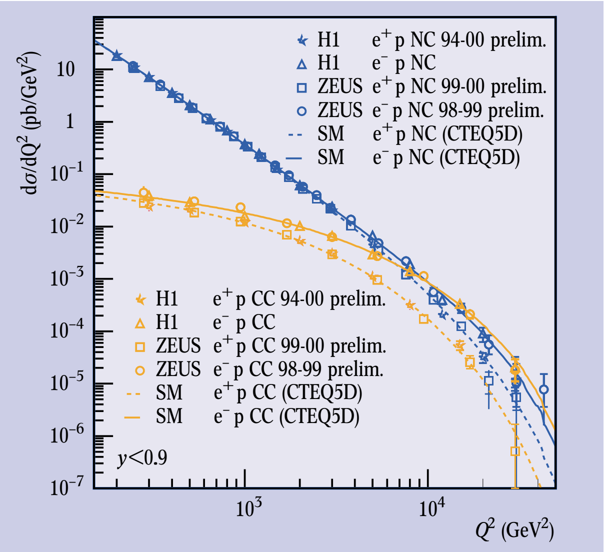

Fig. 4:
Data from the H1 and ZEUS experiments at the HERA electron-proton collider. The horizontal axis shows the four-momentum-transfer squared, inversely proportional to the wavelength of the probe, versus the cross section, which is proportional to the probability of the interaction occurring. The points labelled as „NC“ correspond to data in which the incident electron or positron is scattered and detected in the apparatus and are dominated by the exchange of the photon; only at high Q^2 does the exchange of the Z^0 also become important. The points labelled „CC“ correspond to events in which the incoming electron or positron is converted into a neutrino; these can only occur through the weak interaction via the exchange of a W boson.

will produce a factor of three or so improvement in the (proportional to the number of interactions produced per second) and make longitudinally polarised electrons and positrons available. The experiments have also been improved to take advantage of this. In particular, ZEUS has installed a new sophisticated silicon strip detector close to the interaction point which will greatly improve the detection of charm and bottom quark decays.

Future accelerators

Looking to the future, the turn-on of the Large Hadron Collider (LHC), currently under construction at CERN in the tunnel previously used by LEP, in 2007 will produce collisions between protons approximately seven times more energetic than currently possible. There is a wealth of currently available information that suggests that the Higgs particle, or whatever performs an equivalent function, must lie within the discovery reach of the LHC. Indeed, many extensions of the standard model which solve some of its fundamental shortcomings lead to a rich spectrum of new physics in the LHC range. The energy range of the LHC is achieved by colliding two complex objects, protons, together; the collisions are therefore not controlled, relying on the collision of quarks and gluons which do not have a single, well defined energy. The LHC is thus ideal to cover the full energy range and discover new phenomena. An electron-positron collider, which has a single well defined energy, can be tuned to examine particular phenomena in detail. It also has its own unique discovery potential. Experience in the past has shown the importance of concurrent running of proton and lepton colliders, with the possibility of cross-checking and synergy that this introduces.

There is an unprecedented international consensus to realise a linear electron-positron collider somewhere in the world at soon as practicable. The machine must be linear because a circular machine similar to LEP is ruled out since too much energy would be lost by the leptons as they are bent around circular orbits. The most advanced design for such a machine, TESLA, has been carried out at DESY. It depends on the use of superconducting radiofrequency cavities to accelerate the leptons and has brought about impressive developments, particularly in the cost and the highest attainable field gradients, in superconducting technology. Other designs based on normal-conducting cavities are being vigorously developed in the USA and Japan. As Chair of the European Committee for Future Accelerators, it is my job to promote this exciting project while at the same time ensuring that sufficient resources are earmarked to exploit the LHC machine fully, to allow it to be upgraded and to continue to run current facilities such as HERA for as long as they are producing world-class science. It is a challenging but tremendously exciting task.

Conclusion

When I was interviewed for a place as a research student at Oxford University in 1974, the discovery of the J/ψ particle had just been announced. My thesis was written on the spectroscopy and properties of particles containing the light up, down and strange quarks. With hindsight, the attempt to understand the strong interaction via spectroscopy, angular momentum analysis etc. was doomed to failure. The discovery of heavy quarks and leptons provided an array of new characteristic features in particle physics and stimulated the detector technology to exploit them in a way that was completely unpredictable 30 years ago. This revolution in particle physics is continuing and the new accelerators currently proposed or under construction will surely produce revolutions in our understanding at least as great as those of the „November revolution“. As my dear friend the late Bjoern Wiik, former director of DESY, was fond of quoting, to discover new things, we have to build new things.

Acknowledgement

I would like to thank all of my colleagues with whom I have built new detectors, the laboratories whose new accelerators and world-class facilities have made my work possible, particularly DESY and SLAC, and finally the DPG and the IoP for the great honour of the award of the Max Born Medal and Prize for 2003.

The author

Brian Foster has made outstanding contributions to particle physics. He received is D. Phil. at the University of Oxford in 1978. In the same year he started his successful experimental work at DESY as a member of the British team of researchers. Foster participated in the TASSO experiment at the electron-positron storage ring PETRA and played an eminent and formative role in the design, construction and operation of the ZEUS detector. From 1999 until the end of 2002 Foster was spokesman of the international ZEUS collaboration. He has been professor at the University of Bristol since 1992; he will return to Oxford as Professor of Experimental Physics in October 2003. He was chairman of the UK Particle Physics Comittee; at present he presides over EFCA (European Comittee for Future Accelerators). Brian Foster is well known for the pedagogical talent displayed in his talks and writings for a wider public.