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Standard Model of Particle Physics

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Standard Model of Particle Physics

The Standard Model describes all the confirmed data obtained using particle accelerators and has enabled many successful theoretical predictions to be made. It has been tested with per mille accuracy, at which level its calculable quantum corrections play an essential role. Its only missing feature is a particle, called the Higgs boson, whose coupling to the other particles is believed to generate their masses. However, the Standard Model is theoretically unsatisfactory despite its many successes, and possible extensions to provide a more unified picture of the different particle interactions, the apparent proliferation of different particle species and the origin of their masses are being proposed. Evidence has recently been presented that NEUTRINOS may alter their nature when they propagate over long distances. This is expected if neutrinos have masses, which are not predicted by the Standard Model. If confirmed, this may be the first evidence for particle physics beyond the Standard Model.

The FUNDAMENTAL PARTICLE interactions described by the Standard Model are the electromagnetic, weak and strong nuclear forces. Electromagnetic forces have long been known, since the discovery of electromagnetic wave radiation by Hertz in 1885 and the early days of quantum physics, to be mediated by the exchange of the photon (see figure 1), a massless boson of unit angular momentum (spin 1) with two polarization states. The long-established quantum theory of electrodynamics is called QED. Yukawa conjectured that the weak interactions such as β decay were mediated analogously by the exchange of massive intermediate bosons, as also shown in figure 1. This hypothesis was put on a firm theoretical basis by Glashow, Weinberg and Salam in their unified theory of the weak and electromagnetic interactions, and the intermediate bosons (weighing about 80 and 91 GeV) were discovered at CERN in 1983. The strong nuclear interactions are known also to be mediated by massless bosons called gluons, see also figure 1, which were discovered at DESY in 1979. Thus all the fundamental interactions have very similar structures, but why only the weak bosons are massive is a puzzle to which we return later.

The first elementary matter particle to be identified was the spin-1/2 electron (weighing about 1/2 MeV), followed by the unstable muon (weighing about 100 MeV) that was first detected in COSMIC RAYS. These were shown each to have an associated neutrino, the electron neutrino being produced in weak β decay and the muon neutrino being produced either in association with a muon or in muon decays. These particles do not have strong nuclear interactions, only weak and (in the case of the electron and muon, which are charged particles) electromagnetism, and are called LEPTONS. A third type of charged lepton (the τ weighing about 1.78 GeV) was discovered in accelerator experiments at SLAC in 1975 and is also believed to have its own associated neutrino. Accelerator data have established upper limits on the possible masses of the neutrinos, which are much less than those of the corresponding charged leptons.

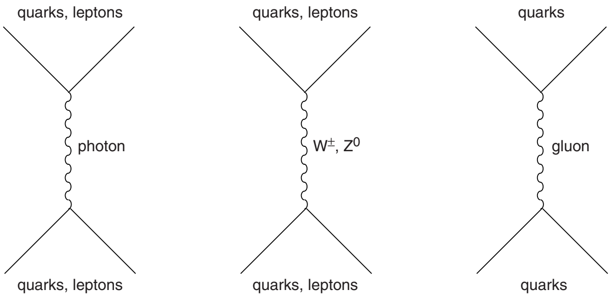

Figure 1. The fundamental forces between elementary particles are mediated by intermediate bosons: the photon of electromagnetism, the massive $W^{\pm}$ and Z^0 bosons of the weak interactions and the gluons of the strong interactions.

From the 1940s onwards, many strongly interacting particles (HADRONS) were discovered. It was proposed in 1964 that these could all be understood as composite bound states of more elementary entities called QUARKS. At that time, all the known hadrons could be constructed out of just three quark species of spin 1/2 and fractional charge Q: up ($Q = 2/3$), down and strange ($Q = -1/3$). Such pointlike constituents inside protons were discovered by experiments at SLAC in 1968. Initially it was a puzzle how quarks could appear almost free at high energies, corresponding to short distances, but were never seen singly, only confined inside hadrons. This puzzle was resolved when it was demonstrated that the couplings of gluons became weaker at high energies (short distances), a property known as asymptotic freedom.

Shortly afterwards, a key step in the establishment of the Standard Model was the discovery in a neutrino experiment at CERN in 1973 of a novel type of weak interaction, called neutral currents, in which the charges of the participating particles do not change, in contrast to the familiar weak interactions, called charged currents, in which the charges of participating quarks and leptons do change. Such neutral-current interactions were predicted by many unified theories of the weak and electromagnetic interactions, and their discovery provided the first circumstantial evidence that some such unified theory might be correct. The second piece of evidence for such a theory was provided by the discovery in accelerator experiments at BNL and SLAC in 1974 of hadrons containing a fourth quark constituent weighing about $1\frac{1}{2}$ GeV. This was baptized charm and had been predicted by unified electroweak theories, in order to explain the fact that neutral-current interactions that would change quark type, e.g. strange → down, are very suppressed, whereas there do exist charged-current interactions: strange → up. The charm discovery briefly pre-dated the τ lepton discovery mentioned earlier. Consistency of the simplest unified electroweak theory then required the existence of two more quark types, and the first of these (bottom), weighing about 5 GeV, was discovered in an accelerator experiment at FNAL in 1977. The spectrum of quarks was apparently completed by the discovery at FNAL in 1995 of the top quark, which weighs about 175 GeV.

The mathematical framework for theories of particle interactions is provided by gauge theories, which offer the only consistent description of the interactions of spin-1 particles. A gauge theory is based on a continuous internal symmetry, e.g. changing the phase of the quantum-mechanical wave function in the case of the prototype gauge theory, QED. When one makes this symmetry local, i.e. allows space-dependent phase transformations, one must introduce a spin-1 gauge field. This is analogous to the way Einstein realized general coordinate invariance with a spin-2 metric field. Gauge theories differ in their choice of gauge group and in the group transformation properties of the matter particles. In the case of the Standard Model, the strong interactions are described by a theory transforming the wave functions of quarks, called QCD. The unified electroweak interactions are described by a combination of transformations acting on both quarks and leptons, first written down by Glashow in 1961, Weinberg in 1967 and Salam in 1968.

The establishment of the Glashow–Weinberg–Salam model as the correct unified electroweak theory proceeded in several steps over the following decade. A series of detailed experiments refined measurements of the neutral currents, verifying that their properties were consistent with the Glashow–Weinberg–Salam model. A crucial step was the observation at SLAC in 1978 of parity violation in deep-inelastic electron–proton scattering, which was followed by similar observations in atomic physics. The culminating step was the discovery of the weak intermediate bosons, $W^{\pm}$ for the charged-current weak interactions and Z^0 for the neutral currents, in proton–antiproton collisions at CERN in 1983.

Subsequent developments have been dominated by a series of precision tests of the Standard Model, including both its strong and its electroweak sectors. In a number of experiments at energy scales varying from about 1 GeV to about 200 GeV, it has been shown that the strong nuclear interactions indeed weaken at higher energies, as seen in figure 2. The 'strong' interactions are truly strong only at energy scales $\lesssim$1 GeV, corresponding to distances $\gtrsim$0.2 fm, where quarks are confined within hadrons. Detailed calculations of hadron spectroscopy require extensive numerical simulations of discretized (lattice) versions of QCD on powerful computers. These are currently able to reproduce experimental measurements to within a few per cent. Calculations at higher energies (shorter distances) may be made using techniques from quantum field theory. They predict an energy dependence of the strong coupling that is in very good agreement with the experimental measurements shown in figure 2. This concordance confirms that there are no other light strongly interacting elementary particles beyond the gluons and quarks introduced earlier. The present data shown in figure 2 indicate that the strong coupling strength, analogous to the fine-structure constant of QED, has the value 0.119 ± 0.004 when measured at an energy corresponding to the mass of the Z^0 weak intermediate boson.

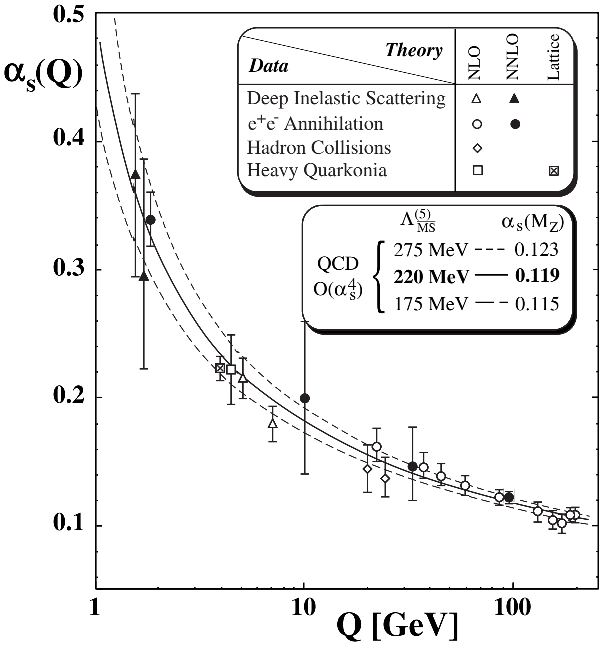

Figure 2. Weakening of strong interactions at high energies.

Tests of the electroweak sector of the Standard Model have been dominated by high-energy experiments on e^+e^- collisions at CERN, using the LEP accelerator, and at SLAC, using the SLC accelerator. A compilation of LEP measurements of the cross sections for e^+e^- annihilation into charged-lepton and quark–antiquark pairs is shown in figure 3. This is dominated by the Z^0 resonance peak, which must be one of the most carefully studied Breit–Wigner resonances in physics, with about 2×10^7 decays observed and measured. The height and width of the peak depend not only on the observed Z^0 decay modes but also on possible unseen decay modes such as those into neutrino–antineutrino pairs. Extra invisible decays would shorten the Z^0 lifetime and hence, by the UNCERTAINTY PRINCIPLE, increase the natural width of the Z^0 resonance peak. The measurements shown in figure 3 tell us that there are precisely three neutrino species, no more and no less. These correspond to the three known charged leptons, the electron, muon and tau. According to the Standard Model, there can only be three corresponding pairs of quarks. We therefore think there can be no further quarks beyond the six already known.

The data shown in figure 3 provide a very accurate determination of the mass of the Z^0: 91.1867 ± 0.0021 GeV. To arrive at this precision, it was necessary to take into account many effects that were considerably larger than the quoted error. These included terrestrial tides, which caused the LEP machine to expand and contract, and hence its energy to vary by $O(10)$ MeV, and even the passing

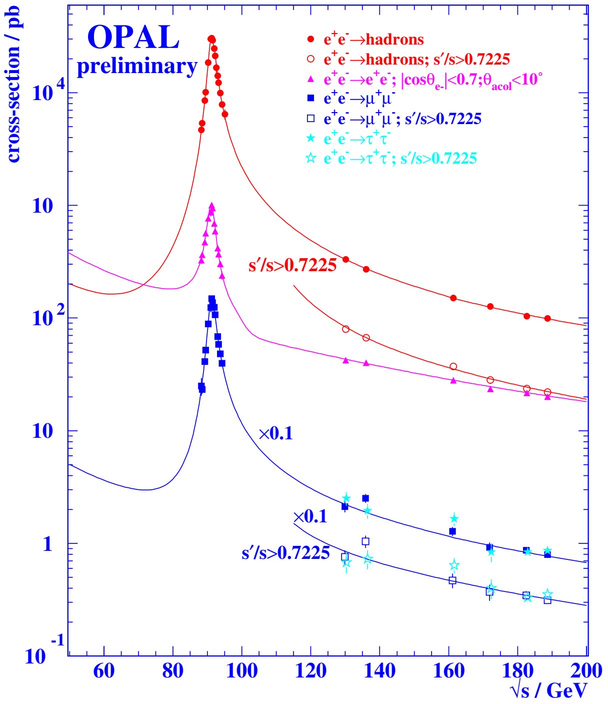

Figure 3. Cross sections for e^+e^- annihilation into charged-lepton and quark–antiquark pairs.

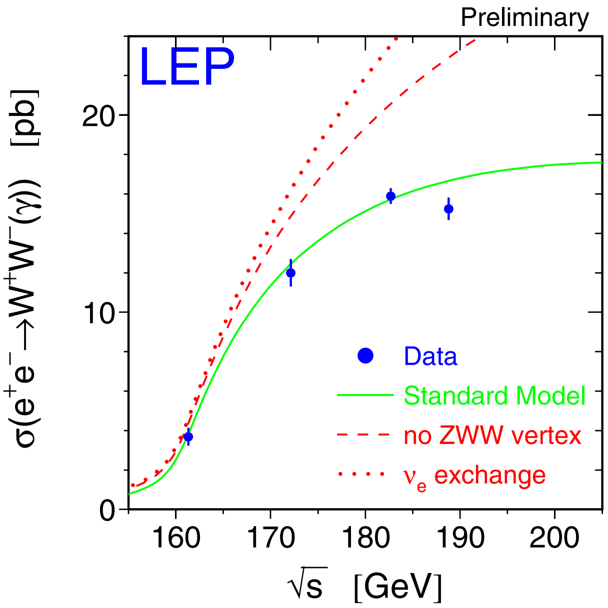

Figure 4. Production of W^+W^- boson pairs.

of nearby electric trains, which generated stray electric currents that perturbed the magnets of LEP and thus its beam energy.

In addition to the cross-section measurements shown in figure 3, LEP and the SLC have provided many other precision measurements, including branching ratios for Z^0 decays into different modes such as heavy quarks, forward–backward production asymmetries and polarization effects. Many of the measurements have per mille accuracy, and none differs significantly from the Standard Model prediction, and all measurements are within 1 or 2 standard deviations. These predictions require detailed calculations in quantum field theory, which were shown to be possible by 't Hooft in 1971. As was emphasized by Veltman, in particular, these calculations are sensitive to the masses of heavy particles that are too heavy to be produced directly at LEP or the SLC. The successes of these calculations were used successfully to predict the mass of the top quark, before it was discovered.

Referring back to figure 3, we see that LEP measurements extend to centre-of-mass energies considerably above the Z^0 peak. One of the principal Standard Model tests possible with higher-energy data is the production of pairs of $W^\pm$ bosons, as shown in figure 4. According to the Standard Model, this reaction receives contributions from the exchanges of the neutrino, photon and Z^0. The first of these is required by the role of the $W^\pm$ bosons in β decay, the second by the electric charge of the $W^\pm$ and the third by the characteristic $Z^0W^+W^-$ coupling of the unified electroweak theory. As seen in figure 4, all these three contributions are required to explain the LEP data, and the values of the couplings extracted from the data are in good agreement with the Standard Model. These data may also be used to measure the mass of the $W^\pm$, and the results are also in good agreement with the Standard Model predictions.

Thus far, we have seen that the Standard Model is passing its experimental tests with flying colors. However, there are still some key features of the Standard Model that have not yet been tested. One of these is the origin of the particle masses. According to the Standard Model, the underlying field theory is formulated in terms of massless particles, and one must find some way to incorporate their masses without spoiling the successes of the theory. This is possible if there exists an additional, as yet unseen, particle called the Higgs boson. The precision electroweak data described earlier are sensitive to the mass of this particle, and currently indicate that it weighs about 100 GeV, with an uncertainty of a factor of about 2. The search for the Higgs boson has been one of the continuing objectives of the LEP experimental program. At the time of writing, these searches have so far been unsuccessful and have established that its mass must exceed about 108 GeV. By the end of its operation, experiments at the LEP accelerator should tell us whether the Higgs boson weighs less than about 114 GeV. Beyond this mass, the full range of possible Higgs masses up to about 1 TeV can be explored at CERN's LHC accelerator, which is scheduled to start taking data in 2005.

Another missing element in tests of the Standard Model is its mechanism for matter–antimatter asymmetry.

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The weak interactions were shown in 1957 to violate not only parity (mirror) symmetry, but also charge conjugation. At first, it was thought that the combination of parity and charge conjugation, called CP, might yet be a good symmetry. However, an experiment in 1964 discovered that CP was also violated in the weak decays of some neutral composite particles called kaons. This means that matter does not behave in exactly the same way as ANTIMATTER, even if one reflects the experiment in a mirror in an attempt to recover the symmetry. In 1973, Kobayashi and Maskawa realized that this matter–antimatter asymmetry could be accommodated within the Standard Model if there were at least six quark species, as we now know to be the case. Subsequently, much theoretical effort has been devoted to evaluating the Standard Model predictions for matter–antimatter asymmetries in different processes, and there is an extensive experimental program to test these predictions. Follow-up experiments on neutral kaon decays are consistent with the Standard Model, but have not yet reached the sensitivity required to verify the characteristic predictions of the Standard Model. A number of experiments are planned to explore its predictions for CP asymmetries in the decays of mesons containing bottom quarks. There is good reason to expect that these experiments will be able to explore these matter–antimatter asymmetries at the levels predicted by the Standard Model.

It may be appropriate at this stage to mention some ways in which astrophysics and cosmology are sensitive to aspects of the Standard Model (see also PARTICLE ASTROPHYSICS). The energy production of main-sequence stars is controlled by nuclear physics and weak β decay, but details of the Standard Model are not directly relevant. These are, however, relevant to objects that are denser and/or hotter, such as collapsing supernovae. Weak neutral-current processes are essential to the understanding of neutrino emission from the collapsing core, and perhaps to the ejection of outer layers of the supernova progenitor. The nuclear equation of state of the remnant may also be sensitive to the underlying QCD theory of the strong interactions. In particular, it is often conjectured that under certain circumstances there may be a transition from conventional nuclear matter to quark matter, possibly with a high fraction of strange quarks.

Looking back to early cosmology, weak neutral-current processes also played an essential role in the reheating and decoupling of neutrinos around the epoch of big bang NUCLEOSYNTHESIS. Prior to that, in standard big bang cosmology the temperature of the early universe, and hence the characteristic particle energies, is believed to have increased as the inverse square of the age of the universe. When it was less than about 10^{-5} or 10^{-6} s old, hadrons would have been 'ionized' into quarks and gluons, and the Standard Model must be used to describe the behavior of the universe at these early times. The laboratory successes of the Standard Model described earlier imply that we possess the basis for a quantitative description of physics in the early universe.

When it was less than about 10^{-10} or 10^{-12} s old, it is thought that the Standard Model underwent a phase transition, before which all the particles of matter would have appeared massless, as well as the weak intermediate vector bosons and the Higgs boson. In addition to the familiar weak interactions, it is thought that other effects in the Glashow–Weinberg–Salam model, that have not been seen in the universe today, would have been important at this early epoch. These effects would have the distinctive feature of violating both baryon and lepton number by 3 units. Hence they must be taken into account in any attempt to understand the baryon density in the universe.

Although the Standard Model of particle physics is very successful, with no confirmed accelerator data that contradict it, there are many theoretical reasons to consider it unsatisfactory and to expect some physics beyond the Standard Model. For example, even if one accepts the quantum numbers of the quarks and leptons as given, the Standard Model contains 19 free parameters that are taken from experiment. These include three independent interaction strengths and a CP-violating parameter for the strong interactions, six quark masses and four parameters to describe how they are mixed by the weak interactions, three charged-lepton masses, the $W^\pm$ and Higgs boson masses. Having so many parameters is surely unacceptable for any candidate for a theory of everything, and attempts to go beyond the Standard Model typically try to simplify one of its aspects.

In a GRAND UNIFIED THEORY one regards the strong, weak and electromagnetic interactions as different aspects of a single interaction with a universal coupling strength. This is made possible by the fact that coupling strengths vary with energy, as exemplified by the asymptotic freedom of the strong interactions shown in figure 2. Calculations indicate that the coupling strengths may become equal at an energy around 10^{15}–10^{16} GeV. Many grand unified theories predict additional perturbative interactions that violate baryon and/or lepton number. These exotic interactions may cause baryons to decay and/or give neutrino masses. There have been many unsuccessful searches for proton decay, and its lifetime must be at least 10^{32} yr. Evidence has recently emerged from studies of solar and atmospheric neutrinos that they may have masses. If confirmed, this would constitute the first concrete evidence for physics beyond the Standard Model.

Other proposals for possible physics beyond the Standard Model try to understand the complicated pattern of lepton masses and quark masses and the way they are mixed by the weak interactions. One of the ideas often discussed in this context is the possibility that leptons and quarks are not elementary but composite bound states of more fundamental constituents. So far, no compelling model of this type has emerged, so it will not be discussed further here.

A third set of proposed extensions of the Standard Model arises from attempts to understand better the observed magnitudes of particle masses. The principal issue here is that the physical values observed seem to require very delicate fine tuning of the parameters of the Standard Model, which strikes many physicists as unnatural. One way to avoid this is to postulate that the Standard Model particles are accompanied by partners with identical internal properties and interactions, but with spins differing by half a unit. These 'supersymmetric' particles would have opposite statistics from the familiar Standard Model particles—normal matter particles such as quarks and leptons are fermions, and would be accompanied by new bosonic particles, whereas intermediate bosons such as the photon would be accompanied by new fermions (see SUPERSYMMETRY). The fine-tuning problem of the Standard Model would be avoided if the supersymmetric partners of Standard Model particles weigh less than about 1 TeV.

These possible extensions of the Standard Model may provide the frameworks for resolving many of the fundamental issues in astrophysics and cosmology. One of these is DARK MATTER. The cold component may be provided by massive stable neutral particles, for which one candidate is the lightest supersymmetric particle, that is expected to weigh $O(100)$ GeV. This possibility will be explored by forthcoming accelerator searches at the proton–antiproton collider at FNAL and at the LHC proton–proton collider at CERN. A hot dark matter component may be provided by massive neutrinos. The indications for neutrino masses from the solar and atmospheric neutrino data do not, however, require any neutrino to be heavy enough to make a significant contribution to the overall dark matter density, although there could be some consequences observable by astronomers.

A second cosmological issue that may be addressed by extensions of the Standard Model is the origin of the matter in the universe. This can be calculated in terms of elementary-particle interactions if they violate baryon number, if they exhibit a matter–antimatter asymmetry and if they depart from thermal equilibrium. As has been discussed above, there are Standard Model interactions that violate baryon number and matter–antimatter asymmetry. Whether they departed from thermal equilibrium in the early universe depends in the Standard Model on the mass of the Higgs boson. The LEP lower limit on its mass, combined with theoretical calculations, indicates that there would have been no significant departure from thermal equilibrium if the Standard Model was sufficient to characterize early cosmology. Therefore some extension of the Standard Model appears necessary to explain the baryonic matter in the universe (see also BARYOGENESIS), which may be possible with grand unification and/or supersymmetry.

Grand unified theories may also be needed to explain the size, age and flatness of the universe via cosmological INFLATION. The measurements of perturbations in the COSMIC MICROWAVE BACKGROUND radiation suggest that they originate from physics at an energy scale of 10^{13}–10^{16} GeV. This is far beyond the scale of particle masses in the Standard Model and comparable with the scale of grand unification estimated using data from LEP and other accelerators.

Finally, we note that many theorists believe that the underlying theory of everything that resolves all the open problems of the Standard Model should be provided by some incarnation of STRING THEORY. This is an apparently consistent quantum theory of gravity, requires supersymmetry and is rich enough to accommodate a grand unified theory. If the self-coupling of the string is strong, it may provide a correct numerical estimate of the scale of grand unification. Astrophysics and cosmology, via inflation, gravitational waves and perhaps a cosmological constant may provide the most important tests of this ultimate extension of the Standard Model.

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