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CHALLENGES AND OPPORTUNITIES IN PARTICLE PHYSICS

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The Standard Model of particle physics describes very accurately all confirmed experimental data from accelerators. It leaves unanswered the origin of particle masses, the unification of the fundamental interactions, and the nature of a quantum theory of gravity. Particle masses may originate from a Higgs boson, and data from CERN's LEP accelerator have provided a first hint for its existence. Data on solar and atmospheric neutrinos indicate that neutrinos have masses, as suggested by grand unified theories. Astrophysics and cosmology may provide other hints about physics at very high energies. Central to the quest for the Higgs and other new particles will be CERN's next accelerator, the LHC.

1 The Standard Model of Particle Physics

Particle physics not only addresses the fundamental structure of matter, its constituents and the forces between them, but also gives us insights into the very early history of the Universe. When the age of the Universe was less than about one second old, its temperature was so high that the typical kinetic energies of elementary particles were above a few MeV. At earlier times, nuclear physics is inadequate to describe their behaviour. Perhaps it is not surprising that particle physicists need large accelerators to recreate the conditions of the Big Bang: the largest CERN accelerator (LEP) has a circumference of about 27 km and collides electrons and positrons with energies around 100 GeV each. It thereby reproduces, in some sense, conditions when the Universe was about 10^{-10} seconds old. CERN's next accelerator, the LHC, will recreate conditions when it was only 10^{-12} seconds old.

What have experiments at LEP and elsewhere been able to reveal so far about the elementary particles and their interactions? It has been established that nuclear matter is fabricated out of quarks, of which there are six types (or flavours) in total: the *up*, *down*, *strange*, *charm*, *bottom* and *top*, in order of increasing mass, and that the electron is followed by two heavier charged siblings (leptons), the *muon* and *tau*, each of which is accompanied by its own neutrino, for a total of three neutrino flavours. Four fundamental forces between these elementary particles have been identified: the familiar electromagnetic and gravitational forces, and the strong and weak nuclear forces.

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Figure 1. The cross section for $e^+e^- \rightarrow W^+W^-$ measured at LEP, as a function of the centre-of-mass energy, compared with theoretical calculations. The dotted lines show that the data require not only neutrino exchange, but also photon and Z^0 exchanges, with the couplings predicted in the Standard Model ⁴.

All these fundamental forces are mediated by the exchanges of some carrier particles: the photon for electromagnetism, eight gluons for the strong interactions, the $W^\pm$ and Z^0 for the weak interactions, and (it is firmly believed) the graviton for gravity. The massless photon has been known since 1900, from the work of Planck and Einstein. The massless gluons were discovered at the DESY laboratory in Hamburg in 1979 ¹, and the massive $W^\pm$ and Z^0 were discovered at CERN in 1983 ². The massless graviton remains to be discovered.

All the quarks and charged leptons are massive, and it now seems that the neutrinos may also have very small masses. The $W^\pm$ and Z^0 weigh as much as medium-sized nuclei, and the heaviest quark, the top ³, weighs as much as a large nucleus. The most pressing problem in particle physics is to understand where these masses come from, and why some particles, such as the photon and gluons, get away without acquiring masses.

This Standard Model has been tested with high precision by experiments at CERN elsewhere. For example, using LEP it was possible to measure the mass of the Z^0 with an accuracy of about two parts in 10^5 , and many other properties of the Z^0 and its decays agree with the Standard Model with an accuracy around 0.1% ⁴. Recently, with increased energies at LEP, it has become possible to measure the mass of the $W^\pm$ with an accuracy around five parts in 10^4 , and to verify that the photon and Z^0 boson couple to the $W^\pm$ just as predicted by the Standard Model, as seen in Fig. 1.

All this sounds very impressive, but many important questions are raised by the Standard Model, and await answers from the next generations of accelerator experiments. Where do the *particle masses* come from? Are the fundamental forces *unified*? Why are there so many different *flavours* (types) of matter particles? Above all, how to explain all the parameters of the Standard Model: six quark masses, three charged lepton masses, two boson masses, four weak mixing angles and phases, three gauge couplings and a CP-violating phase in the strong interactions, for a total of 19 parameters, not to mention the masses and mixing angles of neutrinos?

In the following sections, the prospects for addressing some of these fundamental questions are reviewed.

2 The Problem of Mass

2.1 Broken Symmetry

In the basic formulation of the Standard Model as a gauge field theory, all particles are born massless, reflecting the symmetries of the underlying theory. However, in the real world, only a few of these particles are still massless, namely the photon and the gluons, reflecting the persistence of unbroken local ‘gauge’ symmetries, $U(1)$ in the case of electromagnetism and $SU(3)$ in the case of the strong interactions. The other elementary particles, namely the quarks, leptons, $W^\pm$ and Z^0 , not to mention you and I, are now massive. Presumably this is because other underlying symmetries of the Standard Model are broken, and the game is to discover how.

The mechanism favoured by particle physicists envisages different particles as corresponding to different directions in some internal space. Initially, the equations of the theory do not distinguish between these different degrees of freedom, that can be imagined as different directions in some analogue of a flat plane. In the unbroken case, there is no obstacle to moving in any direction in the plane, corresponding to all the particles being massless. However, the symmetry may be broken by folding the plane, rather like a rift valley created by plate tectonics, or more prosaically by folding a piece of paper, as seen in Fig. 2. After folding once a piece of paper, there is one flat direction and a perpendicular direction that rises and falls. The flat direction might correspond to a particle that remains massless, whereas the ‘hilly’ direction might correspond to a massive particle.

These ‘hills’ and ‘valleys’ are provided in the Standard Model by a new sort of field that permeates all space, much like the more familiar electromagnetic and gravitational fields. Just as the electromagnetic and gravitational

Figure 2. The symmetric phase of theory is analogous to a flat plane, in which there is no obstacle to motion in any direction - all particles are massless - whereas a broken phase has the analogue of a 'rift valley', with obstacles to motion in some directions but not others - corresponding to the appearance of massive particles.

fields have quantum fluctuations called the photon and graviton, so also the quantum fluctuations of this new mass-giving field should yield at least one observable particle, called the Higgs boson ⁵.

It is a classical vacuum expectation value of the Higgs field that enables other particles to gain mass, by breaking the gauge symmetry of the Standard Model. For example, it is this new Higgs field that provides an extra polarization state for each of the $W^\pm$ and Z^0 , enabling them to become massive. Remember that a massless spin-one particle such as the photon has just two polarization states, whereas a massive spin-one particle such as the $W^\pm$ or Z^0 requires three polarization states: one longitudinal state as well as two transverse states. In addition to these 'hidden' Higgs states, even in the minimal version of the Standard Model there is one physical Higgs boson in the spectrum, and more complicated models, such as the supersymmetric extensions discussed below, have more Higgs bosons awaiting discovery.

Although the Higgs mechanism might look at first like a dubious trick, one can in fact show that it is the only way of providing the particles of the Standard Model with masses, if one wants a theory with results that can be calculated reliably ⁶: what a field theorist calls renormalizable.

Many such calculations have been made in the Standard Model, and the results agree very well with experiment, as already mentioned. This good

Figure 3. The likelihood function for the mass of the Higgs boson, as estimated from a global analysis of data on the electroweak interactions. The solid and dotted lines correspond to different estimates of the effective value of the fine-structure constant at the Z^0 energy ⁴.

agreement was used some years ago to predict successfully the mass of the top quark, which had not at that time been detected directly by any experiment ⁷. More recently, similar calculations have been used to predict successfully the mass of the $W^\pm$. These calculations are quite sensitive to the mass of the infamous Higgs boson ⁸, and the agreement between the data and the predictions can be used to estimate its mass ⁴:

$$m_H = 62^{+53}_{-30} \text{ GeV} \quad (1)$$

with a one-sided 95% confidence level upper limit of 170 GeV, as seen in Fig. 3.

2.2 A Supersymmetric Conspiracy?

Although the Higgs boson provides a possible source for particles masses, there is another problem associated with their values ⁹. If one calculates quantum corrections to the masses of bosons, such as those of the $W^\pm$, the Z^0 and the Higgs itself, one finds that they are so large as to risk destabilizing them. There is apparently nothing to prevent the electroweak scale from becoming very large, perhaps as great as the Planck scale $G_N^{-1/2} \simeq 10^{19}$ GeV. In principle, one could evade this problem by fine-tuning the classical values of the boson masses to very large and almost opposite numbers, so that their net values are around 100 GeV. However, this strikes many theorists as unnatural.

This instability may be avoided by postulating equal numbers of bosons and fermions with equal couplings, as in supersymmetric theories¹⁰. In this case, the positive corrections due to the quantum effects of bosons are cancelled naturally by the corresponding negative quantum corrections due to fermions. Supersymmetry is a very beautiful theory, and is required at some energy scale in string theory, which, as discussed later, is the only candidate we have for a quantum Theory of Everything (TOE), including gravity. However, this aesthetic argument does not tell us what masses supersymmetric particles might have. The only hint comes from the naturalness (or fine-tuning) argument summarized above, which suggests that some supersymmetric particles should weigh less than about 1 TeV.

2.3 The Higgs Quest

In order to verify these ideas, it is clear that the highest priority is to discover experimentally the Higgs boson. The precision electroweak data mentioned above suggest that it might be tantalizingly close. Compared with the estimate (1), the direct searches at LEP have established a lower limit of 113.5 GeV, and have attained a sensitivity to a Higgs mass of 115 GeV. Much excitement has been caused recently by the appearance of an apparent excess of Higgs candidates with a mass around 114 to 115 GeV. These include events reported in particular by the ALEPH collaboration, principally in the $H \rightarrow \bar{b}b + Z \rightarrow \bar{q}q$ final state, as seen in Fig. 4¹¹.

Interesting events have also been reported by the L3 collaboration, including one in the $H \rightarrow \bar{b}b + Z \rightarrow \bar{\nu}\nu$ final state, seen in Fig. 5¹². Overall¹³, there is an excess of about 2.9 standard deviations corresponding to $m_H = 115^{+1.3}_{-0.7}$ GeV¹⁴. During the course of this meeting, it was decided not to continue running LEP during 2001 in an effort to confirm or refute this possible signal. Instead, it was decided to push ahead as rapidly as possible with the preparations for the LHC accelerator, which should be able to discover definitively the Higgs boson, whatever its mass. In the mean time, the Tevatron $\bar{p}p$ collider may have a chance to confirm the discovery of the Higgs boson, if its mass really is around 115 GeV.

In addition to the Higgs boson, many experiments are looking for supersymmetric particles, which should have the same internal quantum numbers as the known particles, but spins differing by half a unit. Unsuccessful indirect searches at LEP indicate that many sparticle species must have masses greater than around 100 GeV. If they are to do their job of stabilizing the masses of bosons in the Standard Model, these sparticles should weigh less than about 1 TeV. The LHC will be able to discover strongly-interacting sparticles, the

Figure 4. Display of a candidate for $e^+e^- \rightarrow (Z^0 \rightarrow \bar{q}q) + \text{Higgs}$ seen by the ALEPH collaboration ¹¹.

squarks and gluinos, if they weigh less than about 2 TeV, and will also have interesting sensitivities to other sparticles ¹⁵. In the mean time, in addition to direct searches at the Tevatron, there are many direct and indirect searches for the dark matter that astrophysicists believe to abound in the Universe, much of which may be composed of supersymmetric particles.

3 The Problem of Unification

The Standard Model treats the fundamental forces in a rather messy way, unifying partially the weak and electromagnetic interactions, but leaving the strong nuclear interactions off on one side. Following Einstein, it has been the dream of many ambitious physicists to find a single unified field theory that encompasses them all. If such a Grand Unified Theory (GUT) exists, the unifying symmetry must be broken at very high energy scale, if the manifest differences in strength between the different interactions are to be understood, and if new interactions are not to cause protons to decay more rapidly than is allowed by experiment: the present lower limit on the proton lifetime is about 10^{33} years ¹⁶.

The quantum numbers of the quarks and leptons fit very neatly with the assignments suggested by the simplest GUTs, and there are experimental hints that may favour some GUT scenarios. For example, the strengths of

a)

Run # 933204 Event # 4704 Total Energy : 112 GeV

Figure 5. Display of a candidate for $e^+e^- \rightarrow (Z^0 \rightarrow \bar{\nu}\nu) + \text{Higgs}$ seen by the L3 collaboration ¹².

the different fundamental interactions vary as functions of the effective energy scale, in a manner calculable once one knows the spectrum of matter particles. If one assumes just the particles in the Standard Model, the different interaction strengths would become almost equal at an energy around 10^{14} to 10^{15} GeV as seen in Fig. 6, and the proton lifetime would be about 10^{30} years. Close, but no banana! Both these difficulties are removed by postulating the appearance of supersymmetric particles at energies below about 1 TeV. In this case, the different measured interaction strengths are in perfect agreement with unification at an energy scale around 10^{16} GeV ¹⁷, as seen in Fig. 6, and the proton lifetime exceeds the present experimental lower limit. Such a supersymmetric GUT not only gets the different interaction strengths right, but also offers tantalizing relations between the masses of quarks and leptons.

The key to testing GUTs is surely to find characteristic new forces or particles. One generic prediction of GUTs is that *neutrinos should have small but non-zero masses*, and the first experimental evidence pointing in the GUT

Figure 6. The energy variations of the gauge coupling strengths in theories without and with supersymmetry. The latter are consistent with grand unification at an energy around 10^{16} GeV¹⁷.

direction has been provided by indications that neutrinos may indeed be massive. These hints have been furnished by measurements of neutrinos from the Sun¹⁸ and cosmic-ray interactions in the atmosphere¹⁹. In both cases, fewer neutrinos are seen than would be expected in the Standard Model, and these experiments are interpreted as evidence that the neutrinos produced by the astrophysical sources - electron neutrinos from the Sun and muon neutrinos from the atmosphere - change (oscillate) into other neutrino flavours before reaching the detectors. Such neutrino oscillations are predicted if the different neutrino species mix among themselves like quarks do, and if the mass eigenvalues are different. Experiments are now underway in Japan and being prepared in the United States and Europe to test these ideas with neutrino beams produced by accelerators, which are well-understood and controllable.

If neutrinos do have masses, they might constitute a significant fraction of the missing dark matter postulated by astrophysicists and cosmologists. However, the minimum masses required to interpret the neutrino oscillation experiments are too small to be of great cosmological interest²⁰, and astrophysicists generally prefer much heavier particle candidates for dark matter, such as supersymmetric particles.

The search for *proton decay* has already been mentioned. If proton decay were to be seen, it would constitute very direct and convincing evidence for

Figure 7. A compilation of information about neutrino masses. The regions of mass differences and mixing angles indicated by different solar, atmospheric and accelerator neutrino oscillation experiments are compared with cosmological limits. Apart from the LSND accelerator experiment, the data favour small mass differences, corresponding to masses that are unlikely to dominate the cosmological dark matter, though they may have some astrophysical significance ²⁰.

GUTs : after all, other sources of neutrino masses could be envisaged. For this reason, discussions are underway about the possibility of building a very large next-generation experiment that could continue the search for proton decay.

As for new particles, *magnetic monopoles* are predicted in most GUTs. Unfortunately, according to modern ideas of inflationary cosmology, no magnetic monopole is likely to have remained within our observable Universe.

4 Towards a Theory of Everything

The job description of a Theory of Everything (TOE) is to unify gravity with the other particle interactions. The first step in such a programme is to

formulate a consistent quantum theory of gravity. This is the greatest piece of business left unfinished by twentieth-century physics, and hence the ultimate challenge for theoretical physics in the twenty-first century. The greatest successes of twentieth-century physics were quantum mechanics and general relativity, and its greatest embarrassment has been the failure to combine them.

Hope for making a quantum theory of gravity is provided by string theory ²¹, which also seems sufficiently powerful to incorporate matter particles and the other fundamental interactions in a TOE. However, although string theory has made tremendous advances and resolved some aspects of the problem of quantum gravity, much of its promise remains to be fulfilled.

The first challenge offered by quantum gravity is that *higher-order corrections* to the single-graviton exchange responsible for the classical gravitational field, are horribly infinite. Thus two-graviton exchange would be much greater than one-graviton exchange at, for example, a conjectural e^+e^- collider with a centre-of-mass energy near the Planck scale of 10^{19} GeV. The challenge of making sense of these quantum corrections has been met successfully by string theory.

Further challenges are offered by *black holes*, which have been found in semi-classical treatments to obey the laws of thermodynamics, with non-zero temperature and entropy. The question is raised whether quantum mechanics can survive unscathed in strong gravitational fields with event horizons across which information is apparently lost. These may be present microscopically, because of localized quantum fluctuations in the gravitational field, the so-called *space-time foam* ²². String theory provides a successful accounting for the quantum states of macroscopic black holes, but a complete stringy treatment of space-time foam remains an open challenge.

Finally, how is one to *combine gravity with the other interactions*, given that the graviton has spin two, whereas the carrier particles for the other fundamental interactions have spin one? This sounds like a good assignment for supersymmetry, which automatically relates particles of different spin. Indeed, string theory seems to require supersymmetry for its consistent formulation. However, no specific TOE has yet emerged convincingly from among the myriad possibilities offered by superstring theory.

5 Hints from Astrophysics and Cosmology ?

In view of the high energy scales involved in many theories of physics beyond the Standard Model, it is natural to wonder whether astrophysics and cosmology may be able to answer some of our questions.

One possible hint may come from *ultra-high-energy cosmic rays* ²³. According to conventional physics, they would have been absorbed before reaching us if they came from sources more than about 5×10^7 light-years away. On the other hand, there are no obvious local sources. Perhaps they are due to new physics, for example, the decays of massive GUT particles spread through the galactic halo ?

A major puzzle in astrophysics and cosmology is the *dark matter* that is required to explain the formation of structures in the Universe. As already mentioned, it may be composed of massive weakly-interacting particles, such as neutrinos or supersymmetric particles. Extensive experimental programmes to probe these possibilities are underway around the world.

A more speculative suggestion is to use sources of energetic photons and neutrinos to *probe fundamental physics*, such as special relativity or quantum mechanics. Distant sources that emit pulses of energetic radiation, such as gamma-ray bursters, might be able to test some models of space-time foam ²⁴.

One cosmological observation that seems very likely to take us back to the GUT epoch is the *microwave background radiation* ²⁵, which exhibits perturbations believed to have been generated during an early period of cosmological inflation. These may have been laid down by quantum fluctuations of some Higgs-like scalar field at an energy scale close to that estimated from the GUT unification of particle interactions.

Recent observations of the microwave background, together with observations of distant supernovae and measures of the dark matter density ²⁶, suggest that the Universe may be dominated by *vacuum energy*. If so, this provides a second number to be confronted with any theory of gravity, in addition to Newtons constant $G_N \simeq 1/(10^{19} \text{GeV}^2)$. Calculating the value of this vacuum energy may be the ultimate challenge for string theory.

6 Prospects for the Twenty-First Century

As we have seen, the Standard Model of particle physics works very well, but leaves many questions unanswered. Many theoretical ideas have been proposed that address at least some of these questions, such as the Higgs boson, supersymmetry, grand unification and string theory. As also seen, there may be ways of testing some of these ideas using astrophysical and cosmological data. But many of the best prospects for verifying or refuting these ideas will be provided by forthcoming accelerator experiments, including those using bottom-meson factories and long-baseline neutrino beams. However, the centrepiece of the next generation of particle experiments will be the LHC.

This will collide beams of 7 TeV protons and/or lead nuclei with about

Figure 8. An illustration of the significance to be expected at the LHC for the discovery of a Higgs boson, for different amounts of accumulated collisions ¹⁵.

3 TeV per nucleon. The LHC will be installed in the tunnel previously occupied by LEP, and will have four major experiments. Two of them, ATLAS and CMS, are designed for discovering new particles such as the Higgs boson - see Fig. 8 - and/or supersymmetric particles. Another experiment, LHCb, will mainly be looking at matter-antimatter differences in the decays of particles containing bottom quarks. Finally, the ALICE experiment will mainly be studying ultra-relativistic heavy-ion collisions, to look for signatures of the quark-gluon plasma.

Several ideas for possible accelerators beyond the LHC are being proposed at CERN and elsewhere. One possibility could be a linear e^+e^- collider with a centre-of-mass energy in the TeV range. Another possibility could be a complex for producing, accelerating and storing muons, that could be used as a neutrino factory or to make high-energy muon-antimuon collisions.

We believe that the scientific problems studied at CERN are potentially of

interest to everybody curious about the structure and history of the Universe. We have a number of outreach programmes aimed at answering questions from the general public about these problems ²⁷. These questions exert particular fascination on the young, even those who subsequently move into other technical fields, like the majority of students working on CERN experiments. Over 6000 scientists and engineers from around the world are registered to work on experiments at CERN, including groups from South Africa and a few other African countries. CERN is open to any scientist with a promising scientific programme of work using our facilities, which include some directed at nuclear physics, as well as the high-energy experiments highlighted in this talk. In particular, CERN would welcome extended participation in its programmes by more interested members of the Southern African community.

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