Ideas Beyond the Standard Model

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Phenomenologically, the standard model works extremely well with no experimental data, as of yet, requiring any physics beyond the standard model. (A possible exception is the Universe's baryon asymmetry, which argues for the presence, at some level, of baryon number violating interactions, which are not present in the standard model.) Perhaps buoyed by this practical success, theorists in the last few years have turned their attention to more structural issues in the standard model. To answer some of these deeper questions requires considerable invention.

Roughly speaking, there are three broad classes of question which the standard model leaves open: the question of forces, the question of matter and the question of mass.

i) Forces: Although the standard model describes the strong and electroweak interactions in terms of the SU(3) × SU(2) × U(1) gauge theory, one can well ask why these are the only forces one sees in Nature, apart from gravity? Furthermore, at the scale we presently measure these interactions ($q^2 \cong 100$ GeV^2) the strong and electroweak couplings are very disparate ($\alpha_3 \cong 0.15$ *vs.* $\alpha = 1/137$). Why is this so?

ii) Matter: Although reducing matter to just quarks and leptons is already a great simplification, one would like to know why these are the only excitations we see. In particular, why is it that quarks and leptons come in three families and, if there are no more families, what fixes this number? Furthermore, what physics determines the somewhat peculiar quantum numbers that these excitations have in the standard model. For instance, what is the reason that quarks have 1/3 integral charge, while leptons have integral charge? And why do only the left-handed components of these fields feel the SU(2) forces, giving rise thereby to parity violations in the weak interactions?

iii) Masses: The spectrum of masses in the standard model is both extensive and peculiar. However, only for the gauge fields do we have some understanding of why this spectrum follows. The $W^\pm$ and Z masses are proportional to the scale of the SU(2) × U(1) breaking — the Fermi scale: $\Lambda_F = (\sqrt{2}G_F)^{-1/2} \cong$ 250 GeV, where G_F is the Fermi constant measured in weak decays. The constants of proportionality are the SU(2) × U(1) coupling constants, which are related to that of electromagnetism. Fermion masses are also proportional to Λ_F, since they also are forbidden by the weak SU(2) symmetry. (Mass terms for fermions connect the left-handed with the right-handed components of these fields, but these transform differently under SU(2). Therefore, only because SU(2) × U(1) is spontaneously broken can fermions acquire a mass.) In contrast to the gauge fields, however, the constants of proportionality for fermions are not related to known parameters. In the standard model, one introduces a complex scalar doublet Φ, whose vacuum expectation value serves as an order parameter for the SU(2) × U(1) breakdown: $\langle\Phi\rangle = \Lambda_F/\sqrt{2}$. It

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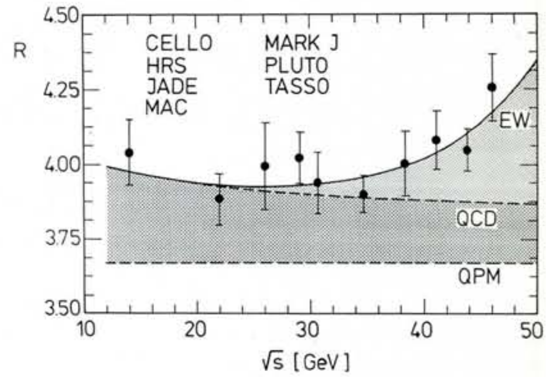
is the couplings of this Higgs field to fermions which serve as the constants of proportionality for fermion masses. Although one can generate fermion masses *via* these Higgs couplings, the large disparity seen in the fermion mass spectrum (e.g. $m_\tau \cong 3400\ m_e$) is not explained.

Two Approaches

These questions of forces, matter and masses are the present day mysteries of particle physics. Their elucidation is being pursued by following two lines of attack which are distinct, both physically and philosophically. In what might be called a "bottom up" approach, one postpones altogether the discussion of the aesthetic aspects of the standard model (why do certain forces and certain types of matter appear), and one concentrates instead on finding the physics behind the poorly understood phenomena of the theory, connected with the SU(2) × U(1) breakdown and mass generation. In the "top down" approach, on the other hand, aesthetics and inner consistency serve as a guide to the physics which underlies the standard model, at a deeper level.

The first approach leads one, almost inevitably, to envisage a new level of structure below that of quarks and leptons. In these speculations, these states are themselves bound states of yet more fundamental objects — preons [1]). Supersymmetry, a boson-fermion symmetry, plays a natural role in the second approach. Indeed, recent developments in superstring theories (see Green p. 999) have given a tremendous boost to the "top down" view, by providing a physical framework which encompasses some of the desired aesthetic requirements. Although none of the speculations connected with preons or superstrings has yet received experimental support, some evidence must eventually turn up for physics beyond the standard model. For only if this physics exists can one hope to understand the origin of the standard model mysteries!

In the standard model, the breakdown of SU(2) × U(1) *via* a non-vanishing Higgs vacuum expectation value is effected in an analogous manner to that of the Ginzburg Landau phenomenological theory of superconductivity. Here also one introduces Φ self interactions, which give rise to an asymmetric potential. The Fermi scale is the parameter to which $<\Phi>$ is driven at the potential minimum. However, if one takes the Higgs sector of the theory as fundamental, and not just as a convenient phenomenological construct, one encounters



The tail of Z^0. Recent results collected by the CELLO group at DESY (G. d'Agostini) on $e^+ + e^- \rightarrow$ hadrons. $R = \sigma(\text{hadron}) / \sigma(\mu^+\mu^-)$. QPM = quark parton model; QCD includes correction for gluon emission; EW = electroweak theory including Z^0.

a problem of naturalness. In a theory of scalar fields, with a high frequency cutoff provided by the Planck mass, M_{Pl}, (page 14) radiative effects shift all massive parameters to values of the order of the cutoff. So maintaining $<\Phi> = \Lambda_F/\sqrt{2} << M_{Pl}$ requires a "fine-tuning" of the parameters of the theory. This hierarchy problem can be avoided if the cutoff is not $O(M_{Pl})$ but $O(\Lambda_F)$ itself, that is, if the Higgs sector is just an approximation to the physics of an underlying theory, in which dynamical SU(2) × U(1) breaking condensates form, with scales of order Λ_F. Preon models are natural candidates for such an underlying theory. However, although compositeness is the simplest solution to the hierarchy problem, it is not the only interesting solution. In a supersymmetric theory, it is no longer true that scale parameters in the theory suffer large radiative shifts, because of boson-fermion cancellations. So an elementary Higgs sector with $\Lambda_F << M_{Pl}$ is not unnatural in this case.

Preon Models

Although preon models can provide a dynamical origin for the Fermi scale, entirely analogous to the formation of Cooper pairs in the BCS theory, the principal difficulty they encounter is connected with the spectrum of the fermionic bound states. These bound states naturally should have masses of the order of the dynamical scale of the theory, which by consistency should be of $O(\Lambda_F)$. But quarks and leptons have masses which are much less than Λ_F! The only reasonable solution found to this conundrum is to construct models with enough chiral symmetries so that some bound states are forced to be mass-less. It is these states which one associates with the quarks and leptons. However, the difficult task remaining is to break these protective symmetries slightly so as eventually to generate the correct mass pattern for the quarks and leptons. Unfortunately, at present, only toy models exist where some of these ideas are realized. Furthermore, the generation of family repetitions, although possible, is not so simple to achieve in practice. So this line of investigation is somewhat at an impasse. Nevertheless, one should ultimately be able to decide experimentally whether the scalar sector is elementary or whether the symmetry breakdown is caused by an underlying strong interaction theory. Unfortunately, physical differences between these two options manifest themselves most readily in processes involving the virtual scattering of W-bosons — processes which can only be probed at extremely high energies or by very precise experiments.

Superstrings

Eschewing a more dynamical origin for the Fermi scale allows one to make bolder suppositions for what physics fixes the nature of matter and forces. In particular, rather beautiful speculative answers on these fundamental questions emerge out of the study of the dynamical consistency of superstring theories (page 15). Instead of discussing these speculations directly, it is helpful first to motivate separately the three main ingredients underpinning this line of thought: unification, supersymmetry and compactification.

Unification: The idea of unifying the existing forces into a larger gauge structure — a grand unified theory (GUT) [2]) — is a natural extension of the process that led to the electroweak theory. Natural GUT groups, like SU(5), SO(10) and E_6, exist and provide at least two conceptual adavantages.

1) For $q^2 >> M_x^2$, the scale of the GUT breakdown, the theory has a unique coupling. The disparate values of the strong and electroweak couplings at low q^2 follow from the different evolution of these couplings below M_x. Further, their numerical values require $M_x \cong 10^{14} - 10^{15}$ GeV.

2) Matter must fit into fixed GUT representations. For instance, all fermions of a given family fit in the 16 dimensional

representation of SO(10). Thus GUT theories force inter-relations between the quantum numbers of quarks and leptons and explain nicely the different charges for these excitations.

Supersymmetry: I have indicated already how supersymmetry can serve to stabilize the scalar sector of the standard model. In the present context, however, one can think of another role for supersymmetry. Given a symmetry group, the number and kind of gauge bosons is fixed uniquely, since they must transform according to the adjoint representation of the group. If there was a (1/2, 1) supersymmetry which associated the matter fermions with the gauge bosons then, given the forces, the matter would be fixed! However, things cannot be so simple since the adjoint representation is real, so that the fermions will always turn out to be chirally paired, in conflict with the chiral asymmetry needed for the weak interactions. The idea that matter and forces are unified via supersymmetry makes no sense unless the above problem is solved.

Compactification: Physical theories in a spacetime of greater than four dimensions can give rise to sensible 4-dimensional theories if the extra dimensions spontaneously compactify. In particular, in spacetimes with $4n + 2$ dimensions one can have fermions which have both reality properties and are chiral. Upon compactification, it is possible that only fermions of a certain chirality survive, with their number in general being determined by topological properties of the compact space. This mechanism can then be used to get rid of unwanted fermionic states.

These three ingredients are present in superstring theories [2]. These theories as we have seen exist in ten dimensions, are supersymmetric and have a fixed gauge group which, for the most promising case, is $E_8 \times E_8$. Besides the fact that superstrings may provide a realistic quantum theory of gravity [1], the excitement surrounding them is connected to the fact that they potentially can explain rather naturally why we have the matter and forces we observe. In the most popular scenario [3] at a scale of $O(M_{Pl})$ compactification is supposed to take place reducing one of the E_8 groups to a subgroup of E_6, which contains the standard model. The emerging fermions are chiral and appear in a number of replicas (families) of the 27-dimensional representation of E_6. Further an overall supersymmetry is preserved.

All these points are very nice. The supersymmetry is useful for the hierarchy problem. Quarks and leptons fit well in the 27-dimensional representation of E_6 and the strong and electroweak interaction emerge naturally. Of course, depending on details of the evolution of the theory below the compactification scale some extra states and/or forces may appear. But to know really whether this happens, one must understand the process by which other scales besides M_{Pl} are generated in these theories. It is thought that phenomena tied to the other E_8 may trigger the breakdown of supersymmetry, which in turn acts as a seed to generate radiatively the breakdown of $SU(2) \times U(1)$. However, no fully convincing demonstration of this has been given. Hence, even though Yukawa couplings can be generated at the compactification scale, it is not clear whether Λ_F will ever emerge from these theories! Here too experiment is needed for illumination. Supersymmetry, although broken, remains a crucial ingredient of these theories. Thus, if this line of speculation is correct, one should expect to observe superpartners of both quarks, leptons and gauge bosons, with masses not much bigger than Λ_F. Results from the next generation of accelerators, probing the 100 GeV energy range, are eagerly awaited.

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