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NEW DIRECTIONS IN HIGH ENERGY PHYSICS

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New Directions in High Energy Physics

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Abstract

Prospects for new discoveries in the next generation of colliding beam machines are discussed. Suggestions for substructure of quarks and leptons, as well as for the presence of bosonic partners of these particles are examined.

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Prospects for new discoveries in the next generation of colliding beam machines are discussed. Suggestions for substructure of quarks and leptons, as well as for the presence of bosonic partners of these particles are examined.

High energy physics has made remarkable progress in the last ten years. As the other speakers in this session have reported, there exists now some very good experimental evidence suggesting that the strong interactions are described by Quantumchromodynamics (QCD) and that the electroweak interactions are given by the Glashow, Salam, Weinberg (GSW) model. The theoretical framework for these interactions is a non Abelian gauge theory, based on the group SU(3) x SU(2) x U(1) - the, so called, standard model /1/.

Although the standard model has been only "confirmed" recently experimentally, the theoretical ideas on which it is based were developed in the 1960's and early 1970's. There exists now a similar theoretical backlog of ideas, which were developed in the last 10 years or so, which are crying for experimental confirmation. These untested speculations follow four main directions: those of (i) supersymmetry (Susy); (ii) grand unification (GUTS); (iii) Compositeness (Preon Models); and (iv) Technicolor (Dynamical symmetry breaking). Colliding beam machines, built or to be build, in the next decade will explore and confirm or discard these ideas, up to scales of the order of a TeV.

The purpose of this talk is to indicate why high energy physicists, even though thinking they have THE THEORY of strong, weak and electromagnetic interactions, keep pursuing new directions. Further, I also want to describe briefly the principal features of the various new speculations, concentrating in particular on some of their experimental signatures.

Although the standard model is theoretically consistent, there exist open questions which indicate its physical limitations. The new theoretical ideas being put forward try to address some of the following "mysteries" of the model:

(1) Why are the interactions gauge interactions and why are they based on SU(3) x SU(2) x U(1)?
(2) Where does gravity fit in the picture?
(3) Why do weak interactions violate parity?
(4) Why are the quarks and leptons replicated in families?
(5) Why do the fermions have the mass patterns they have and how do these masses reflect the charged current mixing angles?
(6) Why is the Fermi scale of weak interactions, $\Lambda_F = (\sqrt{2}G_F)^{-1/2} \simeq 250$ GeV, different from the Planck scale of gravity, $M_P \simeq 10^{19}$ GeV, and what relationship does Λ_F bear to the dynamical QCD scale, $\Lambda_{QCD} \simeq 300$ MeV?
(7) Why are the charges of the leptons and quarks what they are?
(8) Why are the strengths of the weak coupling constants, g_2 and g_1, so different than that of the strong coupling constant g_3?

The first three questions above are very deep and hints for their answer probably will not come from experiment. Theoretical activity trying to address these questions, based on supergravity and Kaluza-Klein theories, has been recently reviewed by Ferrara /2/. I note here only that the lack of left-right symmetry makes life difficult and it would help if "mirror" fermions were to be found.

The question of families and their related masses and mixing angles are more amenable to experimental investigation. For instance, we have heard from C. Rubbia /3/ at this meeting some preliminary evidence for the top quark, with mass $m_t = 40 \pm 10$ GeV. Also, an accurate measurement of the Z^o width, at Lep or SLC, can provide, within the context of the standard model, direct evidence for the number of generations. However, only from theory beyond the standard model can these parameter be predicted. Roughly speaking, from experiments at the next generation of colliders one may expect some hints at the "mass questions" 4)-6), but one is unlikely to learn much about the "structure questions" 7) and 8).

GUTS /4/ address the "structure questions" by postulating that the standard model is part of a larger set of gauge interactions, based on a group $G \supset SU(3) \times SU(2) \times U(1)$. By having quarks and leptons in the same representation of G their charge ratios are fixed. Further in G there is a unique coupling constant g_u. However, if G is broken at a superheavy scale, $M_x \gtrsim 10^{14}-10^{15}$ GeV, into SU(3) x SU(2) x U(1) [This is similar to the breakdown of SU(2) x U(1) in the GSW model at Λ_F into $U(1)_{em}$] one can understand the disparity between g_1, g_2 and g_3 at laboratory energy scales. The point is that coupling constants are really scale dependent, because of vacuum polarization effects, and even though at M_x one has $g_1 = g_2 = g_3 = g_u$, at lower scales these couplings can well be widely different.

GUTS physics is really high energy physics ($E \sim 10^{15}$ GeV), so the early universe is its laboratory. Earthly windows for GUTS are provided by their prediction of proton instability and the existence of superheavy magnetic monopoles. Collider experiments, although far from the relevant energy scale, can, nevertheless, provide two important pieces of information for GUTS:
(i) Is there more than the standard model and its three generations of quarks and leptons? [One must know what needs to be unified!]
(ii) Accurate measurements near the Z^o will give very precise ratios for g_2/g_1. This will test specific GUT models which predict this ratio from the coupling constants' evolution.

The "mass questions" are not addressed by GUTS. More useful here are Composite models, Susy and Technicolor. Indeed, there are two separate issues here - the one of pattern and masses of the fermions, and the issue of the Fermi scale. Preon models try to tackle the fermion question, although some versions have also implications for the Fermi scale. Technicolor and Susy deal principally with the Λ_F issue, but the raison d'etre of Susy may be much deeper. The next generation of colliders will operate in the energy range of the Fermi scale and should really clarify the origin of the SU(2) x U(1) symmetry breakdown. If there is "low energy" compositeness, these experiments may also throw light on some of the quark and lepton mysteries. However, these questions may well remain a persistent mystery.

Preon models /5/ assume that quarks and leptons are composed of yet more fundamental building blocks (preons). In principle, therefore, the fermion mass spectrum and generation structure are calculable bound state properties of the preon theory. In practice, however, the best that one has been able to achieve theoretically is to construct models where the known fermions (plus a few undesired states) emerge as $m = 0$ bound states and where generations appear as mechanically repetitive structures. The disparity between what is achieved and what is wanted is due to the fact that preon models must overcome an extremely hard dynamical problem. Quarks and leptons appear experimentally very "elementary" and if they have an intrinsic size $\langle r \rangle$ at all, this size is certainly very much smaller than their Compton's wavelength λ. Our experience in bound state problems up to now has been with systems where $\langle r \rangle \gg \lambda$ (Atoms) or $\langle r \rangle \simeq \lambda$ (Hadrons).

It has become customary to talk of a compositeness scale Λ_c, related to $\langle r \rangle^{-1}$. Bounds on Λ_c follow from the absence of deviations from standard model predictions for e^+e^- scattering and for g - 2 and, typically, one finds that $\Lambda_c \gtrsim 1$ TeV /5/. Preon dynamics must therefore be able to bind states - the quarks and leptons - which are very light with respect to Λ_c:

$$m_q, m_\ell \ll \Lambda_c \qquad (1)$$

This difficult dynamical problem, up to now, has only been "solved" by postulating some protective symmetry which forces certain bound states to zero mass ($\lambda \to \infty$). Two favorite ideas are to incorporate in the preon theory either some unbroken chiral symmetry or some supersymmetry in conjunction with some broken global symmetries. The more successful models are able to produce the desired quarks and leptons as massless excitations. However, how to generate the observed mass spectrum remains still a very open question. This problem is compounded by a lack of understanding of why the family structure emerges and an uncertainty on where the compositeness scale Λ_c really is. If $\Lambda_c \sim M_p$, clearly the mass question is beyond experimental hint. On the other hand, compositeness could be nearby, with $\Lambda_c \sim$ 1 TeV, and Λ_c and the Fermi scale Λ_F could be interconnected.

Most theoretical effort now is connected to the Fermi scale, perhaps because there is some not too distant hope of experimental illumination. The Fermi scale is the scale at which, in the GSW model, SU(2) x U(1) is broken to $U(1)_{em}$. Thus the W and Z masses are proportional to Λ_F and, experimentally, these relations have been checked at the CERN collider recently. In the GSW model itself the spontaneous SU(2) x U(1) breakdown is generated by introducing an elementary Higgs field ϕ with non zero vacuum expectation value. The Fermi scale is the value of the (asymmetric) minima of the Higgs potential

$$V = \lambda \left(\phi^{\dagger}\phi - \Lambda_F^2\right)^2 \tag{2}$$

and is a parameter put in by hand. In fact, there are theoretical questions whether such a parameter is stable under radiative corrections. Roughly speaking, if one thinks of a theory with a natural cutoff Λ - such as gravity could provide - whatever value of Λ_F one puts in initially, in the end it is replaced by the cutoff value Λ. This is illustrated, for example, by studying the Higgs mass. The lowest order value, computed from harmonic oscillations around V_{Min}, gets an enormous radiative shift, for large cutoff Λ :

$$m_H^2 = 2\lambda \Lambda_F^2 + \alpha \Lambda^2 \tag{3}$$

To render the symmetry breaking sector of the standard model stable one has two options. Either one finds a way to control the radiative corrections, or the physical cut off Λ is itself of order Λ_F. Susy, by pairing bosons with fermions, stabilizes the radiative corrections, making them depend only logarithmically on Λ and not quadratically /6/. Technicolor /7/, on the other hand, effectively deals with a composite scalar sector. More precisely, the Fermi scale is the result of the dynamical formation of condensates of some underlying theory and it is related to the dynamical scale Λ_{TC} of this theory.

Supersymmetry is a symmetry which transforms fermions into bosons and viceversa. Its spinorial charge, (or charges for $N > 1$ Susy) and its adjoint close under anticommutation to the momentum operator, constituting a unique graded extension of the Poincaré group. N = 1 Susy multiplets always contain matching bosonic and fermionic degrees of freedom. For instance the chiral $[1/2,0]$ multiplet has a 2 component Weyl fermion and two spin zero excitations. If the cure to the stability problem of the Higgs sector is provided by Susy /6/, particles in the standard model must acquire Susy partners (spartners). For instance the 45 (2-component Weyl) quarks and leptons of the three known families must be accompanied by 90 spin zero squarks and sleptons. The 8 gluons have as spartners 8 spin 1/2 gluinos, etc.

Susy extensions of the standard model are totally predictive as far as coupling go. Essentially, transforming 2 particles into 2 sparticles gives the same coupling. Of course, since no spartners are observed one must assume that Susy is broken. This breaking is rather arbitrary, but if one wants to use Susy to stabilize the Fermi scale one cannot push the spartners to arbitrary large mass. Most popular models now are based on N = 1 supergravity where the mass spectrum is ruled by the size of the gravitino mass, $m_{3/2} \sim \Lambda_F$.

If Susy is correct, and $m_{3/2}$ is not too large, the principal business of future colliders will be to sort out the Susy-Zoo of sparticles! In fact we may be already beginning to do this.

The monojet events reported by Rubbia /3/ at this meeting could be due to gluino production and their subsequent decays into photinos, provided that the gluino mass is not much above 40 GeV. Conversely, very light gluinos are probably already ruled out by present collider data.

Susy may, however, not be present in nature, or if present be broken at scales much above Λ_F. Technicolor would then provide a natural solution to the Higgs stability problem. In Technicolor /7/ one assumes that the vacuum expectation value $\langle\phi\rangle = \Lambda_F$ of the elementary Higgs field of the GSW model is replaced by a condensate of Techniquarks $\langle\bar{T}T\rangle$. These objects are the elementary fermions of a QCD-like theory, whose dynamical scale Λ_{TC} is, however, much larger than Λ_{QCD}:

$$\Lambda_{TC} \sim \Lambda_F \gg \Lambda_{QCD} \qquad (4)$$

If the Techniquarks carry non trivial SU(2) x U(1) quantum numbers, as assumed, then the $\langle\bar{T}T\rangle$ condensate,which dynamically form,break this symmetry down.

In the Technicolor scheme, the W and Z get a mass by absorbing the Goldstone excitations arising from the $\langle\bar{T}T\rangle$ condensate formation. The presence of the strong Technicolor forces, however, does more than this. One expects at the scale where Technicolor becomes strong that there will be also a strong interaction among the W-bosons. A conservative estimate is that this will occur at energies of the order $\sqrt{16\pi}\,\Lambda_F \simeq$ 1.5 TeV, but this phenomenon could occur much sooner. In this latter case some effects may be seen at Lep or, if the Techniquarks carry color and couple to gluons, at the $p\bar{p}$ colliders.

My own view is that it is more likely that the stability problem in the Higgs sector is solved the Technicolor way than the Susy way. However, inventing a whole new strong interaction theory to generate the Fermi scale seems wasteful. Thus I find it reasonable to pursue the idea that a preon model could give the same effects as Technicolor. That is, not only would quark and leptons be preon bound states, but also preon condensates would serve to break SU(2) x U(1). The Fermi scale Λ_F would then be related to the compositeness scale Λ_c. Although the present bounds on Λ_c present some dynamical difficulties, some interesting toy models in this direction have been developed recently /8/

Experimentation in the next 10 years at $p\bar{p}$, e^+e^- and ep colliders should bring us closer to understanding some of the mysteries of the standard model. My only safe prediction is that exciting times are ahead, which will generate their own set of mysteries!

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