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SUBSTRUCTURE: A BRIEF SUMMARY*

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ABSTRACT

The present status of substructure theories for Higgs particles, quarks, leptons and gauge bosons is briefly summarized.

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The possibility of discovering further substructure within the "fundamental particles" of the standard model remains a viable option for the physics which lies beyond that model. Candidates for substructure (in descending order of plausibility) are Higgs particles, quarks and leptons, W and Z, gluons, photons.

The Motivation for substructure is as good as ever. Higgs substructure is motivated by the fine-tuning problem. Quark and lepton compositeness—by the observed connections between quarks and leptons, by the generation puzzle and by the existence of too many free parameters in the standard model. W and Z substructure is motivated by their relation to a composite Higgs and by the observation that all other short-range interactions are residual interactions.

The experimental limits on substructure are slowly crawling upwards. The "radius" of Higgs particles, quarks, leptons, W and Z could still be[1] of order $(\text{TeV})^{-1}$. However, certain puzzles already lead us to higher energy scales. In particular, an understanding of the generation puzzle seems to require a scale of at least[2] 50-100 TeV, possibly much more.

The explicit detailed models for substructure are as bad as ever. All existing models seem to be inadequate. Many clever ideas have been proposed, both for the new underlying dynamics and for the underlying symmetries. Some of these ideas may be correct; others may need improvements; most are clearly wrong. The correct theory of substructure, if and when discovered, may contain some important ingredients which have been introduced within some of the existing unsuccessful schemes.[3]

Future directions of the substructure hypothesis are likely to be dictated by experiments. The simple theoretical ideas have been tried. They do not work. Most of them introduce a new underlying interaction which simply copies the previous one, utilizing a nonabelian local gauge symmetry. If nature has selected a more subtle way, its most likely method of informing us of this selection is to give us experimental hints.

Strangely enough, not only the future of substructure physics depends on experiments but also the future of experimental high-energy physics depends on substructure. If no substructure is found up to, say, 1 PeV ($\equiv$ 1000 TeV), all the interesting cross sections will continue to fall like $1/s$, eventually reaching rates which will never be detected even if we have the technology and the money for producing higher energy machines. Recall that, at $\sqrt{s}$ = 1 PeV, $\sigma(e^+e^- \to \mu^+\mu^-) \sim 10^{-43}$ cm^2. For 100 $\mu^+\mu^-$ events per month, we need an e^+e^- luminosity of 10^{39} cm^{-2}sec^{-1}!

The theoretical attitude towards substructure can be characterized by five broad categories:

(i) **"Ultra-Conservative"**: This approach would claim that quarks, leptons, gauge bosons and Higgs particles are, and will always remain, fundamental. This probably means that the fine-tuning problem is solved by supersymmetry, that the quark-lepton connection and the unification of interactions are achieved by GUTS, and that the generation puzzle will somehow be solved, allowing for the calculability of many of the fundamental parameters of the standard model without introducing any substructure.

On the experimental side, cross-sections will decrease like $1/s$ and will eventually become unobservable. Supersymmetric partners must be found at or below O(TeV). Since, at present, there is no experimental evidence for any substructure, the "*Ultra-Conservative*" approach must be considered at least as likely as all other alternatives combined. Whether this remains unchanged, only future experiments will tell us.

(ii) **"Conservative"**: The conservative approach allows for Higgs substructure, but keeps quarks, leptons and gauge bosons fundamental. Higgs substructure, either according to the Technicolor scenario or according to the composite Higgs scenario,[4] can solve the fine-tuning problem without invoking supersymmetry. It requires a new fundamental interaction ("Technicolor", "Ultracolor") operating among the constituents of the Higgs particle and it inevitably leads to new physics at the TeV scale. We have recently learned that its phenomenological difficulties may not be as severe as was earlier believed.[5]

Experimentally, this probably leads to a rich spectrum of "Technihadrons" or "composite friends of the Higgs particle" at the TeV range. It also predicts relatively light pseudo-Goldstone-bosons. In some versions we may discover a new world of strongly interacting Higgs particles,[6] yielding large cross sections for the production of longitudinal W's and Z's. Often, but not always, practitioners of the "conservative" approach find themselves moving towards a "*moderate*" attitude,[4] when they try to understand the origin of fermion masses.

(iii) **"Moderate"**: This approach assumes that quarks, leptons and Higgs particles are composite, presumably all of them at the TeV scale, but possibly at two different scales (one for Higgs and one for quarks and leptons). All gauge bosons are elementary. Cross sections for processes such as $e^+ + e^- \to \mu^+ + \mu^-$, $e^+ + e^- \to \bar{q} + q$ reach an approximately constant value $\sigma \sim \mathcal{O}(\Lambda^{-2})$ where Λ^{-1} is the "size" of a lepton or a quark. Multilepton production amplitudes may be large. Excited quarks and leptons are expected at $m \sim \mathcal{O}(\Lambda)$.

Note, however, that if the "radius" of quarks and leptons is as low as $O(\text{TeV}^{-1})$, the generation puzzle cannot be solved at the same energy scale. Limits from processes such as $K^0 \to e\mu$, $K \to \pi e\mu$, $\mu \to e\gamma$, $\mu N \to eN$, $\mu \to 3e$ and $\Delta M(K_S - K_L)$ indicate[2] that a resolution of the generation puzzle is unlikely to occur below O(100 TeV). It is, however, possible[7] that leptons have a radius of TeV^{-1} but the $e - \mu$ difference can only be probed, say, at a distance of PeV^{-1}. There is no logical contradiction between these two statements.

(iv) **"Radical"**: Here one adds compositeness of the massive gauge bosons W and Z, in addition to quark, lepton and Higgs compositeness. The weak interaction is not a fundamental interaction and it is replaced[8] by the new interaction which binds preons within quarks, leptons, W, Z and Higgs. Photons, gluons and possible new massless gauge bosons ("hypergluons"?) remain fundamental.

Experimentally, we expect excited W and Z bosons, possible corresponding $J = 0$ states, deviations from the WWW gauge coupling, large cross sections for $\bar{p} + p \to z + \gamma +$ anything, etc. In this case the compositeness scale of W and Z, if it exists, is almost certain to be around TeV. Consequently, quark and lepton compositeness is also expected at O(TeV), with a second higher scale resolving the generation structure.

(v) **"Ultra-Radical"**: All particles of the standard model, including massless gauge bosons, are composite in some sense. All known interactions somehow emerge from a more fundamental mechanism. This is not a very likely proposition. Even if it is true, the substructure will probably appear only at a very high energy scale, possibly the Planck scale. At that scale, physics will be very different from that of the standard model. A rich spectrum of additional states is expected at $m \sim \mathcal{O}(\Lambda)$. However, below that scale—all particles would appear to be pointlike and the experimental predictions should resemble those of the standard model.

In politics, the two extremes of the political spectrum often become indistinguishable. In the "politics" of substructure a similar situation happens. A common substructure of *all* particles at the Planck scale ("*ultra-radical*" option) is experimentally similar to no substructure ("*ultra-conservative*" option). In fact, superstring theory is both: There is no substructure in the sense of the existence of preons but all particles have a substructure in the sense of not being point objects at the Planck scale.

To summarize:

At present there is no experimental evidence for substructure. No viable explicit composite models are known. The new underlying interaction does not appear to be color-like. The mechanism which creates almost massless composite objects has not been determined.

On the other hand, Higgs particles, quarks, leptons, W and Z can still have substructure at the TeV scale. There are good theoretical motivations for such substructure. The new underlying interaction may have novel features, unlike previously observed interactions. Chiral symmetry, supersymmetry and possibly other mechanisms may lead to almost massless composites.

Substructure enthusiasts continue to hold "*moderate*" to "*radical*" views.

Progress is unlikely without new experimental information.

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