PROCEEDINGS OF SCIENCE

Reflections On LHC Physics

Edward Witten[*†]
Theory Group, CERN, Geneva Switzerland
E-mail: witten@ias.edu

Some of the basic questions in particle physics – like the nature of electroweak symmetry breaking – have been with us since practically the beginning of the Standard Model. With the LHC, we are finally poised to answer some of these longstanding questions. This talk is devoted to an overview.

2008 Physics at LHC
September 29 - 4 October 2008
Split, Croatia

[*]Speaker.
[†]On leave from Institute for Advanced Study, Princeton NJ 08540, USA.

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PoS(2008LHC)098

1. Some Questions

I will organize this talk around some questions. In fact, the questions are mostly not at all new, which I guess means that we have needed the LHC for a long time. Hopefully, the next conference in this series will have some of the answers.

Anyway, here are some questions:

(i) How is the electroweak gauge symmetry broken? Can this symmetry breaking be described by a Standard Model Higgs field, or is something more elaborate required? In that second case, what is the missing ingredient? Supersymmetry? Technicolor? Something more exotic?

(ii) Given the answer to this, is the electroweak energy scale natural?

(iii) Is the measured value of the weak mixing angle an "accident" or an indication of further unification?

(iv) Does dark matter come from the TeV scale?

(v) Does Nature have a bigger surprise in store for us, such as large extra dimensions or a low quantum gravity scale?

(vi) And are we asking the right questions?

2. Electroweak Symmetry Breaking

The main reason that we can expect to answer at least some of these questions at the LHC is that we know something about the energy scale of weak interactions. After all, the weak scale is something that we have probed indirectly and semidirectly for a long time. Finally the LHC will give us the chance to "open the box."

Even before there was a Standard Model, physicists had some idea of the relevant energy scale of the weak interactions, since it appears in the Fermi constant $G_F \sim 10^{-5}/(1\ \mathrm{GeV})^2 \sim (300\ \mathrm{GeV})^{-2}$. Of course, nowadays, we know that the W and Z bosons are a little lighter than 300 GeV, and the Standard Model explains why; the relation between the Fermi constant and the gauge boson masses involves a coupling constant, so $G_F \sim e^2/M^2$.

But the weak interactions must involve more than just the W and Z particles that we have discovered so far. One way to see this is to consider the propagator of a massive vector meson of momentum k:

$$\frac{-g_{\mu\nu} + \frac{k_\mu k_\nu}{M^2}}{k^2 - M^2}. \tag{2.1}$$

The term $k_\mu k_\nu/M^2$ in the numerator grows rapidly with k. This means that the ultraviolet behavior of a theory with a massive vector meson is potentially very bad. Concretely, at high energies, that term describes the propagation of a longitudinal W or Z boson, i.e., one of zero helicity. Unless something else happens first, longitudinal vector mesons become strongly coupled a little below 1 TeV, and a better theory is needed.

There actually would not be a problem in a theory with only photons and Z's. The Z boson could couple to a conserved current, and then the troublesome term in the propagator could be dropped. There is a problem when W bosons are included, since Z and W bosons couple to each other and not only to conserved currents.

Concretely, of course, in the Standard Model we do not get strong coupling for longitudinal gauge bosons because long before one gets to 1 TeV, there is a Higgs field. The combined model has a spontaneously broken gauge invariance which is responsible for the gauge boson masses and which again lets one drop the troublesome term in the propagator.

As we all know, the Higgs field is a spin zero field H that transforms as an $SU(2)\times U(1)$ doublet and has a potential of the symmetry-breaking form $V(H)=\lambda(\bar{H}H)^2-m^2\bar{H}H.$. This potential is renormalizable in four dimensions, and is the most general possible renormalizable potential for H (except that we could add a constant, which would affect only the large scale curvature of the Universe, and we could reverse the sign of the quadratic term so as to not get symmetry breaking). It is actually quite beautiful that in four dimensions there is just barely "room" for symmetry breaking via a renormalizable potential constructed from elementary scalar fields. That this just works is one of the many nice features of the Standard Model.

Another way to see that the Higgs field is not needed in a theory with only photons and Z's (plus charged matter) is to observe that, if the gauge group were $U(1)\times U(1)$ broken to $U(1)$ (instead of $SU(2)\times U(1)$ broken to $U(1)$), then the Higgs field H would simply be a one-component complex field. Then the Higgs model has a limit with $m^2\to\infty$ and $|\langle H\rangle|$ fixed. We just set $H=\rho\exp(i\phi)$, where ρ is kept fixed as $m^2\to\infty$. In the limit of large m^2, ϕ becomes a free field. This doesn't work in the case of $SU(2)\times U(1)$ broken to $U(1)$, for then H is a complex doublet, and the limit $m^2\to\infty$ gives a "nonlinear sigma model" which in four dimensions has the same bad ultraviolet behavior that we saw at the beginning with the $k_\mu k_\nu/M^2$ term in the propagator.

Concretely, the problem is clear in the electroweak fits, which have terms proportional to[1] $\log M_H$ and thus have no limits for $M_H\to\infty$. As we all know, those fits favor a value of M_H that is between the observed lower bound of 114.4 GeV and an upper bound that is in the range of 160 to 200 GeV, depending on confidence level.

There is an amazing and perhaps not fully enough appreciated fact about the lower bound. The pure Standard Model becomes unstable at a value of the Higgs mass that is amazingly close to 114 GeV. The instability arises because, to make the Higgs mass small while keeping its expectation value fixed, we must make the Higgs self-coupling small. But then one-loop corrections become important and can actually make the Higgs effective potential become negative for large values of H. This is actually quite an old story that has been re-examined lately from a new vantage point – for old and new viewpoints, see [1] and [2] (and many additional papers cited in the second reference). If it turns out that the pure Standard Model holds up at TeV energies, it will be fascinating to learn how close we are to the instability that occurs when M_H is too small.

The instability for small M_H does not necessarily occur in extensions of the Standard Model. For example, it does not occur with supersymmetry; supersymmetry, on the contrary, would have thrived with a value of M_H well under 114.4 GeV. With supersymmetry, there are superpartners that cancel the dangerous part of the one-loop correction to the Higgs potential, avoiding any possible instability. Something analogous will happen in many other extensions of the Standard Model. The special role of 114 Gev as being very close to the threshold of instability is largely limited to the pure Standard Model.

Even though the Standard Model has held up pretty well through a very large number of tests,

[1] Here M_H is the physical Higgs particle mass, as opposed to the mass parameter m that appears in the Lagrangian.

many of which have been reviewed at this meeting, there are some cogent criticisms of it. These criticisms are all rather old – dating to the mid-1970's – and we are all hoping that the LHC will get us to the bottom of things. This brings us to our next topic.

3. Naturalness Of The Weak Scale

The most fundamental question about the Standard Model explanation of electroweak symmetry breaking involves "naturalness" or the "hierarchy problem." It is a problem that affects the Higgs particle and not any other known particles because the Higgs particle, if we find it, will be the only elementary scalar particle we know. Of course, that is part of why the Higgs particle will be interesting to find.

Let us suppose that the Standard Model is valid up to a mass scale Λ – where it breaks down and is replaced by a more complete theory, perhaps involving some more complete unification of the laws of Nature. If m – the Higgs mass parameter in the Standard Model Lagrangian – is of order Λ, then we consider the Standard Model to be potentially "natural." (Before signing off on this naturalness, we also would like to know that the more complete theory at a mass scale Λ gives some explanation of why m cannot be much bigger than Λ.) But if the dimensionless number m/Λ is extremely small, then there is something to explain.

For example, if we think that the Standard Model is valid all the way up to the mass scale of Grand Unification – perhaps $\Lambda \cong 10^{16}$ GeV – then m is ridiculously small and "unnatural."

One might be skeptical of this reasoning, since the Standard Model has unexplained small parameters, for instance the ratio of the electron mass to the top quark mass is about 1/300,000. However, the Standard Model has extra symmetry if the electron mass is zero, so the smallness of the electron mass, though unexplained, is considered technically natural.

The claim that naturalness requires $\Lambda \lesssim m$ is very attractive since it certainly puts new physics within reach – perhaps too much so, in view of experimental limits on new physics that we have already. An alternative, more conservative point of view has been advocated (for example, this viewpoint is incorporated in [3]). We think of Λ as a cutoff in the Standard Model, and we ask how m is renormalized. For example, the one-loop correction is of order $\Delta m^2 \sim \alpha\Lambda^2$, where α is the fine structure constant. Higher order corrections are smaller (higher powers of α). The "observed" value of m^2, or at least the value that we hope to observe before too long, is the sum of the bare value and the quantum corrections: $m^2 = m_0^2 + \alpha\Lambda^2 + \ldots$, where m_0 is the bare value. It is "unnatural" to have a large cancellation between the bare value and the quantum corrections. Absent such a cancellation, we expect $|m|^2 \gtrsim \alpha\Lambda^2$.

The conclusion that $|m|^2 \gtrsim \alpha\Lambda^2$ is obviously a little more conservative than the more naive claim that $|m| \gtrsim \Lambda$. It leads us to expect that the Standard Model will break down at a scale around or below 1 TeV, giving us good hopes for LHC physics.

Not just any breakdown of the Standard Model at an energy below about 1 TeV will make it "natural." Specifically, the Standard Model has to be incorporated in a bigger model that does not allow an arbitrary bare mass for the Higgs particle. There have been many attempts to do this.

The oldest is technicolor. Motivated in part by the analogy between electroweak symmetry breaking and superconductivity, one replaces the Higgs field with a bound state of two heavy fermions, which interact strongly at a mass scale Λ. The model is natural because at energies above Λ, there is no Higgs field.

Despite its appeal, this approach has a few drawbacks (its status was summarized at this meeting by F. Sannino). It is difficult to generate quark and lepton masses; we cannot simply write renormalizable Yukawa couplings such as $H\overline{E}L$, because there is no fundamental H field. One can try to generate quark and lepton masses from unrenormalizable couplings (possibly generated from "extended" technicolor couplings), but this is clumsy and tends to induce unwanted flavor changing neutral currents. The S and T parameters of the weak interactions tend to come out wrong. Another possible problem is that Grand Unification is rather difficult.

At any rate, the analogy with superconductivity, where the analog of the Higgs field is a bound state, reminds us of something we should also know from our experience with particle physics: finding an elementary spin zero particle, if that is what we are going to find at the electroweak scale, is very special and interesting. No close analog is known.

Apart from technicolor, the other traditional approach is supersymmetry. Here the relative smallness of the Higgs mass can be natural, because supersymmetry relates the Higgs mass to fermion masses, which can vanish because of chiral symmetries.

To me supersymmetry is the approach that has the most concrete successes – we will come back to that later. The main drawback of supersymmetry, apart from the fact that it has not been found yet, may be the experimental lower limit $M_H \geq 114.4$ GeV, which is a little awkward for many supersymmetric models.

Apart from these two traditional approaches to stabilizing the electroweak scale, there are also many newer ones, ranging from "little Higgs" theories that incorporate the relation $m^2 \sim \alpha\Lambda^2$ to more radical proposals with large extra dimensions, a relatively small quantum gravity or string scale, etc. We will later say a little more about these models, too.

Roughly speaking, particle theorists have spent the last 30 years – or actually a little more – dreaming up natural explanations of the electroweak scale. Meanwhile, the Standard Model has kept working, at least challenging the more aggressive interpretation of naturalness with $|m| \gtrsim \Lambda$, and giving difficulty to some models with $m^2 \gtrsim \alpha\Lambda^2$.

At the same time, naturalness has been called into question because of developments on another front – the observation of the cosmic acceleration. If we apply the same reasoning that we applied to the Higgs mass parameter, then the measured vacuum energy of $(10^{-3}\,\mathrm{eV})^4$ is highly unnatural – as far as we can see. This might be telling us that "naturalness" – as understood by particle theorists for the last 30 years – is not the right concept.

Learning whether the electroweak scale is natural may be one of the most important things to come out of the LHC. We could learn it is natural by confirming a natural theory of the TeV scale, such as technicolor, supersymmetry, or one of the more recent ones; we could learn it is unnatural by confirming a fine-tuned theory such as split supersymmetry.

4. Is the Observed Value of $\sin^2\theta_W$ an Accident?

In fact, the known successes of supersymmetry really have to do mostly with supersymmetric grand unification. The observed quarks and leptons, with their fractional electric charges and parity-violating weak interactions, fit beautifully into multiplets of a GUT group such as $SU(5)$.

This is a fact of life that does not directly involve supersymmetry. But indirectly it involves supersymmetry because unification of couplings works beautifully in, and only in, the supersymmetric case.

Of course, the appearance of unification of the strong, weak, and electromagnetic couplings at a very high energy may be an accident – just as we consider it an accident that the Sun and the Moon, as seen from the Earth, are so nearly equal in angular size. However, this would be a pity. It is very tempting to believe that coupling unification is real and contains a very deep message about physics at much higher energies.

If the LHC finds supersymmetry, we will have much more confidence that Grand Unification is on the right track, and that the value of $\sin^2\theta_W$ has been interpreted correctly. Also, as a result of measuring superpartner masses and couplings, we might get new insights about Grand Unification.

There is also, in "split supersymmetry" [4], an "unnatural" version of this in which one keeps the supersymmetric explanation of the value of $\sin^2\theta_W$, but drops the traditional use of supersymmetry to explain the electroweak scale. (This was discussed at the present meeting by D. Toback.) In this version, possibly, the LHC might strongly disfavor the concept of naturalness, while supporting supersymmetry and Grand Unification. Concretely, gauginos would possibly be found at the LHC, with couplings that would have a natural interpretation in terms of supersymmetry and Grand Unification, but the scalar partners of quarks and leptons would be heavier, contradicting the idea of naturalness.

Another important thing to say about TeV scale supersymmetry is that despite its attractiveness, which includes its importance for string theory as well as the points that I have mentioned, there is not really a compelling theoretical model in detail.

Gravity mediation is regarded as a benchmark, but avoids unwanted flavor-changing neutral currents and CP violation by invoking a not-well-motivated assumption of flavor universality. Gauge mediation solves these and other problems and is a very elegant idea, but it has a bit of a problem in the Higgs sector (the μ problem), and there certainly is not a preferred model. So if supersymmetry is discovered, this will not entail merely confirming a theoretical picture; the details will come as a surprise.

Another important point is that for natural supersymmetry, it would be really nice if the Higgs particle is very close to the present experimental lower bound at 114.4 GeV. Failure to observe the Higgs particle already is probably the greatest disappointment for supersymmetry – in its conventional, non-split version. The problem arises because of the way natural supersymmetry relies upon radiative corrections to increase the Higgs mass. Split supersymmetry abandons naturalness and can put the Higgs mass higher.

5. Dark Matter

A famous calculation shows that if galactic dark matter is made of weakly interacting elementary particles (WIMPS's) that are produced thermally, then these particles should have masses of a few hundred GeV to be produced in the early Universe with the right abundance. Natural models of the weak scale can easily produce dark matter candidates with the right properties, and the same is true for some unnatural models such as split supersymmetry.

So weak scale dark matter is certainly a natural target for the LHC. However, there is no guarantee. Even if dark matter is made of WIMP's, they certainly could be just out of reach.

Also, there are lots of other dark matter candidates, though there is no known candidate that leads to the right mass density quite as naturally as WIMP's do. I will mention two relatively interesting dark matter candidates, just to emphasize the wide range of imaginable possibilities.

Axions are a very naturally solution to the strong CP problem. In the context of cosmology, axions are produced nonthermally. With standard assumptions, to get the axion mass density to be about right, we need the axion coupling parameter F_a to be about 10^{11} GeV. This puts it in a range that is accessible experimentally and is the target of ongoing searches. Unfortunately, there is not really a clear independent theoretical justification for putting F_a in that range.

Another option does not involve directly interpreting dark matter in terms of elementary particles. Galactic centers contain giant black holes. It is not clear how these could be formed by gravitational collapse in relatively "recent" cosmological epochs, so perhaps this process was seeded by "primordial" black holes. Then dark matter could consist of black holes in galactic haloes, but again there is no independent motivation for the necessary black hole masses and abundance.

In short, WIMP's may be wrong, but they remain as the candidate that comes with a well-motivated computation that leads to more or less the right answer for the dark matter density.

6. More Exotic Models

Possibilities such as large extra dimensions or a "low" quantum gravity scale are much more exciting than the more conventional possibilities that I have discussed. Part of the adventure of the LHC is that it is at least conceivable that something like that could emerge. Possibilities can range over quite a wide terrain.

One general point perhaps worth making is that fears expressed in the popular press about black holes at the LHC are actually maximally wrong. More realistically, the problem would be instead whether, even if the basic idea of a light quantum gravity scale is correct, it would be possible to get a clear black hole signature. At the LHC, we would be, at best, not too much above the quantum gravity threshold, and black holes produced at the LHC would behave as very short-lived elementary particles. It is not clear at what mass a semiclassical black hole picture becomes useful. For example, see [5, 6] for discussions of black hole signatures.

7. Are We Asking The Right Questions?

This may be the most interesting question of all. It would be nice if the answer turns out to be, "not entirely."

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