Prospects For LHC Physics

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Physics at the LHC

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I will organize this talk around some questions.

In fact, the questions are mostly not at all new, which I guess shows that we've needed the LHC for a long time.

Hopefully the next conference in this series will have some of the answers.

(1) How is the electroweak symmetry broken?

   Pure Standard Model? Supersymmetry?

   Technicolor? Something more exotic?

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

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

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

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

(6) And are we asking the right questions?

(1) 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.

The weak scale is something that we have probed indirectly and semi-directly in many ways and now we are finally going to get the chance to "open the box."

We have had an idea of the energy scale of weak interactions even before the Standard Model, since the value of the Fermi constant

$$G_F \cong 10^{-5} \text{GeV}^{-2}$$

or

$$G_F \cong (300 \, \text{GeV})^{-2}$$

suggests that the relevant energy scale is about 300 GeV.

Of course, nowadays we know that the W and Z bosons are a bit lighter than this, and the Standard Model explains why; the relation between the Fermi constant and the gauge boson masses involves a coupling constant

$$G_F \sim \frac{e^2}{M^2}$$

But the weak interactions involve more than the W and Z.

One way to see that there has to be something in the weak interactions beyond the massive W and Z particles is to consider the propagator of a massive vector meson

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

Because of the second term, the high energy behavior of a theory with a massive vector boson is potentially bad.

Concretely, at high energies the second term describes the propagation of a longitudinal (zero helicity) W or Z boson. Unless something else happens first, longitudinal gauge bosons become very strongly coupled a little below 1 TeV and a better theory is needed.

There actually wouldn't necessarily be a problem in a theory with only photons and Z's: the Z boson could couple to a conserved current and the second term in the propagator could be dropped. There is a problem when W bosons are included

since the W and Z couple to each other and not just to conserved currents.

Concretely, of course, in the Standard Model
we don't 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 $k_\mu k_\nu / M^2$ term.

Writing H for the Higgs field, its potential has a familiar form:

$$V(H) = \lambda(\bar{H}H)^2 - m^2\bar{H}H$$

Assuming that $m^2 > 0$, the minimum of V is for nonzero H, leading to symmetry breaking and to the existence of a massive "Higgs boson."

Another way to see that the Higgs boson isn't needed in a theory with only photons and Z's is to observe that, if the gauge group were U(1) x U(1) broken to U(1), then the Higgs field H would be simply complex-valued. 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 for $m^2 \to \infty$

In the limit of $m^2 \to \infty$, ϕ becomes a free field.

This doesn't work if we add W's and the gauge group is

supposed to be SU(2) x U(1) broken to U(1), since 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 ultraviolet problem that we had at the beginning from the bad propagator $\dfrac{-g_{\mu\nu} + \dfrac{k_\mu k_\nu}{M^2}}{k^2 - M^2}$

Concretely, the problem is clear in the electroweak fits which have terms proportional to $\log M_H$ and so have no limit as $M_H \to \infty$

As we all know, the electroweak fits actually favor a value of M_H between the observed lower bound of 114.4 GeV and an upper bound of roughly 160 to 200 GeV (depending on confidence level).

There is an amazing fact about the lower bound: The pure Standard Model becomes unstable at a value of Higgs mass that is amazingly close to 114 GeV.

The instability arises because, to make the Higgs mass small, we must make the quartic coupling λ small, and then one-loop corrections can actually make the Higgs potential negative for large H.

(This goes back to Cabibbo et al 1979, Hung 1979; for a recent analysis see Feldstein et al hep-ph/0608121.)

This doesn't necessarily happen in extensions of the Standard Model. For example, Supersymmetry would have allowed a Higgs mass well below 114 GeV with a perfectly stable vacuum (and this would have made model-building a little easier).

Superparticles cancel the troublesome quantum correction.

Likewise in many extensions of the Standard Model.

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

(2) Is the weak scale natural?

The most fundamental problem involves "naturalness" or the "hierarchy problem"

and is a problem that afflicts the Higgs and not other particles because – if it exists – it will be the only elementary spin zero particle we know.

That is also one reason the Higgs 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 bigger theory – perhaps involving some more complete unification of the laws of nature.

If m -- the mass parameter in the Standard Model Lagrangian – is of order Λ , we consider the Standard Model to be "natural." But if the dimensionless number m/Λ is small, 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 $\Lambda \cong 10^{16}\,\mathrm{GeV}$ -- then m is ridiculously small and "unnatural."

One might be skeptical of this reasoning. The Standard Model has other unexplained small dimensionless numbers, for example

$$m_e/m_{\text{top}} \sim 1/300,000$$

This is unexplained but technically "natural" since the Standard Model has extra symmetry if $m_e = 0$. There is no extra symmetry if the Higgs mass is zero.

The claim that naturalness requires $\Lambda \sim m$ is very attractive since it certainly puts new physics in reach – perhaps too much so. An alternative, more conservative reasoning has been proposed.

We think of Λ as a cutoff in the Standard Model and we ask how m is renormalized in perturbation theory.

For example, the one-loop correction is of order

$$\Delta m^2 \cong \alpha \Lambda^2$$

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 a "bare" value and the quantum corrections.

We write

$$m^2 = m_0^2 + \alpha\Lambda^2 + \dots$$

where m_0^2 is the bare value.

It is "unnatural" to have a very large cancellation between the bare value and the quantum corrections. Absent such a cancellation, we expect $|m^2| \sim \alpha\Lambda^2$.

This conclusion $|m^2| \sim \alpha \Lambda^2$ is obviously a little more conservative than the naïve claim that $|m| \sim \Lambda$ and 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 the LHC.

Not just any old 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 doesn't allow an arbitrary bare mass for the Higgs boson.

There have been lots of tries to do this:

(a) 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 new heavy fermions, which interact strongly at a mass scale Λ. The model is natural because at energies above Λ, there is no Higgs field.

A couple of problems are difficult to solve

(status was described by F. Sannino):

i) generating quark and lepton masses, while limiting FCNC's. This is hard because we can't just write Yukawa couplings $H \bar{E} L$, etc., as there isn't any H.

ii) S and T parameters of weak interactions tend to be wrong.

Another possible problem is that grand unification may be 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.

(b) A second approach is supersymmetry –
to me the one that has the most concrete
successes, especially in the value of the
weak mixing angle.   We'll come back to
this.

Main drawback may be the bound
$$m_h \geq 114.4 \text{ GeV}$$
which is a little awkward for many
supersymmetric models.

(c) Clever models like "little Higgs" in which we really get $m^2 \sim \alpha \Lambda^2$

(d) More dramatic proposals with large extra dimensions, low quantum gravity or string scale .... A little more on this later, also.

Roughly speaking, particle theorists have spent the last 30 years – or 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 that says $m \sim \Lambda$ -- and giving difficulties for some models in which $m^2 \sim \alpha \Lambda^2$

Meanwhile, 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, the measured vacuum energy of about $(10^{-3} \, \text{eV})^4$ 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.

I think that 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 one of those I mentioned; we could learn it is unnatural by confirming a fine-tuned theory such as split supersymmetry.

# (3) Is the 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 doesn't directly involve supersymmetry.

But indirectly, it seems to involve supersymmetry because unification of couplings seems to work only in the supersymmetric case.
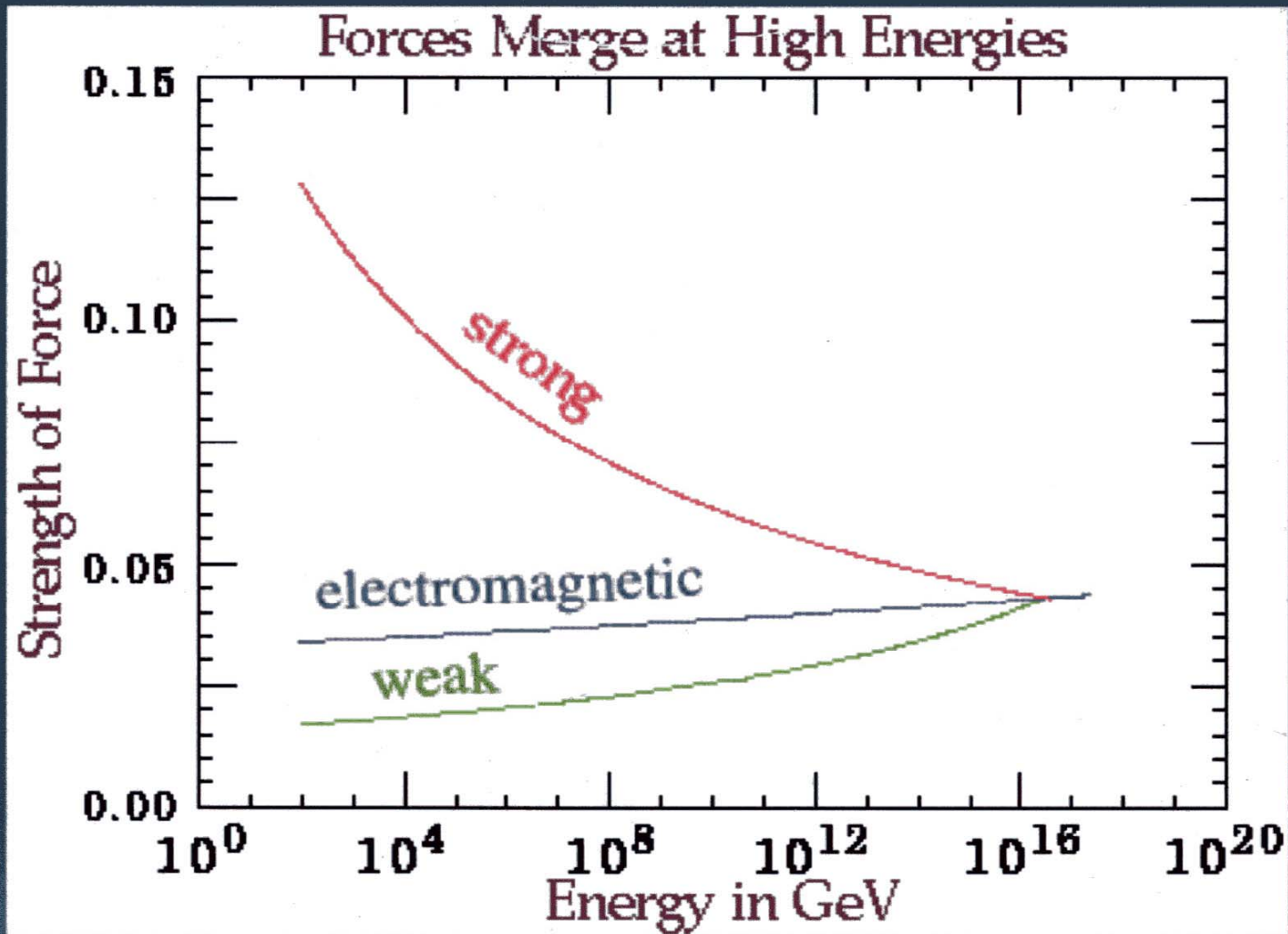
If the LHC finds supersymmetry, we will have much more confidence that Grand Unification is on the right track and $\sin^2 \theta_W$ has been interpreted correctly.

Also, as a result of measuring superpartner masses and couplings, we might get new probes of Grand Unification.

There is also, in "split supersymmetry," an "unnatural" version of this in which one keeps the supersymmetric calculation of $\sin^2 \theta_W$ but drops the attempt to use supersymmetry to explain the electroweak scale.

In this version, possibly, the LHC might strongly disfavor the concept of naturalness, while supporting supersymmetry and Grand Unification.

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

Gravity mediation (… mSUGRA) is regarded as a benchmark but avoids FCNC's with an unconvincing flavor universality.

Gauge mediation solves these and other problems and is a very elegant idea, but has a bit of a μ problem and there isn't a preferred model.

Finding supersymmetry won't mean just confirming a theoretical picture; on the contrary the details will be a bit of a surprise.

Another point is that, for natural supersymmetry, it would be nice if the Higgs is close to 115 GeV. Failure to observe the Higgs already is probably the biggest embarrassment for supersymmetry … in its non-Split version.

(D. Toback) Split SUSY abandons naturalness and can put the Higgs higher.

(4) Dark Matter

A famous calculation shows that if galactic dark matter is made of elementary particles 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 or WIMP's is certainly a natural target for the LHC.

However, no guarantee: even if WIMP's do make dark matter, 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.

Two relatively interesting competing dark matter candidates:

(i) axions – very natural solution of the strong CP problem – in the context of cosmology, they are non-thermally produced. With standard assumptions, to get the axion mass density to be about right, we need $F_a \sim 10^{11} \, \text{GeV}$

more or less, a range that is accessible experimentally (but is not well-motivated independently).

(ii) Galactic centers contain giant black holes. It is unclear that these can form in the "recent" universe (post star formation) so it is an interesting hypothesis that they may have been 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.

(5) Large extra dimensions and light quantum gravity or string scale

Such possibilities are obviously much more exciting than the more conventional ones that I have discussed.

Part of the adventure of the LHC is that it is at least conceivable that evidence for something like that could be revealed.

One point perhaps worth making is that fears expressed in the popular press about black holes at the LHC are actually maximally wrong. Actually, 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.

Near the quantum gravity scale, one
   probably would see short-lived resonances
   that wouldn't seem that different from
   other unstable elementary particles,
   though of course they wouldn't fit into the
   Standard Model.

Even well above the quantum gravity scale,
   black holes would have microscopic
   though longer lifetimes.

(6) Are we asking the right questions?

Probably this is the biggest question, and it would be nice if the answer turns out to be "not entirely."