THE ROLE OF PRECISION MEASUREMENT

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To assess what the physics of the Linear Collider might be, we really need to discuss where we are in particle physics.

Most aspects of the Standard Model are pretty well tested experimentally. The one real exception involves in a way the most basic question of all:

How is the electroweak symmetry broken?

Why are the weak interactions not obvious in everyday life, in the same sense that electromagnetism is obvious?

According to the Standard Model, the weak interactions and electromagnetism basically have a common origin. The underlying equations treat the W and Z bosons quite like the photon – even though we detect photons with our eyes while W and Z bosons need modern accelerators.

According to the Standard Model, the reason is that the symmetry is “spontaneously broken.’’   But how?

For a long time, this question has been the key indication that something really new is in store. Experiment is surely approaching the decisive stage. What we learn will determine the future direction of the field.

The most simple possibility is the original and textbook form of the Standard Model, which assumed a single elementary Higgs boson and nothing else.

In this model, there is perfect symmetry between the weak and electromagnetic interactions at high temperatures. In the early Universe, Higgs particles move at random, like other particles. As the Universe cools, the Higgs particle forms a

Bose condensate – somewhat analogous to what happens in liquid Helium at low temperatures. The “direction” of this condensate – in a space with coordinate axes labeled by the W and Z bosons and the photon – breaks the symmetry and determines which bosons get mass and which interactions become “weak.”

On the whole, although there are some very small discrepancies, this model is in very good agreement with experimental data, which moreover suggest (in the context of the pure Standard Model) that the Higgs mass is no more than about 200 GeV

Some alternative theories predict a Higgs particle plus many additional things; some predict no Higgs particle but many other things instead.

The pure Standard Model with only the Higgs is really the only picture that *doesn’t* predict a host of new particles for current and planned accelerators

The pure Standard Model with only the Higgs has numerous virtues:

- It is simple
- It agrees quite well with a mass of experimental data
- It explains a lot of things that would otherwise be puzzles, like why flavor changing neutral currents and baryon, lepton, and CP violating interactions are so suppressed

As against this, the pure Standard Model has one really serious problem, which convinces most physicists that it is probably not the whole story.

This is the “hierarchy problem”:

A scalar field ϕ can have a bare mass term m^2. Moreover, the quantity m^2 is not stable against quantum corrections; in the Standard Model, the renormalization of m^2 is quadratically divergent, so that if the Standard Model is somehow cut off at a mass scale M, the one-loop renormalization is of order αM^2

This is unnatural for $m^2 << \alpha M^2$

The Higgs boson mass and expectation value (which cannot be too much greater than the mass) set the scale for masses of quarks and leptons and gauge bosons, so it is unnatural for the W and Z (for example) to be below 100 GeV, and the Higgs to be below 200 GeV, unless the the Standard Model is somehow “cut off” at a mass M that is no greater than about 1 TeV.

Alternatives to the Standard Model differ in the nature of this cutoff.

In any approach to solving the problem, the key thing to explain is why the cutoff M is so much less than other mass scales we know about or suspect in physics – notably

- the Planck scale of gravity, which is close to 10^{18} GeV
- the mass scale of Grand Unification, apparently about 10^{16} GeV
- the mass of inflation, seemingly again close to 10^{16} GeV.

The problem of explaining why M, the electroweak cutoff, is so far below those other very high masses, is a modern version of Dirac’s “problem of the large numbers.”

Dirac asked why the electrical force between two protons or two electrons is 10^{40} times greater than the gravitational force between them.

Dirac’s own answer was to relate this to another large number. The age of the Universe, measured in units of the time for light to cross an atomic nucleus, is again roughly 10^{40}. Dirac conjectured that this relation holds at all times, leading him to expect that the gravitational force is becoming weaker, relative to electricity, by about 10^{-10}/year.

We now know that this is not so.

Dirac’s question is equivalent to asking why the proton and electron are so much lighter than the Planck scale of gravity.

From a modern point of view, the electron mass and part of the proton mass arise from electroweak symmetry breaking, and the question becomes: “Why is the scale of electroweak symmetry breaking so small compared to the Planck scale of gravity?”

Particle physics is one area of science where we set lofty goals and we really do heed, sometimes to a fault, the dictum that “A man’s reach should exceed his grasp, or what’s a heaven for?”

However, the hierarchy or Large Numbers problem is one big problem that really is destined to soon be answered, or at least greatly clarified.

We either are going to find at the LHC (or maybe the Tevatron) the components of a rational solution of the Large Numbers problem – a mechanism that explains why the Higgs mass is so small compared to other masses in physics – or we'll find, say, only a pure Standard Model Higgs boson, in which case the problem first proposed by Dirac will become far sharper.

Let me compare this to another problem that has emerged in the last few years: the acceleration of the expansion of the Universe, which points to a cosmological constant or to some more elaborate form of "dark energy."

This actually poses a fine-tuning problem similar to the problem of the Higgs boson. In the Standard Model, the energy of the vacuum is quartically divergent.

The simplest approximation is simply to add up zero point energies

$$\pm \quad \tfrac{1}{2}\,\hbar\,\omega$$

for every Bose mode or Fermi mode of momentum k and energy $\hbar\,\omega = \sqrt{k^2 + m^2}$

The integral over k

$$\pm \int d^3k \;\sqrt{k^2 + m^2}$$

is quartically divergent, so the best we can say is that the energy of the vacuum is expected to be of order M^4, where M is the cutoff energy at which “something else” happens and the contributions to the vacuum energy are cut off.

Experiment appears to point to a dark energy Λ of order $(10^{-3}\ \mathrm{eV})^4$, where the mass scale 10^{-3} eV is way below any possible Standard Model cutoff – it actually is relatively close to what appears to be the neutrino mass scale, but so far no one has had much success in explaining this.

Let us compare this story to the question of electroweak symmetry breaking …

In each case, there is a minimal hypothesis

- “cosmological constant” for the dark energy

- pure Standard Model Higgs boson for electroweak symmetry breaking

In each case, the minimal hypothesis fits the facts but has a serious flaw: fine-tuning.

In each case one can conceive of more elaborate scenarios that might resolve the fine-tuning:

- new scalar particles, more exotic forms of “quintessence,” and more radical options like modifications of General Relativity
- Technicolor, supersymmetry, “large” extra dimensions, little Higgs….

(However, at the moment, the more elaborate alternatives are more convincing in the case of electroweak symmetry breaking.)

For each of these problems, future experiment is either going to confirm the minimal hypotheses or show that one of the more elaborate options is correct.

If one of the more elaborate hypotheses is confirmed, we will want to explore the new structure as thoroughly as possible. That is where we will get the clues about a new level of understanding nature.

In the case of astronomy, the best measurements we can make will require specialized satellites. For particle physics, the analog is the Linear Collider.

What if instead the minimal hypotheses are confirmed? Then we will be stuck with problems of “fine-tuning” and puzzling over what to make of it.

It seems inevitable that under these conditions, whether we like it or not (and I don’t), “anthropic” explanations would grow in popularity.

According to these explanations, the Higgs mass and the dark energy take different values in different parts of the Universe – but we inevitably live in a region in which they are small.

Whether this proves to be the right explanation or not, the fact that we'd even consider such a radical reinterpretation of the Universe because of the dark energy and the Higgs boson shows that, if the minimal hypotheses do appear to be confirmed, it will be important to pin this down as precisely as possible.

So again, we’ll want to make the best measurements we can – requiring specialized satellites and the Linear Collider.

In this situation, the role of the Linear Collider will be to serve as a Higgs factory – as LEP and SLC did for Z – and a super Z factory (“Giga-Z”) enabling us to disprove the “fine-tuned” pure Standard Model or to prove it as precisely as possible.

The alternatives to the Standard Model are compelling enough, however, to encourage us to hope that instead of finding only the Higgs boson and “confirming” that Nature is “fine-tuned,” the LHC (or Tevatron) will discover how Nature solved Dirac’s “large numbers problem.”

If so, how?

Numerous suggestions have been made:

- “Higgsless” models – Higgs as a bound state
- Models with branes and large extra dimensions
- “Little Higgs” models
- Supersymmetry

No perfect model is known. All known proposals have faults as well as virtues. I will concentrate in the remaining time today on one proposal whose virtues and faults seem especially interesting.

This is Supersymmetry.

First the virtues:

* SUSY can make a “small” Higgs mass natural;

* SUSY is part of a larger vision of physics, not just a technical solution;

* The measured value of $\sin^2\theta_W$ favors SUSY GUT’s;

- SUSY has survived the very stringent electroweak tests;

- The “large” top quark mass was anticipated based on SUSY.

- Possible source of dark matter with About the right properties

SUSY is a unique new symmetry that relates bosons to fermions, in a sense explaining why fermions exist. Relating bosons to fermions also makes it possible to explain the smallness of the Higgs mass, since we do know why smallness of fermion masses can be natural. So that is at least the germ of how SUSY solves the fine tuning problem.

SUSY inherits the successes of Grand Unification, because given modern measurements of $\sin^2\theta_W$, as well as bounds on the proton lifetime, the supersymmetric version of Grand Unification is the one that works.

So here we really must remember the merits of Grand Unification, which are substantial in their own right:

- it makes sense of the quark and lepton quantum numbers, which look like quite a mess in the Standard Model ….a generation of quarks and leptons turns into a simple $\bar{5} + 10$ of SU(5), or 16 of SO(10)

- The unification scale M_{GUT} inferred from low energy data is relatively close to the Planck scale … but high enough to avoid disaster with the proton lifetime

- The neutrino mass scale suggested in the late 1970's based on GUT's,
  $m_\nu \sim M_W^2/M_{GUT} \sim 10^{-2}$eV,
  has apparently turned out
  to be about right

- Grand Unification fits neatly with strings and Quantum Gravity

- The observed fluctuations in the cosmic microwave radiation are naturally (but speculatively) interpreted in terms of an inflationary epoch close to the GUT scale

In short, Grand Unification is a really nice story. But it really only makes sense with Supersymmetry, for two reasons:

* the measured value of $\sin^2\theta_W$ agrees with Grand Unification only if supersymmetry is included

* the unification scale and proton lifetime come out to be too small without SUSY

So the successes of GUT's encourage the search for supersymmetry, and discovery of supersymmetry would enhance the attractiveness of GUT's

As I have tried to argue, SUSY is not just a technical solution to problems like the hierarchy problem. It is

- a unique new symmetry principle
- part of an attractive larger picture in GUT's
- and actually, needed in an even more ambitious picture in "string theory"

In fact, the concept of supersymmetry emerged historically at least in part because of its role in string theory.

Experimental discovery of supersymmetry would certainly give string theory a big boost, and learning how supersymmetry is broken might very well give string theorists crucial clues about how to proceed.

Moreover, while some alternative theories of the smallness of the electroweak scale – like models of composite Higgs bosons – have repeatedly run into trouble, supersymmetry is comfortably consistent with the precision electroweak tests.

For good or ill, the SUSY models considered today are the same ones that were considered viable twenty years ago. In fact the old models remained viable because the top quark turned out to be sufficiently heavy, as was required for electroweak symmetry breaking.

(Not entirely good: the models have held up, but some problems haven't been solved!)

So that is the good news, but today, we also want to consider the drawbacks of supersymmetry.

The most obvious drawback is simply that supersymmetry hasn’t been found yet, though we have been hoping for a long time.

It is disappointing that we have not found SUSY yet, but for the most part it is perhaps not too surprising….

If charged superpartners are just a little bit above M_Z, we would not have seen them yet. Superpartners get masses from electroweak breaking *and* SUSY breaking so it is natural for them to be a bit above the Z, which gets mass only from electroweak breaking.

But there is perhaps one missing particle that is a little embarrassing – the Higgs boson.

Assuming the minimal supersymmetric spectrum, one has at tree level

$$M_{Higgs} < M_Z \sim 91 \text{ GeV}$$

Compared to experiment

$$M_{Higgs} > 114 \text{ GeV}$$

Actually, there is a large radiative correction due to the heavy top quark, and the theoretical bound on the Higgs mass is usually quoted as

$$M_{\mathrm{Higgs}} < 130 \text{ GeV}$$

So there is not quite a contradiction… but rather optimistic assumptions go into getting the radiative correction so large

One needs couplings not favored by many of the models, and/or superpartner masses so large as to make the smallness of M_Z look a little unnatural.

Though there is no contradiction yet, it would certainly clarify things a lot to know what M_{Higgs} is.

And it would be really nice if it turned out to be 115 GeV, the value hinted at by LEP.

At a different level, supersymmetry would have been more convincing if it had achieved some simplification in the Standard Model … for example, could the Higgs boson be a superpartner of the electron?

Unfortunately, no: Models that tried things like that did not work…. So the Minimal SUSY Standard Model essentially doubles the spectrum.

SUSY (like many attempts to resolve the fine-tuning problem) actually complicates some successes of the Standard Model:

One triumph of the Standard Model is to naturally conserve baryon and lepton number, because there are no renormalizable (perturbative) couplings of Standard Model fields that violate those symmetries.

This is lost with supersymmetry, where renormalizable interactions causing catastrophic proton decay are possible.

The most commonly adopted solution to this problem is to assume a new symmetry called R-parity; this is possible but not obviously compelling.

Supersymmetry also potentially undoes some of the successes of the Standard Model in suppressing Flavor Changing Neutral Currents and CP violation, by introducing troublesome new loop diagrams involving superpartners

And supersymmetry introduces at the GUT scale a new scenario for proton decay via dimension five operators …

This is troublesome for many models given modern experimental limits on the proton lifetime.

And how is SUSY broken? Two major approaches:

- Gravity Mediation – supersymmetry broken at a very high scale and SUSY breaking mediated to the standard model via supergravity interactions

- Gauge Mediation – supersymmetry broken at 100 TeV or so and communicated to the known world via gauge forces

Each type of model has its virtues, and neither has yet given a clear path to solving all the problems.

For example, thinking about the cosmological constant might lead us to favor gravity mediation:

$$V = | DW/D\varphi|^2 - G_N |W|^2$$

(G_N is Newton's constant.)

To make V small, gravity is needed, suggesting gravity mediation

If instead we consider excessive new sources of Flavor Changing Neutral Currents and CP violation, we find that gauge mediation gives much more obvious ways to eliminate them. …. In short, we don’t have a fully convincing picture of supersymmetry breaking.

But the less theorists understand supersymmetry, the more exciting it is for experimentalists to find it and study it if it is there!

Learning how nature solved the problems would be quite dramatic. That is where we might get clues for how to do Grand Unified Theories or String Theory, if one or both of those is on the right track.

Studying the Superworld would be a golden opportunity for the Linear Collider, because of the great complexity of the Superworld, with numerous new particles and interactions whose details may hide crucial clues about Nature.

We’d want to unravel this complicated story in detail.

High precision will very likely be needed to learn how Nature solved the problems to which human model-builders do not have convincing answers, and thereby possibly extract the crucial clues about further Unification. Only a lepton collider can achieve this sort of high precision.

I’ve emphasized supersymmetry since I think it has particularly interesting successes and failures. However, other ideas for a rational solution to Dirac’s large numbers problem generally lead also to elaborate structures – large extra dimensions or new gauge forces with many new particles and interactions in each case – that will again be a challenge to unravel.

Again, the precision of a lepton collider will be needed!