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Chapter 1

The LHC – A "Why" Machine and a Supersymmetry Factory

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> *"It is as absurd to think about the origin of life*
> *as it is to think about the origin of matter.*
>
> –Charles Darwin

The Standard Model of particle physics, and the Standard Model of cosmology, are remarkable and elegant achievements. They synthesize four centuries of steady progress in understanding our world. They successfully describe all the physical universe that we see, from the everyday world around us, to the smallest objects and largest ones, back to the beginning of the visible universe and out to its boundaries. Everything we see is formed from fundamental quarks and leptons that interact via the electromagnetic, weak, strong, and gravitational forces. The forms of the forces are determined by symmetry and invariance principles. A few interaction strengths and quark and lepton masses are measured and input to the theory, and the rest can be calculated.

As is well known, even with the great success of the Standard Models there is still much we would like to understand. The Standard Models tell us what is there and how it works to form our world, but it does not tell us why it is that way. We know that about a quarter of the universe is matter, and that about a fifth of the matter is made of quarks and leptons (and that the rest of the matter is not made of quarks and leptons), but we don't know what form the rest of the matter takes. We know the universe is made almost entirely of matter and not antimatter even though it began in a big bang with equal amounts of matter and antimatter, but we don't know why. There is good evidence that the big bang was preceded by a period of rapid inflation of space-time, but we don't know what the actual physical cause of that inflation was – it is called an "inflaton", and many possible physical causes have been examined, but so far none are convincing. 'The Standard Model cannot provide these understandings – it is not that the Standard Model has not yet provided them, we know it cannot.

While some information from cosmology can still constrain the answers to these basic questions, no amount of cosmology can answer these questions. The CERN Large Hadron Collider (LHC) is a new tool that could provide, through its discoveries, what is needed to construct a more comprehensive theory that leads to the answers to these questions and many others.

More concretely, the LHC will extend testing of the Standard Model, but that is not why we are excited about it. The Standard Model includes Higgs physics that allows the quarks and leptons and the W and Z bosons that mediate the weak force to have mass, but it does not tell us the origins of the Higgs field (of which the Higgs bosons are quanta) and how it works, nor the amounts of mass the particles have. From LEP and Fermilab data there is strong indirect evidence that Higgs bosons do exist. If so, LHC will detect them. That is exciting.

Similarly, there is strong indirect evidence that nature has a symmetry, called supersymmetry. Quantum theory taught us that there are two kinds of particles, called fermions and bosons. For example, the matter particles (electrons and quarks) are fermions, while the particles whose exchange mediates the forces (photon, gluons, W and Z bosons) are bosons. Our present description of particles and their interactions that shape our world treats the particles very differently. Supersymmetry is the surprising idea that the fundamental theory actually treats fermions and bosons in a fully symmetric way – if you interchange them in the basic equations the resulting theory looks just like what you started with. One of its implications is that every particles has a "superpartner", and that makes the theory very testable. If nature is indeed supersymmetric in a way that helps answer the above questions, the superpartners must exist, and some of them can be detected at LHC. There is very strong indirect evidence for superpartners, and if the evidence is not misleading coincidences signals from superpartners should emerge early at LHC. Our space dimensions are bosonic ones in the sense of quantum theory. Supersymmetry also can be thought of as formulated by having every space dimension have an associated fermionic dimension. If we collide particles with enough energy we can knock particles into the fermionic dimension and produce their superpartners. That's why LHC is so important.

If supersymmetry indeed provides the explanation for some aspects of what the Standard Model does not, it also implies a rather light Higgs boson exists (consistent with the indirect evidence for Higgs bosons), and that is another important test. Finding Higgs bosons at LHC is challenging for technical reasons (as is described in other chapters) but detecting the basic signals of the superpartners is likely to be easier since they produce a number of possible effects that can be distinguished from the Standard Model particles. Once the superpartners and the Higgs bosons are observed, their properties will help point the way to the form of the underlying theory and to how it answers the questions of the matter asymmetry and the dark matter and the identity of the inflaton.

If supersymmetry indeed is part of the correct description of nature at LHC energies there is another remarkable bonus. The supersymmetric theory can be extrapolated to near the Planck scale, so string theories can be written at their naive natural scale and then their predictions for LHC energies can be calculated. Or conversely, data from LHC and associated experiments can be extrapolated to study its implications for string scale physics.

1.1. A "Why" Machine

The Standard Model describes what we see very well. It tells us how things work. In my view arguably the main result that has been learned in the past two decades is that in order to understand nature at the most fundamental level the underlying theory must be formulated in more than three space dimensions. String theory requires for consistency that we live in extra space dimensions, probably wrapped up in a tiny volume at each of our three dimensional space-time points. When we project that world into our three space dimensions there are implications for the existence of forces and particles, and for cosmology. All the questions that are not answered by the Standard Model are at least addressed by string theory. The data from the LHC may allow us to connect the string theories to the additional questions they address, and to test whether the questions are indeed answered.

An optimist can make a defendable argument that the data from LHC and other experiments underway could be sufficient to allow us to point to and test string theories, and answer many of the unanswered questions in such a comprehensive theory. Thus I view the LHC as a "why" machine, one that may lead us to a much greater understanding of why the main things we want to understand about the world are the way they are. Today everything we know is consistent with an elegant simple picture of the laws of nature. There is an encompassing underlying eleven dimensional M-theory that describes nature at short distances of order the Planck scale. It has solutions with six- or seven-dimensional small submanifolds. Three space dimensions inflate and grow to become our three space dimensions. At the Planck scale there is only one force, but as distances increase families of quarks and leptons emerge, and the familiar forces emerge and appear to act differently. At the short distances nature is supersymmetric, and at larger distances, lower energies, the form the interactions take depends on how the supersymmetry is broken. Although we have some clues today about how supersymmetry is broken, from the absence of various rare decays and from the fact the electroweak symmetry is broken so that quarks and leptons and W's can have mass, from the existence of the superpartners themselves and their properties we will learn much more. That knowledge, combined with an increasing understanding of the theory and with clues from cosmology such as the amounts of dark matter, the fact the universe is matter and not antimatter, and properties of inflation encoded in the large scale structure, could provide enough information and clues to allow clever physicists to guess the form of the underlying higher dimensional theory.

Then the theory will suggest additional tests and correlations among different phenomena, and as has always happened historically there will be great progress in understanding. What will be different this time is that the theory will address and provide answers to all the questions we have asked about the natural universe and the law(s) of nature. While some may see this framework as wishful speculation, there is today no reason to reject such a simple outcome, and much to support it. We should not give it up until we have to.

Of course the results from LHC and a few related experiments may turn out not be enough to lead to the underlying theory. Other facilities such as upgrades of the LHC, and/or a linear collider may be necessary, and would certainly make it easier to get to the final primary theory. I like the name "primary theory" because it suggests a ladder of effective theories. Define an effective theory as one in which some quantities (such as quark masses and force strengths) and some principles (such as the rules of quantum theory) are input. The Standard Model of particle physics, and even the supersymmetric Standard Model, are effective theories. The primary theory is not, in that all the needed quantities and principles emerge from one underlying theory.

When I present such arguments not all listeners are immediately convinced. Of course they should not be – there are many alternative approaches to the simple world view, and many different ways the universe and the laws of nature could work. These should be studied. LHC and related data will allow tests and distinctions. One often heard argument is that historically each step has led to more puzzles, and that will always continue. There are two encouraging rejoinders to this argument. The quest for understanding the laws of nature and the origin of the universe resembles the exploration of the surface of the earth. It went on for many centuries, but then one day it was over. There were answers, and they were found. It is reasonable to argue the same thing will happen in our quest. There is nothing special about our time ("why now?") – it took many centuries too, and finally today all the major questions about the physical universe are being addressed as research questions (rather than philosophical ones). Once they are addressed as research questions usually they are answered within few decades. The LHC may be the last major expedition needed.

Second, the Standard Model emerged in a similar way. In the late 1960s everyone felt the situation was chaotic and frustrating. Many paths were pursued. Some crucial data was known, such as parity violation, the hadron spectrum, deep inelastic scattering rates and scaling, pion and beta decay, but no coherent picture. The theory had opportunities but was puzzling. Then within a few years everything fell into place for both theory and experiment. It is certainly defendable that we are in a similar era. Some exciting approaches are right and others are not. In the case of field theory with fundamental particles versus the bootstrap theory one approach was fruitful and the other not. While data point toward some approaches and not toward others, these are not simple yes-no tests. Rather the relevant theorists vote with their choice of what to pursue.

1.2. A Superpartner Factory

For the simple world view described above to be right and fruitful it is essential that the description of nature includes low scale supersymmetry. Why do we expect that? There are several motivations for a supersymmetric extension of the Standard Model to be the actual description of nature at the energies where we do experiments. While these reasons have mostly been known since the 1980s I have found that not only more general readers, but also many younger physicists, and many experimenters, and many string theorists, have not had much exposure to them, so I repeat them here in some detail.

- Supersymmetry allows the theory to have two stable but widely separated mass scales, which would in general not be possible in a quantum theory – the infamous so-called "hierarchy problem". These are the scale of the weak interactions, of order 100 GeV, and the natural scale of a fundamental theory of the forces, the Planck scale where gravitational interactions are of the same order as the other forces. Supersymmetry alone does not tell us the numerical value of the weak scale, but it stabilizes it *if the superpartners have about the same mass as the weak scale, below a TeV.*
- The electroweak symmetry is broken, by the Higgs mechanism, to accommodate the quark and lepton and gauge boson masses. In the Standard Model this breaking is imposed in an ad hoc way, but in the supersymmetric extension the breaking of the electroweak symmetry emerges from the theory. Further, it only does so if the supersymmetry is also a broken symmetry, so at a basic level the two breakings are related and not two separate ones.
- In a quantum theory the effects of a force can be calculated at any energy, so the effects of the forces can be examined at higher and higher energies. They become more and more similar, encouraging the view that the forces can be unified into one deeper understanding In the Standard Model they become similar but far from equal at any energy, while in the supersymmetric extension they become equal within a few per cent at about 2x10^{16} GeV. A further extrapolation to the Planck scale near 10^{19} GeV is quite plausible (and can be studied in any specific theory). The jargon for this is "gauge coupling unification" because the strengths of the separate forces are determined by the gauge theory couplings.
- It has been known for over two decades that the dark matter of the universe can be accounted for if a stable particle exists with a mass of order the weak scale, 100 GeV or so, and can annihilate with itself with a cross section of typical weak interaction strength. Generically the lightest of the superpartners (the "LSP") is such a particle. Both Standard Model particles and superpartners are

produced in the Big Bang. After a while all the particles have decayed but photons, neutrinos, electrons, up and down quarks, and the LSP. The amount of energy density supplied by the LSP is typically about right to account for the actual dark matter. Indeed, before it was known that dark matter not made of normal matter actually formed most of the dark matter it was predicted that the LSP would provide such dark matter.

- In the Standard Model it is not possible to explain why the universe is matter rather than equal amounts of matter and antimatter. In the supersymmetric extension there are actually several ways to explain this. Each has tests, and the LHC can provide crucial information for some of the tests.
- The LEP collider at CERN taught us four major qualitative results. One is that the number of families with light neutrinos is three. Second is the values of the force strengths to high accuracy so they could be extrapolated to high energies and be seen to unify in the supersymmetric extension of the Standard Model. Third, LEP measured accurately some 20 independent properties of the Z boson and its decays, all of which were predicted by the Standard Model. The Standard Model predictions depended on only one unmeasured parameter, the mass of the Higgs boson. A good fit to all the data could be found if the Higgs boson mass were less than about 165 GeV, implying the Higgs boson existed with a mass in that range. Higgs bosons occur naturally in supersymmetric theories, and in general there is an upper limit of about twice the Z boson mass, about 180 GeV, on the mass of the lightest Higgs boson in supersymmetric theories that stay perturbative to the unification scale. Thus this LEP result is consistent with the supersymmetry prediction. The experimental result is reinforced by the logically independent result that the range of Higgs masses giving the measured W and top quark masses (adding Fermilab data) also has an upper limit of about the same value as the LEP fit.
- The fourth LEP result is that no measurement deviated significantly from the Standard Model prediction. That is natural in a supersymmetric world where the superpartners are either light enough to be produced directly, or only enter in loops and are therefore at most of order a part in a thousand. All alternative models would naturally have strong interactions at the TeV scale

and would give significantly larger deviations from the Standard Model. The alternative models can be adjusted and tuned to not disagree with the data, but before the data one would have expected larger effects.

- All the above successes occur simultaneously. Often models can explain one thing but then they get into problems with another. Further, the supersymmetry theory existed (since the mid-1970s) before any of the listed successes. It was not invented to fit or explain any of them. They were recognized as the theory was studied, from about 1980 through the early 1990s.

Thus the motivation for finding that supersymmetry is a part of our description of nature at the TeV scale is very strong. If that is indeed so, then at least some of the superpartners must not be too heavy, and will be produced at LHC. In order to retain the above listed successes probably the partners of the gauge bosons and Higgs ("gauginos") must be at or below about a TeV. The production rates of these particles depend on their masses, which are not yet calculable from what is known about the theory, but the rate for gluinos has a minimum value from the QCD coupling to gluons, and gives a large rate if the LHC luminosity is as expected. For example, a gluino of mass 750 GeV will give about 500 events in the first 100 pb^{-1} of integrated luminosity. If the initial running goes as expected that amount of data could be taken in a week or so. That number of events is sufficient to recognize a signal for new physics. After a couple of years and the higher luminosities expected there will be tens of thousands of gluinos. They will decay into other superpartners, and other superpartners will be produced in additional ways, and all can be studied.

The above arguments that supersymmetry must exist at the weak scale is based on indirect evidence, and is not compelling for some people. There are a few worrisome isssues that could be of concern. One can basically think of them as first that the Z boson mass is too small, second that the Higgs boson mass is too large, and third that flavor mixing effects should already have been seen. The Z mass seems too small because the theory explains it in terms of superpartner masses, and the relevant superpartner masses seem to be at least a few times the Z mass, so one is calculating a small number in terms of several that are noticably larger. Effectively one is invoking cancellations to get the small answer, and that usually is not a good thing. The HIggs boson mass is too large in the sense that there is a lower limit on it under most conditions, and that lower limit is uncomfortably large in many simple cases. There are a number of ways around this concern, but some require somewhat special circumstances. The third says if one thinks of supersymmetry as a low scale theory then it would be typical for flavor mixing to occur, so decays such as $\mu \to e + \gamma$ should occur and so far they do not. For me and many other theorists these are interesting puzzles (puzzles of course are meant to be solved) but not nearly as negative as the successes are positive.

1.3. After the Champagne

The first challenge will be to establish that a signal of new physics is present. That will be done by the experimenters, based on our understanding of the Standard Model.

Then two challenges/opportunities are paramount. First we need to establish that what is seen is indeed supersymmetry. I think that will not be difficult. If production of gluinos and/or squarks is large, it will be fairly easy to establish their spins are what is needed for them to be superpartners of the Standard Model particles. Additional characteristic signatures and related channels are likely to occur, such as same sign dileptons that arise from the Majorana gauginos.

The second is to learn about the dark matter of the universe. If the LSP is escaping the detectors we can study it (yes!), e.g. get information about its mass, and determine in what channels it is produced, which will tell us about the main things we need to know to calculate the associated relic density, and even learn about the cosmological history of the universe as well.

Then as data accumulates we will begin to relate what is observed to the underlying theory, and hopefully test string theory predictions. Progress may be rapid in that quest too.

The LHC and its results have been anticipated for a long time:
"Many shall run to and fro, and knowledge shall be increased",

– Book of Daniel 12:4