String Theory at Snowmass

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This is the summary talk for the String Theory subgroup of the TeV and Beyond working group at Snowmass, 2001. At Snowmass, a group of physicists interested in string theory, quantum gravity, and related issues met to discuss the questions: which future facilities would be most likely to provide information about the issues which currently confront string theory, and can string theorists make predictions for these facilities before they turn on. There was a strong concensus that the LHC program, followed by a linear collider, would provide crucial clues to our understanding of physics at extremely short distances.

1. Introduction

Many physicists are convinced that string theory is the framework in which we will ultimately understand the basic forces of nature, including gravity. Many of the features of the theory look promising. It incorporates gravity and gauge interactions in a consistent, quantum mechanical framework. It has solutions in which four dimensions are large, and with other basic features of the real world: realistic gauge groups, repetitive generations and candidate Higgs particles. Recently, string theory has successfully resolved some of the profound questions which have been raised through the years about quantizing gravity. Indeed, it has many of the hallmarks which we might expect of a complete theory. These are all extraordinary results, and account for the fascination of so many theorists with this theory.

Yet there is much that is not understood about the theory. We do not have a general, non-perturbative formulation, in which the symmetries and degrees of freedom are manifest. Such a formulation may well be necessary before we can make detailed contact with experiment. Even at the level of qualitative questions, such as "does the theory predict low energy supersymmetry" we are currently at a loss to make definitive statements.

At Snowmass, a group of string theorists as well as physicists interested in extra dimensions, black holes, and other exotic phenomena met to discuss the future of particle physics in relation to our understanding of fundamental issues in string theory. In addition to discussion among themselves about ways in which string theory might make contact with experiment, they also participated vigorously in the larger debate about future priorities for the high energy physics community. The goals of the string theory subgroup were modest:

- To provide an opportunity for members of the string theory community to learn about issues we face in making decisions about future facilities, and to participate in the general discussion (for example, Gross and Witten participated with experimentalists Jon Womersley and Paul Grannis, and more phenomenologically oriented theorists Joanne Hewett and Jim Wells in a panel discussion about future facilities).
- To discuss how physics at different types of facilities might provide clues to a better understanding of string theory.
- To discuss ideas and possible research programs geared to bringing string theory into contact with experiment.
- To present recent developments in string theory to the larger community. Ed Witten gave two general talks on string theory for the larger Snowmass community. Members of the group spoke about large compact dimensions, the possibility of producing black holes at

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the LHC and other colliders, problems associated with the cosmological constant, and other issues. Participants in this group made presentations to the HEPAP subpanel.

2. String Theory in the 20th Century

It seems unlikely that consistent theories of gravity are common. String theory is, as Witten explained in his general talks on the subject, remarkable in that it automatically gives us general relativity and gauge theory in a quantum mechanically consistent framework. This alone would make it an important object for study. In the past few years, we have learned that all of the known string theories are limits of some larger theory. To many, this suggests that we may have stumbled on the unique structure which can encompass the things we know about nature.

One might have imagined that such a theory would be hopelessly complex, and it would take a very long time to obtain even a rudimentary, qualitative understanding. Yet it has been clear from nearly the beginning that, in a number of important ways, string theory closely resembles the real world. String theory has scored a number of striking successes:

- Low energy supersymmetry emerges quite naturally.
- String models provide a framework in which to understand generations, the origin of gauge and Yukawa couplings, and other mysterious features of the standard model.
- In the MSSM, discrete symmetries must be postulated in order to understand the stability of the proton. In string models, such symmetries are common.
- Unification of couplings is a property of a large class of string models. At the same time, many of the problematic features of grand unified models are not intrinsic to string theory. One can easily obtain light doublets (Higgs) without light color triplets, for example. Problematic relations among quark and lepton masses do not necessarily hold.
- Axions have been widely discussed as solutions of the strong CP problem and candidates for dark matter. In conventional effective field theory, however, it is very hard to understand how axions can arise with the necessary properties. In string theory, this is automatic
- String theory possesses compact dimensions, which can be large. It also contains branes, and Horava and Witten early on suggested that the standard model fields might live on a brane[1]. The more radical suggestion that the extra dimensions might be macroscopic or nearly so, while at first sight implausible, has attracted great attention in the past few years[2, 3].
- Related to these ideas is a rich phenomenology. There has been a great deal of progress in understanding black holes in the past few years, and we heard presentations at this meeting about the possibility that, if the large dimension picture is correct, future colliders may be black hole factories[5, 6]. Indeed, it has been argued that this might mean the end of short distance physics.

String theory has also proven useful as a framework in which to develop and explore new ideas and proposals for particle phenomenology, and this aspect of string theory was discussed by the participants. Examples include:

- Large Dimensions: The idea that extra dimensions might be significantly larger than the Planck scale, with the standard model located on branes, originated from considerations of string theory[1]. The exciting possibility that the fundamental scale is as low as a TeV only makes sense – and can only be seriously explored in a quantum theory of gravity[2].
- Anomaly mediation[7], and related to it the idea of gaugino mediation[8], have been widely discussed as models of supersymmetry breaking in the context of higher dimensional theories. Recent analyses, however, indicate that the anomaly mediated picture is not a robust outcome of string theory. Generic string states which satisfy the basic criteria believed to be required for anomaly mediation in fact do not have an anomaly mediated spectrum[9].

- Very light scalars have been proposed as a way to obtain anthropic solutions of the cosmological constant problem[10]. However, rather general arguments suggest that scalars with the desired properties are not a likely outcome of string theory[11].

- Other anthropic solutions of the cosmological constant problem do find a natural setting in string theory. Models with quantized fluxes were discussed by Polchinski[12]. These models have the potential to produce a "discretum" of ground states, i.e. a large set of vacuum states with a nearly continuous distribution of energies. Within our present understanding of string theory, it is not clear whether this phenomenon actually occurs. Arguments about its plausibility were reviewed in these sessions. No definitive conclusions were reached, and this crucial question will certainly be a subject of further extensive study.

3. Challenges for the 21st Century

String theory has many of the features we might expect of a truly unified theory. Still, it is not surprising that a theoretical program so ambitious is also difficult. Our understanding is still rather fragmentary, and there are many obstacles to developing a robust string phenomenology. The two most serious of these are:

- At the classical level, there are a vast array of ground states. We do not know what physical principle might choose between them. These vacua include states with various numbers of dimensions and various amounts of supersymmetry (from zero to 32 conserved supercharges). General principles insure that many of these are good ground states, perturbatively and non-perturbatively.

- In ground states with $N \leq 1$ supersymmetry, it is not clear what principle might explain the vanishing (or smallness) of the cosmological constant.

The question of how future facilities will help string theory make contact with nature featured heavily in the string theory discussions. Ideas for how string theory might yield convincing predictions were discussed. But given that we may well not succeed in making such predictions on a ten year time scale, participants also addressed the question: if, at the time the LHC turns on, physicists have failed to make such predictions, what questions would these facilities help us to address.

Absent a "solution" of the theory, one approach to making predictions is to focus on features that are true of large classes of string solutions. Participants noted that we might be able to address certain generic questions:

- Is low energy SUSY a prediction of string theory? One might try to establish such a statement by ruling out broad classes of non-supersymmetric models. For example, many such models contain tachyons in subspaces of their moduli spaces, or suffer from Kaluza-Klein instabilities[13, 14]. It has also been suggested that some string models might have non-perturbative anomalies.

- Are large[2, 3] or warped [4] dimensions a prediction of string theory? One might argue this if one could show that they provided a solution of the cosmological constant problem. Otherwise, we will need experimental input.

If we fail to predict by theoretical reasoning that one of these possibilities is an outcome of string theory, it is certainly true that each makes distinctive predictions for future accelerators, and that experiments at the LHC and a future linear collider will distinguish these possibilities. Several talks and much of the discussion focussed on these predictions.

3.1. Supersymmetry

Much of the focus of the discussion was on supersymmetry. Low energy supersymmetry, almost all of the participants agreed, was the most likely outcome of string theory. This opinion arises from a combination of theoretical and phenomenological observations:

- Low energy supersymmetry arises quite readily in string theory.
- Supersymmetry, with a minimal set of assumptions, explains the unification of couplings. A broad class of string models predict such unification, even though these theories don't look like conventional grand unified field theories.
- Supersymmetry provides a plausible explanation of the hierarchy problem.
- Supersymmetry quite naturally yields a good candidate for the dark matter.

But if SUSY is observed, accelerator experiments will also be exploring Planck scale physics. In most pictures of supersymmetry breaking (the exception being gauge mediation, of which more below), supersymmetry is broken by new interactions in a "hidden sector". The 105 soft-breaking parameters arise through couplings of ordinary fields to hidden sector fields, suppressed by powers of the Planck scale. Measuring these parameters thus gives us access to physics at very high energy scales. Indeed, in the event that supersymmetry is discovered, it is quite possible that the LHC and a future linear collider will be exploring the physics of the Planck scale.

Of course, we might despair of making sense of this information. But there is good cause for optimism. While we don't have a convincing, detailed theory of these parameters, we know that they are not simply random numbers. The fact that susy particles do not mediate substantial flavor-changing neutral currents highly constrains the soft breakings. Only a small number of proposals exist for how these constraints might be satisfied, and experiments, particularly at a linear collider, can help determine whether one of these proposals – or something different – is operative.

While we are far from a complete understanding of the various suggestions, string theory has already made some statements, and it is likely that further understanding will develop over the next few years. To give some examples:

- Gravity mediation: The bulk of supersymmetry phenomenology has been based on the idea that gravity is the interaction which mediates supersymmetry breaking. More precisely, one supposes that the typical scale of the theory is the Planck mass, and one postulates some simple form for the Kahler potential (which in turn determines the pattern of soft breaking). This potential is assumed to have a flavor blind structure. The symmetries of supergravity alone, however, do not enforce this. In string theory, one finds that generically, even at weak coupling, the assumptions of gravity mediation do not hold. However, in some limits, one does obtain approximate degeneracy. The best known of these is called "dilaton domination," in which the dilaton dominates supersymmetry breaking[15]. But we do not currently have real string models which implement this idea, and the expected degree of degeneracy is unclear. Some phenomenology has been done assuming that corrections to this picture are of order one loop in the unified coupling[16], but at strong coupling, one might expect corrections to be larger[9]. Further progress on these questions should be feasible.
- Anomaly mediation and gaugino mediation: These proposals are based on brane pictures, and seem to give predictive results for the soft breakings. However, they are based on a set of assumptions which do not seem to be robust in string theory, but rather hold only in special cases[9].
- Approximate flavor symmetries: Here the idea is that one has, at some high energy scale, flavor symmetries (usually assumed discrete) which are broken by a small amount (say of order the Cabbibo angle). Such symmetries arise quite frequently in string theory.

These proposals all have distinctive experimental implications. One of the most interesting signals, potentially accessible to a linear collider, is slepton mixing. Many of theses scenarios predict a high degree of degeneracy among the sleptons, and thus the potential for large mixing. One has the possibility, for example, of seeing significant flavor violation in e^+e^- and especially e^-e^- collisions[17, 18]. As a result, one can imagine that at the first stage of a linear collider, one might produce, say, only three slepton states. However, flavor violating interactions – or their absence – would give a great deal of information about the underlying mechanisms of supersymmetry breaking.

Gauge mediation is the one proposal for understanding the soft breakings which does not invoke very high scale physics. In some ways, this makes it the most exciting possibility, since, over time, we might experimentally explore the physics responsible for supersymmetry breaking. Gauge mediation has also been suggested as a plausible outcome of string theory. In a situation in which all of the moduli are massive (compared to the scale of supersymmetry breaking), carry gauge quantum numbers, or in which there are simply no moduli at all, it seems quite likely that gauge mediation would be an outcome[19].

String theorists should focus on these questions and further progress seems possible. It is not totally inconceivable that before, say the LHC turns on, we will establish that supersymmetry is or is not an outcome of string theory. But experimental input will ultimately be crucial, and will teach us a great deal.

3.2. String Theory and Large Dimensions

From a phenomenological viewpoint, large dimensions are perhaps the most exciting phenomenon one can envision for future colliders. If the fundamental scale of physics is at 1 TeV, the problem of the hierarchy becomes the question: why are the extra dimensions so large[2]? While no compelling picture has been presented of why this might emerge, it is a plausible outcome of string theory, where, at the classical level, extra dimensions can indeed be arbitrarily large.

At this meeting, the focus both of talks and discussion was on the implications of this possibility for colliders. A particular focus was on the possibility of producing black holes at the LHC, and their signatures[5, 6].

It is also possible that very large dimensions might yield an understanding of some of the pressing fundamental issues in string theory and gravitational physics. In particular, various proposed solutions to the cosmological constant problem might fit into such a framework. No definitive answers to these questions were offered, but it was generally agreed that this is an important area for further work.

There was a general sense, for reasons indicated earlier, that supersymmetry is a more likely outcome of string theory than large dimensions. However, were the large dimension picture to provide insight into some of these fundamental issues, this prejudice would certainly change.

4. String Theory and Cosmology

Cosmology could well prove to be an important proving ground for string theory. Observations of the past few years have provided great support for the inflationary paradigm, but in a very fundamental sense, we have no theory of inflation. The existing models are finely tuned, and require assumptions about high scale, non-renormalizable interactions. In string theory, one might hope to address these questions. Indeed, one cannot address questions such as the nature of the dark energy, without a sensible theory of gravity. As we mentioned earlier, some widely discussed dark energy candidates, for example, are implausible within the framework of string theory. Some ideas which might lead to an anthropic solution of the cosmological constant were discussed at this meeting[20]

One appealing feature of string theory from the perspective of cosmology is the presence of light moduli, fields which may play the role of inflatons, for example. The Horava-Witten limit of string theory has been suggested as a framework in which the requisite scales for inflation might emerge naturally[21].

In string theory, one might hope to gain insight into larger questions, such as the nature of the initial singularity and of the initial conditions. Even without realistic models, one might hope to explore these issues. During the past few years, string theory has allowed study of many of the basic questions of black hole physics. This is despite the fact that realistic, Schwarschild black holes are very difficult to study in string theory. The point is that one can study models which, while unrealistic, pose all of the same conceptual challenges as the Schwarschild black hole, and which are significantly more tractable[22]. Similarly, we might search for theories with big bang or big crunch singularities, which, while not fully realistic, could provide models for how such singularities are resolved[11].

5. Concensus

While string theory has made great strides, there are many aspects of the theory which remain poorly understood. Supersymmetry is at the center of many of the most pressing questions. At a fundamental level, supersymmetry seems a crucial part of the theory. But we have only conjectures about how, and at what energy scale, it is broken. Experimental guidance on this issue will almost certainly be crucial to progress on an array of questions, both phenomenological and foundational, in the subject. If low energy supersymmetry is discovered, this will be a major clue. If it is not, but large or warped dimensions are, this will also provide critical focus for further work.

This group considered various possible future facilities from the perspective: what sorts of information are likely to shed light on the questions of fundamental importance to string theory. All members of this group would make a forceful case for a linear collider at 500 GeV, upgradable to an energy of order 1 TeV. All members of this group agree that the physics of electroweak symmetry breaking will provide crucial guidance in addressing these issues. If supersymmetry is discovered, a linear collider will be crucial to understanding the nature of supersymmetry breaking. As explained above, determining the pattern of soft breakings is likely to provide direct information about Planck scale physics. If supersymmetry is not discovered, probing the physics of electroweak breaking for clues to the next important scale will be crucial. Moreover, it seems likely that this physics is likely to provide greater insight than, for example, discoveries in quark flavor or neutrinos (including CP). This is not because this physics is not fascinating and beautiful, but because within our present understanding, *the details* of this physics seem less likely to be accessible to theoretical understanding any time soon. Indeed, most current ideas for understanding the features of the quark and lepton neutrino masses rely on low energy supersymmetry in some crucial way. It does seem plausible that in the future, say, having discovered supersymmetry, it will be possible to sort out many aspects of flavor symmetry. Absent an unanticipated theoretical breakthrough, real progress will require establishing, first, whether or not the low energy supersymmetry hypothesis is correct, and basic features of the soft breakings. For example, in some models, neutrino masses and mixings are correlated with the soft breaking parameters.

All of the participants felt strongly that given the success of precision electroweak physics, there is very likely to be a Higgs particle accessible to a 500 GeV linear collider. From the successful unification of couplings, and from the fact that supersymmetry plays such a crucial role in string theory, there is a good chance that supersymmetry will be discovered at the LHC, and that the linear collider will be crucial in understanding the way in which supersymmetry is realized in nature.

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