String/M-theories About Our World Are Testable in the Traditional Physics Way∗

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January 28, 2016

Abstract

Some physicists hope to use string/M-theory to construct a comprehensive underlying theory of our physical world – a “final theory”. Can such a theory be tested? A quantum theory of gravity must be formulated in 10 dimensions, so obviously testing it experimentally requires projecting it onto our 4D world (called “compactification”). Most string theorists study theories, including aspects such as AdS/CFT, not phenomena, and are not much interested in testing theories beyond the Standard Model about our world. Compactified theories generically have many realistic features whose necessary presence provides some tests, such as gravity, Yang-Mills forces like the Standard Model ones, chiral fermions that lead to parity violation, softly broken supersymmetry, Higgs physics, families, hierarchical fermion masses and more. All tests of theories in physics have always depended on assumptions and approximate calculations, and tests of compactified string/M-theories do too. String phenomenologists have also formulated some explicit tests for compactified theories. In particular, I give examples of tests from compactified M-theory (involving Higgs physics, predictions for superpartners at LHC, electric dipole moments, and more). It is clear that compactified theories exist that can describe worlds like ours, and it is clear that even if a multiverse were real it does not prevent us from finding comprehensive compactified theories like one that might describe our world. I also discuss what we might mean by a final theory, what we might want it to explain, and comment briefly on multiverse issues from the point of view of finding a theory that describes our world.

∗This writeup is based on an invited talk at the meeting “Why Trust a Theory? Reconsidering Scientific Methodology in Light of Modern Physics”, LMU, Munich, December 2015, and some related talks.
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1 Outline

- Testing theories in physics – some generalities.
- Testing 10-dimensional string/M-theories as underlying theories of our world obviously requires compactification to four space-time dimensions.
- Testing of all physics theories requires assumptions and approximations, hopefully eventually removable ones.
- Detailed example: existing and coming tests of compactifying M-theory on manifolds of $G_2$ holonomy, in the fluxless sector, in order to describe/explain our vacuum.
- How would we recognize a string/M-theory that explains our world, a candidate “final theory”? What should it describe/explain?
- Comments on multiverse issues from this point of view. Having a large landscape clearly does not make it difficult to find candidate string/M-theories to describe our world, contrary to what is often said.
- Final remarks

2 Long Introduction

The meeting "Why Trust a Theory" provided an opportunity for me to present some comments and observations and results that have been accumulating. The meeting was organized by Richard Dawid, author of String Theory and the Scientific Method, a recent and significant book. Near the end I will comment on some of Dawid’s points.

String/M-theory is a very promising framework for constructing an underlying theory that incorporates the Standard Models of particle physics and cosmology, and probably addresses all the questions we hope to understand about the physical universe. Some people hope for such a theory. A consistent quantum theory of gravity must be formulated in 10 or 11 dimensions. The differences between 10 and 11 D are technical and we can ignore them here. (Sometimes the theory can be reformulated in more dimensions but we will ignore that too.) Obviously the theory must be projected onto four space-time dimensions in order to test it experimentally. The jargon for such a projection is “compactification”.

Remarkably, many of the compactified string/M-theories generically have the kinds of properties that characterize the Standard Models of particle physics and cosmology and their expected extensions! These include gravity, Yang-Mills gauge theories (such as the color $SU(3)$ and the electroweak $SU(2) \times U(1)$), softly broken supersymmetry, moduli, chiral fermions (that imply parity violation), families, inflation and more. For some theorists the presence of such features is sufficient to make them confident that the string/M-theories will indeed describe our world, and they don’t feel the need to find the particular one that describes our vacuum. For others, such as myself, the presence of such features stimulates me to pursue a more complete description and explanation of our vacuum.

The cosmological constant problem(s) (CC) remain major issues, of course. We will assume that the CC issues are effectively orthogonal to the rest of the physics in finding a description/explanation
of our world. That is, solving the CC problems will not help us find our underlying theory, and
not solving the CC problems will not make it harder (or impossible) to find our underlying theory.
The evidence we have is consistent with such an assumption. Ultimately, of course, it will have to
be checked.

The value of the CC may be environmental, a point of view attractive to many. Some physicists
have advocated that a number of the constants of the Standard Model and beyond are environ-
mental. In particular, their values are then not expected to be calculable by the normal methods
of particle theory such as a compactified string/M-theory. One problem with that attitude is that
apparently not all of the constants are environmental. Perhaps the strong CP angle, or the proton
lifetime, or the top quark mass are not, and perhaps more. In particular, note that some advocate
that the Higgs boson mass is environmental, but (as described below) we argue that in the com-
 pactified M-theory the Higgs mass (at least the ratio of the Higgs mass to the Z mass and perhaps
the Higgs vev) is calculable. It seems possible that the strong CP angle and the proton lifetime
are also calculable. If so, it is still necessary to explain why some parameters seem to have to be
in certain somewhat narrow ranges or the world would be very different. Note that the allowed
ranges are quite a bit larger than the often stated ones - e.g. if the forces are unified one must
change their strengths together, weakening typical arguments (ph/0408169). But the issue remains
that some parameters need to lie in rather narrow ranged, and need to be understood. In a given
vacuum, one can try to calculate the CC.

Much has been written and said about whether string/M-theories are testable. Much of what
has been said is obviously not serious or interesting. For example, obviously you do not need
to be somewhere to test a theory there. No knowledgeable person doubts our universe had a
big bang, although no one was there to observe it. There are several very compelling pieces
of evidence or relics. One is the expansion and cooling of the universe, a second the properties of the
cosmic microwave background radiation, and a third the nucleosynthesis and helium abundance
results. Amazingly, scientists probably have been able to figure out why dinosaurs became extinct
even though almost everyone agrees that no people were alive 65 million years ago to observe the
extinction. You don’t need to travel at the speed of light to test that it is a limiting speed.

Is the absence of superpartners at LHC a test of string/M-theory, as some people have claimed?
What if superpartners are found in the 2016 LHC run – does that confirm string/M-theory? Before
a few years ago there were no reliable calculations of superpartner masses in well-defined theories.
An argument, called “naturalness”, that if supersymmetry indeed solves the problems it is said to
solve then superpartners should not be much heavier than the Standard Model partners, implies
that superpartners should have been found already at LEP or FNAL, and surely at Run I of LHC.
All predictions up to a few years ago were based on naturalness, rather than on actual theories,
and were wrong. It turns out that in some compactified string/M-theories one can do fairly good
generic calculations of some superpartner masses, and most of them (but not all) turn out to be
quite a bit heavier than the heaviest Standard Model particles such as the top quark, or W and
Z bosons. Generically scalars (squarks, sleptons, Higgs sector masses except for the Higgs boson)
turn out to be a few tens of TeV (25-50 TeV), while gauginos (partners of gauge bosons such as
gluinos, photinos, winos, binos) tend to be of order one TeV. I will illustrate the mechanisms that
produce these results later for a compactified M-theory.

Thus actual compactified string/M-theories generically predict that superpartners should not
have been found at LHC Run I. Typically some lighter gauginos do lie in the mass region accessible
at Run II. It seems odd to call the results of good theories “unnatural”, but the historical (mis-)use
of natural has led to that situation.

Interestingly, many string theorists who work on gravity, black holes, AdS/CFT, amplitudes, and so on do not know the techniques to study compactified string/M-theories, and their comments may not be useful. Older theorists may remember. Much of what is written on the subject of testing string theory does not take into account the need for compactification, particularly in blogs and some popular books, which is quite misleading. That’s often also the case for what supposed experts say – in 1999 a well known string theorist said at a conference “string theorists have temporarily given up trying to make contact with the real world”, and clearly that temporary period has not ended. Sadly, string theory conferences have few talks about compactified string/M-theories, and the few that might be there are mainly technical ones that do not make contact with experiments. String theorists seldom read papers about, or have seminars at their universities about, compactified string/M-theories that connect to physics beyond the Standard Model.

But I want to argue that string/M-theory’s potential to provide a comprehensive underlying theory of our world is too great to ignore it. String/M-theory is too important to be left to string theorists.

Before we turn to actual compactified theories, let’s look a little more at the meaning of testing theories. In what sense is “F=ma” testable? It’s a claim about the relation between forces and particle properties and behavior. It might have not been correct. It can be tested for any particular force, but not in general. The situation is similar for the Schrödinger equation. For a given Hamiltonian one can calculate the ground state of a system and energy levels, and make predictions. Without a particular Hamiltonian, no tests. What do we mean when we ask to “test string theory”? The situation for string/M-theories is actually quite similar to F=ma. One can test predictions of particular compactified string theories, but the notion of “testing string theory” doesn’t seem to have any meaning. If you see something about “testing string theory”, beware.

Quantum theory has some general properties, basically superposition, that don’t depend on the Schrödinger equation (or equivalent). Similarly, quantum field theory has a few general tests that don’t depend on choosing a force, such as that all electrons are identical (because they are all quanta of the electron field), or the connection between spin and statistics. Might string/M-theory have some general tests? Possibly calculating black hole entropy, but I don’t want to discuss that here, because it is not a test connected to data. Otherwise, there don’t seem to be any general tests. Compactified string/M-theories generically give 4D quantum field theories, and they also imply particular Yang-Mills forces and a set of massless zero-modes or particles, so it seems unlikely they will have any general tests.

In all areas of physics normally one specifies the “theory” by giving the Lagrangian. It’s important to recognize that physical systems are described not by the Lagrangian but by the solutions to the resulting equations. Similarly, if string/M-theory is the right framework, our world will be described by a compactified theory, the projection onto 4D of the 10/11D theory, the metastable (or stable) ground state, called our “vacuum”.

One also should recognize that studying the resulting predictions is how physics has always proceeded. All tests of theories have always depended on assumptions – from Galileo’s using inclined planes to slow falling balls so they could be timed, or assuming air resistance could be neglected in order to get a general theory of motion, to assuming what corner of string theory and compactification manifold should be tried. Someday there may be a way to derive what is the correct corner of string theory, or the compactification manifold, but most likely we will first find ones that work to describe/explain our world, and perhaps later find whether they are inevitable.
Similarly, in a given corner and choice of manifold we may first write a generic superpotential and Kähler potential and gauge kinetic function and use them to calculate testable predictions. Perhaps soon someone can calculate the Kähler potential or gauge kinetic function to a sufficient approximation that predictions are known to be insensitive to corrections.

It’s very important to understand that the tests are tests of the compactified theory, but they do depend on and are affected by the full 10/11D theory in many ways. The curled-up dimensions contain information about our world – the forces, the particles and their masses, the symmetries, the dark matter, the superpartners, electric dipole moments, and more. There are relations between observables. The way the small dimensions curl up tells us a great deal about the world.

Just as a Lagrangian has many solutions (e.g. elliptical planetary orbits for a solar system), so the string/M-theory framework will have several or many viable compactifications, many solutions. This is usually what is meant by “landscape”. The important result to emphasize here is that the presence of large numbers of solutions is not necessarily an obstacle to finding the solution or set of solutions that describe our world, our vacuum. (See also the talk of Fernando Quevedo at this meeting.) That is clear because already people have found, using a few simple guiding ideas, a number of compactified theories that are like our world. Some generic features were described above, and the detailed compactified M-theory described below will illustrate this better. It is not premature to look for our vacuum.

3 What might we mean by “final theory”? How would we recognize it?

In each vacuum perhaps all important observables would be calculable (with enough grad students and postdocs encouraged and supported to work in this area). What would we need to understand and calculate to think we had an underlying theory that was a strong candidate for a “final theory”? We don’t really want to calculate hundreds of QCD and electroweak predictions, or beyond the Standard Model ones. We probably don’t need an accurate calculation of the up quark mass, since at its MeV value there may be large corrections from gravitational and other corrections, but it is very important to derive $m_{up} < m_{down}$, and that $m_{up}$ is not too large. It’s interesting and fun to make such a list. Here is a good start.

✓ What is light?

• What are we made of? Why quarks and leptons?

• Why are there protons and nuclei and atoms? Why $SU(3) \times SU(2) \times U(1)$?

• Are the forces unified in form and strength?

• Why are quark and charged lepton masses hierarchical? Why is the down quark heavier than the up quark?

• Why are neutrino masses small and probably not hierarchical?

• Is nature supersymmetric near the electroweak scale?

• How is supersymmetry broken?
- How is the hierarchy problem solved? Hierarchy stabilized? Size of hierarchy?
- How is the $\mu$ hierarchy solved? What is the value of $\mu$?
- Why is there a matter asymmetry?
- What is the dark matter? Ratio of baryons to dark matter?
- Are protons stable on the scale of the lifetime of the universe?
- Quantum theory of gravity?
- What is an electron?

▷ Why families? Why 3?
▷ What is the inflaton? Why is the universe old and cold and dark?
◊ Which corner of string/M-theory? Are some equivalent?
◊ Why three large dimensions?
◊ Why is there a universe? Are there more populated universes?
◊ Are the rules of quantum theory inevitable?
◊ Are the underlying laws of nature (forces, particles, etc) inevitable?
◊ CC problems?

The first question, what is light, is answered – if there is an electrically charged particle in a world described by quantum theory, the phase invariance requires a field that is the electromagnetic field, so it has a check, $\checkmark$. The next set, with the bullet, are all addressed in the compactified M-theory; some are answered. They are all addressed simultaneously. The next two, with the $\triangleright$, are probably also addressed in compactified string/M-theory. The last six are still not addressed in any systematic way, though there is some work on them.

The list is presented somewhat technically, but the idea is probably clear to most readers. Other readers might have a somewhat different list. I’d be glad to have suggestions. The most important point is that compactified string/M-theories do address most of the questions already, and will do better as understanding improves.

The compactified M-theory described below assumed that the compactification was to the gauge-matter content of the $SU(5)$ MSSM, the minimal supersymmetric Standard Model. Other choices could have been made, such as $SO(10), E_6, E_8$. So far there is no principle to fix that content. There are probably only a small number of motivated choices.

4 Three new physics aspects:

In compactified theories three things emerge that are quite important and may not be familiar.
• The “gravitino” is a spin 3/2 superpartner of the (spin 2) graviton. When supersymmetry is broken, the gravitino gets mass via spontaneous symmetry breaking. The resulting mass sets the scale for the superpartner masses and associated phenomena. For the compactified M-theory on a $G_2$ manifold the gravitino mass is of order 50 TeV. That is the scale of the soft-breaking Lagrangian terms, and thus of the scalars and trilinear couplings, as well as $M_{H_u}$ and $M_{H_d}$. It also can contribute to the dark matter mass. Two different mechanisms (described below) lead to suppressions of the gaugino masses from 50 TeV to $\sim 1$ TeV, and the Higgs boson.

• The second is “moduli”, which have many physics effects, including leading to a “non-thermal” cosmological history. The curled up dimensions of the small space are described by scalar fields that determine their sizes, shapes, metrics and orientations. The moduli get vacuum expectation values, like the Higgs field does. Their vacuum values determine the coupling strengths and masses of the particles, and they must be “stabilized” so the laws of nature will not vary in space and time. The number of moduli is calculable in string/M-theories (the third Betti number), and is typically of order tens to even over 200. In compactified M-theory supersymmetry breaking generates a potential for all moduli, and stabilizes them. The moduli fields (like all fields) have quanta, unfortunately also called moduli, with calculable masses fixed by fluctuations around the minimum of the moduli potential. In general inflation ends when they are not at the minimum, so they will oscillate, and dominate the energy density of the universe soon after inflation ends.

The moduli quanta couple to all particles via gravity, so they have a decay width proportional to the particle mass cubed divided by the Planck mass squared. Their lifetime is long, but one can show that generically the lightest eigenvalue of the moduli mass matrix is of order the gravitino mass, which guarantees they decay before nucleosynthesis and do not disrupt nucleosynthesis. Their decay introduces lots of entropy, and therefore washes out all earlier dark matter, matter asymmetry, etc. They then decay into dark matter and stabilize the matter asymmetry. That the dark matter and matter asymmetries both arise from the decay of the lightest modulus can provide an explanation of the ratio of matter to dark matter, though so far only crude calculations have been done along these lines. When moduli are ignored the resulting history of the universe after the big bang is a simple cooling as it expands, dominated by radiation from the end of inflation to nucleosynthesis, called a thermal history. Compactified string/M-theories predict instead a “non-thermal” history, with the universe matter dominated (the moduli are matter) from the end of inflation to somewhat before nucleosynthesis. All the above results were derived from the compactified M-theory before 2012.

Compactified string theories give us quantum field theories in 4D, but they give us much more. They predict generically a set of forces, the particles the forces act on, softly broken supersymmetric theories, and the moduli that dominate cosmological history and whose decay generates the dark matter and possibly the matter asymmetry.

• The third aspect is that because there are often many solutions we look for “generic” results. We have already used "generic" several times above. Generic results are probably not a theorem, or at least not yet proved. They might be avoided in special cases. One has to work at constructing non-generic examples. Importantly, predictions from generic analyses are generically not subject to qualitative changes from small input changes. Most importantly, they
generically have no adjustable parameters, and no fine tuning of results. Many predictions of compactified string/M-theories are generic, and thus powerful tests. When non-generic Kähler potentials are used, the tests become model-dependent and much less powerful.

5 Compactified M-theory on a $G_2$ Manifold (11-7=4)

Now we turn to looking at one compactified theory. Of course, I use the one I have worked on. The purpose here is pedagogical, not review or completeness, so references are not complete, and I apologize to many people who have done important work similar to what is mentioned. References are only given so those who want to can begin to trace the work. From 1995 to 2004 there was a set of results that led to establishing the basic framework.

- In 1995 Witten discovered M-theory.
- Soon after, Papadopoulos and Townsend (th/9506150) showed explicitly that compactifying 11D M-theory on a 7D manifold with $G_2$ holonomy led to a 4D quantum field theory with $N=1$ supersymmetry. Thus the resulting world is automatically supersymmetric – that is not an assumption!
- Acharya (th/9812205) showed that non-Abelian gauge fields were localized on singular 3-cycles. The 3-cycles can be thought of as “smaller” manifolds within the 7D one. Thus the resulting theory automatically has gauge bosons, photons and Z’s and W’s, and their gaugino superpartners.
- Atiyah and Witten (th/0107177) analyzed the dynamics of M-theory on $G_2$ manifolds with conical singularities and their relations to 4D gauge theories.
- Acharya and Witten (th/0109152) showed that chiral fermions were supported at points with conical singularities. The quarks and leptons of the Standard Model are chiral fermions, with left-handed and right-handed ones having different $SU(2)$ and $U(1)$ assignments, and giving the parity violation of the Standard Model. Thus the compactified M-theory generically has the quarks and leptons and gauge bosons of the Standard Model, in a supersymmetric theory.
- Witten (ph/0201018) showed that the M-theory compactification could be to an $SU(5)$ MSSM, and solve the doublet-triplet splitting problem. He also argued that with a generic discrete symmetry the $\mu$ problem would have a solution, with $\mu = 0$.
- Beasley and Witten (th/0203061) derived the generic Kähler form.
- Friedmann and Witten (th/0211269) worked out Newton’s constant, the unification scale, proton decay and other aspects of the compactified theory. However, in their work supersymmetry was still unbroken and moduli not stabilized.
- Lucas and Morris (th/0305078) worked out the generic gauge kinetic function. With this and the generic Kähler form of Beasley and Witten one had two of the main ingredients needed to calculate predictions.
- Acharya and Gukov brought together much of this work in a Physics Reports (th/0409191)
To extend previous work, we explicitly made five assumptions:

- Compactify M-theory on a manifold with $G_2$ holonomy, in the fluxless sector. This is well motivated. The qualitative motivation is that fluxes (the multidimensional analogues of electromagnetic fields) have dimensions, so are naturally of string scale size. It is very hard to get TeV physics from such large scales. There are still few examples of generic TeV mass particles emerging from compactifications with fluxes. Using the M-theory fluxless sector is robust (see Acharya referenced above, and recent papers by Halverson and Morrison, arxiv:1501.05965; 1412.4123), with no leakage issues.

- Compactify to gauge matter group $SU(5) - MSSM$. We followed Witten’s path here. One could try other groups, e.g. $SU(3) \times SU(2) \times U(1), SO(10), E6, E8$. There has been some recent work on the $SO(10)$ case, and results do seem to be different (Acharya et al 1502.01727). Someday hopefully there will be a derivation of what manifold and what gauge-matter group to compactify to, or perhaps a demonstration that many results are common to all choices that have $SU(3) \times SU(2) \times U(1) - MSSM$.

- Use the generic Kähler potential and generic gauge kinetic function.

- Assume the needed singular mathematical manifolds exist. We have seen that many results do not depend on the details of the manifold (see below for a list). Others do. There has been considerable mathematical progress recently, such as a Simons Center semester workshop with a meeting, and proposals for $G_2$ focused activities. There is no known reason to be concerned about whether appropriate manifolds exist.

- We assume that cosmological constant issues are not relevant, in the sense stated earlier, that solving them does not help find the properties of our vacuum, and not solving them does not prevent finding our vacuum. Of course, we would like to actually calculate the CC in the candidate vacuum or understand that it is not calculable.

We started in 2005 to try to construct a full compactification. Since the LHC was coming, we focused first on moduli stabilization, how supersymmetry breaking arises, calculating the gravitino mass and the soft-breaking Lagrangian for the 4D supergravity quantum field theory, which led to Higgs physics, LHC physics, dark matter, electric dipole moments, etc., leaving for later quark and lepton masses, inflation, etc. Altogether this work has led to about 20 papers with about 500 arXiv pages in a decade.

Electric dipole moments are a nice example of how unanticipated results can emerge - when we examined the phases of the terms in the soft-breaking Lagrangian all had the same phase at tree level, so it could be rotated away (as could the phase of $\mu$), so there were no EDMs at the compactification scale. Then the low scale phase is approximately calculable from known RGE running, and indeed explains why EDMs are much smaller than naively expected (0906.2986; 1405.7719), a significant success.

One can write the moduli superpotential (see below). It is a sum of exponential terms, with exponents having beta functions and gauge kinetic functions. Because of the axion shift symmetry only non-perturbative terms are allowed in the superpotential, no constant or polynomial terms. One can look at early references (Acharya et al, th/0606262, th/0701034, arxiv:0801.0478, arxiv:0810.3285) to see the resulting terms.

We were able to show that in the M-theory compactification supersymmetry was spontaneously broken via gaugino and chiral fermion condensation, and simultaneously the moduli were indeed all stabilized, in a de Sitter vacuum, unique for a given manifold. We calculated the soft-breaking Lagrangian, and showed that many solutions had electroweak symmetry breaking via the Higgs...
mechanism.
So we have a 4D effective softly-broken supersymmetric quantum field theory. It’s important to emphasize that in the usual “effective field theory” the coefficients of all operators are independent, and not calculable. Here the coefficients are all related and are all calculable. This theory has no adjustable parameters. In practice, some quantities cannot be calculated very accurately, so they can be allowed to vary a little when comparing with data.

6 Some Technical Details

Here for completeness and for workers in the field we list a few of the most important formulae, in particular the moduli superpotential, the Kähler potential, and the gauge kinetic function. Readers who are not working in these areas can of course skip the formulae, but might find the words somewhat interesting.

The moduli superpotential is of the form

$$W = A_1 e^{ib_1 f_1} + A_2 e^{ib_2 f_2}.$$  \(1\)

The \(b\)'s are basically beta functions. Precisely, \(b_k = 2\pi/c_k\) where the \(c_k\) are the dual coxeter numbers of the hidden sector gauge groups. \(W\) is a sum of such terms. Each term will stabilize all the moduli – the gauge kinetic functions are sums of the moduli with integer coefficients (written below) so expanding the exponentials a potential is generated for all the moduli. With two (or more) terms one can see in calculations that the moduli are stabilized in a region where supergravity approximations are good, while with one term that might not be so. With two we can also get some semi-analytic results that clarify and help understanding, so we mostly work with two terms, though some features are checked numerically with more terms. This is not a “racetrack” potential; the relative sign of the terms is fixed by axion stabilization. The generic Kähler potential is

$$K = -3 \ln(4\pi^{1/3} V_7)$$  \(2\)

where the 7D volume is

$$V_7 = \sum_{i=1}^{N} s_i^{a_i}$$  \(3\)

with the condition

$$\sum_{i=1}^{N} a_i = 7/3.$$  \(4\)

The gauge kinetic function is

$$f_k = \sum_{i=1}^{N} N_i^k z_i.$$  \(5\)

with integer coefficients. The \(z_i = t_i + is_i\) are the moduli, with real parts being the axion fields and imaginary parts the zero modes of the metric on the 7D manifold; they characterize the size and shape of the manifold.
Generically two 3D sub-manifolds will not intersect in the 7D space, so no light fields will be charged under both the Standard Model visible sector gauge group and any hidden sector gauge group, and therefore supersymmetry breaking will be gravity mediated in M-theory vacua. This is an example of a general result for the compactified M-theory, not dependent in any way on details of the Kähler potential. It is not automatic in other corners of string theory, and indeed often does not hold in others. The 11D Planck scale is

\[ M_{11} = \sqrt{\pi \frac{M_{pl}}{V_7^{1/2}}} \]  

and lies between the unification scale and the 4D Planck scale, which is related to the absence of fluxes. Acharya and Bobkov have calculated the cross term in the Kähler potential between the moduli and the matter sector; the only results currently sensitive to that are the Higgs mass and the precise value of the gravitino mass, and it has been included in their calculation (arxiv:1408.1961).

7 Main Results, Predictions, and Tests of the Compactified M-theory So Far, and In Progress

The results listed here follow from the few discrete assumptions listed above. Note that the results hold simultaneously. The only dimensionful parameter is the Planck constant, which is related to Newton’s constant G.

- All moduli are stabilized. Their vacuum expectation values (vevs) are calculated, and typically \( \lesssim \frac{1}{10} M_{pl} \). The moduli mass matrix is calculable and one can find its eigenvalues (th/0701034).

- The lightest moduli mass matrix eigenvalue has about the same mass as the gravitino, for general reasons (arxiv:1006.3272).

- The gravitino mass is calculated approximately to be about 50 TeV, starting from the Planck scale; see Figure 1 (arxiv:1408.1961).

- The supersymmetry soft-breaking Lagrangian is calculated at high and low scales. Scalar masses (squarks, sleptons, \( M_{Hu}, M_{Hd} \)) are heavy, about equal to the gravitino mass at the compactification scale. RGE running leads to the third family being significantly lighter than the first two at the electroweak scale, and \( M_{Hu} \) driven to \( \sim 1 \) TeV there (arxiv:0801.0478; 0810.3285).

- Trilinear masses are calculated to be somewhat heavier than the gravitino mass.

- Gaugino masses are always suppressed since the visible sector gauginos get no contribution from the chiral fermion F-terms. This is completely general and robust and just follows from the the supergravity calculations. Since the matter Kähler potential does not enter, the results are reliable. The suppression ratio is approximately the ratio of 3-cycle volumes to the 7D volume (in dimensionless units), so the gluino mass is about 1.5 TeV (\( \pm 10 - 15\% \)). The wino mass is about 640 GeV and the bino is the LSP, with a mass of about 450 GeV.(th/0606262)

- The hierarchy problem is solved as long as there are about 50 or more hidden sectors, which is generically true. That is, all solutions have gravitino masses in the tens of TeV. This is another result that does not depend on details or the manifold. Technically the number is
given by the 3rd Betti number, which Joyce has shown ranges from a few tens to somewhat over 200 (for non-singular manifolds) (th/0701034).

- When we set the potential to zero at its minimum by hand (since we do not solve the CC problem), we find the gravitino mass is in the tens of TeV region automatically. In other corners of string theory this does not happen.

- The cosmological history should be non-thermal, with moduli giving a matter dominated universe from soon after inflation until the lightest modulus decays somewhat before nucleosynthesis (arxiv:0804.0863).

- The lightest modulus generates both the matter asymmetry and the dark matter, and thus also their ratio. Calculations are consistent with the observed ratio but are very approximate at this stage (arxiv:1108.5178).

- No approach could be complete without including $\mu$ in the theory. Witten took the first step to do that (ph/0201018) by exhibiting a generic matter discrete symmetry that led to $\mu = 0$. But the moduli are generically charged under that symmetry, so it is broken when they are stabilized. We have not been able to calculate the resulting value of $\mu$ after moduli stabilization – it is not clear whether the original discrete symmetry is broken, or perhaps a new discrete symmetry emerges. We can make an estimate of $\mu$ because we know that $\mu$ should vanish if either supersymmetry is unbroken or if the moduli are not stabilized, so $\mu$ will be proportional to a typical moduli vev times the gravitino mass, implying $\mu \lesssim \frac{1}{10} M_3/2$ given the calculated moduli vevs. Thus $\mu$ will be of order 3 TeV (arxiv:1102.0556).

- Axions are stabilized (Acharya et al 1004.5138), giving a solution to the strong CP problem, and a spectrum of axion masses. The axion decay constant is allowed to be as high as about $10^{15}$ GeV.

- We calculated the ratio of the Higgs boson mass to the Z mass, or equivalently the coefficient $\lambda$ of the $h^4$ term in the Higgs potential (before the LHC data was reported). The calculation is done via the soft-breaking Lagrangian at the compactification scale, and then the results are run down to the electroweak scale (so there is no simple formula for $M_h$). One looks for all solutions that have electroweak symmetry breaking, and calculates the resulting $M_h$. Because the scalars are heavy, the theory is in what is known as the supersymmetry decoupling Higgs sector, so the Higgs mass is the same for all solutions, 126.4 GeV. Because the top mass is not measured precisely, and the RGE equations depend on the top Yukawa coupling (and $\alpha_3$ somewhat less), the running introduces an error of about 1.2 GeV purely from Standard Model physics. In the decoupling sector the Higgs boson properties are close to those of a Standard Model Higgs, so the branching ratios were predicted to be those of the Standard Model (to within a few percent, from loops), as is indeed observed. The Higgs potential is stable, with $\lambda$ never falling below about 0.1, so the vacuum instability is not an interesting question. The Higgs mechanism occurs because of radiative electroweak symmetry breaking and is generic.

The size of the Higgs vacuum expectation value is calculable as well, and it is one of the most fundamental quantities we want to understand. The mechanism for the Higgs getting a vev is fully understood. It is called “radiative electroweak symmetry breaking” (REWSB),
because radiative corrections lead to a Higgs potential with a minimum away from the origin, giving a non-zero vacuum value. One might think that because the gravitino mass and the scalars are tens of TeV that the predicted vacuum value would also be that size, but in fact the corrections lead to a weak scale value of $M_{H_u}$ of about a TeV near the weak scale, and as just described $\mu$ is at most a few TeV, so the naive REWSB would give a Higgs vev of a few TeV, a full order of magnitude smaller than the gravitino mass. This is an important success of the compactified theory. Further, the EWSB conditions imply a cancellation occurs. For a certain value of $M_{H_u}$, the theory would actually give the observed Higgs vev. The value of $M_{H_u}$ is given by an expression of the form $f M_0 M_0^2 - f A_0 A_0^2$, where $f M_0$ and $f A_0$ are fully calculable Standard Model physics. $M_0$ and $A_0$ are from the soft-breaking Lagrangian calculated from the compactification, and are calculated at tree level. $M_0$ and $A_0$ can have loop corrections and Kähler corrections, unfortunately, that are large enough so that the degree of cancellation cannot currently be determined. So the compactified theory might actually explain numerically as well as conceptually the Higgs vacuum value, but we don’t yet know. This can only work because the compactified theory predicted large trilinears, about 1.5 times the gravitino mass. That range had not been previously studied phenomenologically. In any case, the predicted value of the Higgs vacuum value is within about an order of magnitude of the observed value, so it is probably qualitatively understood, and not a mystery.

- Interestingly, electric dipole moments are calculable. At tree level the non-perturbative superpotential leads to all soft-breaking terms having the same phase, which can therefore be rotated away. Similarly, $\mu$ and $B$ have the same phase and a Peccei-Quinn rotation removes their phase. So at the high scale EDM's are approximately zero. When running the down to the weak scale non-zero EDM's are generated, with the phases entering via the Yukawa couplings in the trilinears. If those were completely known one could calculate the low scale EDM's precisely. Because there is still some model-dependence in the high scale Yukawas, we can only calculate upper limits on the EDM predictions. These are about a factor 20 below the current limits. Thus the compactified M-theory explains the surprisingly small EDM's, and provides a target for future experiments (arxiv:0905.2986; 1405.7719).

- There are no flavor or weak CP problems.

- Combining the electroweak symmetry breaking results and $\mu$, tan $\beta \approx 5$.

- LHC can observe gluinos, the lighter chargino, and the LSP. To see higgsinos and the scalars (via associated production with gluinos or winos) one needs a pp collider with energy near 100 TeV. (arxiv:1408.1961)

- Many results, such as the gravitino mass of 10’s of TeV; the heavy high scale scalars; the suppressed gaugino masses (gluinos, LSP); gravity mediation; small EDMs; and more are generic and do not depend on details of the manifolds.

- Our main current work is on dark matter. As we’ve discussed above the physics of the hidden sectors plays several roles. We live on one that is our visible sector. Others with large gauge groups have couplings that run fast, and lead to gaugino condensation and associated supersymmetry breaking at about $10^{14}$ GeV (the scale at which F-terms become non-zero). Others have small gauge groups so they run slowly, and condense at MeV or GeV or TeV scales, perhaps giving stable particles at those scales. We can calculate the relic density of
Figure 1: Figure showing the various scales in M-theory compactified on a G2 manifold, with the MSSM as the low energy effective theory.

those light particles, which must be done in a non-thermal universe in compactified M-theory (and probably in string-theory worlds in general). (arxiv:1502.05406) We are doing this systematically, expecting to find some dark matter candidates. The bino LSP will decay into these lighter stable “wimps”. We are looking at how generic kinetic mixing is in M-theory. While some people have looked at what they call “hidden sectors”, mostly what they look at are not actual hidden sectors of a compactified string/M-theory (they should probably be called hidden valleys to distinguish), and almost all of them have calculated the relic densities in a thermal history which is unlikely to be relevant for string/M-theory hidden sectors.

It’s interesting to put together the various results on scales to see how the physics emerges and is connected from the Planck scale to the gaugino masses and the Higgs mass. This is shown in Figure 1.

It’s worth emphasizing that the gluino (and wino, bino) mass prediction is not one “just above current limits”, or a tuned calculation. It is actually very generic and robust, and simple to
understand. F-terms are generated by gaugino (and chiral fermion) condensation, at about a scale \( \Lambda \approx 10^{14} \) GeV, a generic result of the theory, from the running of the largest hidden sector gauge groups. The superpotential is then the ratio of this scale to the compactification scale cubed, and the gravitino mass is the superpotential times \( e^{K/2} \); the latter factor is basically the inverse of the 3-cycle volume, as shown on the figure. The gaugino suppression is very general, because of the absence of the chiral fermion contribution to the gaugino mass since it is a derivative of the visible sector gauge kinetic function which has no dependence on the chiral fermion F-term (th/0606262). All this is illustrated in the figure, on the top half and the left side. The Higgs mass suppression is illustrated on the right side.

The gluino production cross section at LHC is 10-15 fb. Note that this is significantly smaller (because of the suppressed heavy quark contribution) than cross sections often quoted in the literature. Because the third family is lighter due to the RGE running, somewhat over half of the gluino decays are to third family final states, and the rest to first + second families. Those signatures make detection more difficult than most LHC studies report for a given gluino mass, and require larger luminosities than naively expected according to our background estimates, probably over 40 fb\(^{-1}\). The largest background is top pair production.

There is still of course a lot to do to complete the M-theory compactification, both the physics and the mathematics. It will be very interesting to try compactifications to other gauge-matter groups in M-theory, and to pursue other corners of string theory compactifications.

8 A Comment on Landscape and Multiverse Issues

There is clearly a landscape of string/M-theory solutions. The question is whether the resulting universes are viable ones, or too short-lived to have galaxy formation (with the resulting solar systems, etc. Some recent studies (Dine, Paban; Mersini, Perry; Greene et al; Shiu et al and others) suggest most of the landscape does not give viable universes. Even if there is a large landscape, compactification studies have demonstrated that it is not hard to find vacua that are good candidates for describing our world and calculating its properties (except maybe for the CC) – Quevedo and collaborators; Nilles and collaborators; Acharya, Kane and collaborators; Vafa, Heckman. Sometimes it is argued that in a landscape it will be hard to find our vacuum. It’s now clear that finding such candidates is not an obstacle to finding a final theory for our world.

9 Final Remarks

Here is a list of remarks. Some address the topics of the meeting, “Why Trust a Theory?”, some summarize points made about compactified string/M-theories, and some focus on the M-theory \( G_2 \) example. I want to emphasize again that this is not a review, and it has several pedagogical aspects. In particular, there are basically no references, but some are given (only to arXiv postings) in order to help people look further into topics they might want to pursue. There is some overlap among remarks since the point is communication rather than conciseness.

- String/M-theory is too important to be left to the string theorists.

- If you want an underlying theory that is a quantum theory and includes gravity and the other forces, and the quarks and leptons, a 10/11 dimensional theory with curled up small
dimensions is probably the simplest framework that could incorporate and explain all that you want to understand.

- The compactified M-theory on a manifold of $G_2$ holonomy is a promising candidate to describe our vacuum – this at least demonstrates that it is not premature to look for such theories, even in the presence of a landscape of solutions.

- Moduli are generically present in string theories and are inevitable in M-theory. They imply a non-thermal cosmological history and may explain the ratio of matter to dark matter.

- The compactified M-theory anticipated the mass and decay branching ratios of the Higgs boson. It is the lightest eigenvalue of the Higgs mass matrix of a two-doublet decoupling supersymmetric Higgs sector that satisfies the electroweak symmetry breaking conditions. The Higgs potential does not vanish at any scale, and the universe is metastable. The vacuum value of the Higgs field is not a mystery.

- The compactified M-theory predicts that superpartners are too heavy to have been seen in LHC Run I, but gluinos and winos and the LSP bino can be seen in Run II at 13 TeV with sufficient luminosity. Backgrounds for gluinos, mainly from top quark production, imply over 40 fb$^{-1}$ are needed to see the signal.

- The discovery of the Higgs boson is evidence for supersymmetry. In a supersymmetric full theory one computes the supersymmetry soft breaking Lagrangian at the compactification scale. It contains a potential for scalars. The RGE running down to the TeV scale implies that potential has a minimum away from the origin. One can calculate accurately the ratio of Higgs mass to Z mass, and gets 126.4 GeV for the Higgs mass that way. It does not depend on parameters. The calculation was done before the data, but the calculation is determined so the answer would be the same whenever it is done.

- Compactified string/M-theory imply naturalness predictions are wrong so superpartners should not have been seen in Run I. Some superpartners can be seen in LHC Run II with sufficient luminosity (gluinos, winos, binos). Full testing of the superpartner spectrum will require colliders with total energy in the 100 TeV region, and sufficient luminosity. The squarks can only be directly seen at such a facility, in associated production.

- The LSP will decay into lighter stable particles from hidden sectors. Such candidates are generic and probably inevitable. We are doing systematic studies of such dark matter in non-thermal cosmological histories.

- The statement that estimates of the cosmological constant are off by $10^{120}$ is a red herring, or worse. First, in supersymmetric theories the value of the potential at its minimum is generically $M_{3/2}^2 M_{pl}^2 \sim 10^{48}$ GeV$^4$. But this is the potential, and people think in terms of mass, so take the 4th root, giving $10^{12}$ GeV as the meaningful value. The Higgs potential and the QCD phase transition give similar values. Still not so good.

But the QCD strong CP problem requires setting a number naively of order unity to a value $10^{10}$ times smaller, almost the same! Why is there so much anguish over one and none over the other? Partly it’s because there are possible solutions to the strong CP problem, such as axions, and good models that solve it (like compactified string theories), while we
don’t understand the CC problem. But partly it is just hype. It is reasonable to think that the CC problem(s) are orthogonal to the rest of physics, in the sense that solving the CC problem will probably not help us solve the rest of the issues about understanding our vacuum, and not solving the CC problem probably will not prevent us from making progress with understanding our vacuum.

• Are string/M-theories falsifiable? Yes, in the same sense as traditional theories – one makes predictions from the compactified theories and tests the predictions. Such predictions are tests of the full underlying theory plus the gauge-matter compactification group. You do not have to be there to test whether there was a big bang, and you do not have to be at Planck scale energies to test string/M-theories formulated there. There are always relics and implications.

• Are 10D theories science? Yes, the curled up dimensions after compactification contain information about the forces and particles – such information is not lost, but characterizes the predictions. There are a number of predictions that test the theories, but not directly the 10D theories. What could it mean to test a 10D theory? Lots of people talk about that, but ask them what they mean.

• What does “empirically testable” mean for string/M-theories?
  – If it means project the the theory onto a 4D world, i.e. compactify, and find generic predictions, then it is well-defined, has been going on, and is the way traditional physics has worked. Compactified string/M-theories are not post-empirical science.
  – If it means including non-generic predictions with additional assumptions about (say) the Kähler potential, then it tests the cleverness of the people doing it as well as testing the theory, and is much less powerful.
  – If it is done for non-compactified theories it does predict a landscape of solutions, but it cannot address the issue of how many of those solutions lead to viable worlds that live long enough to contain planets. Even if the non-viable ones are not universes with people, perhaps they could still have an effect on the wave function of the universe as part of a superposition.

• Are string/M-theories forever beyond possibility of testing? For example, because they are formulated at energies too high to ever reach? No! Just as no one was at the Big Bang but every knowledgeable scientist knows it is well tested, by the universe’s expansion, by nucleosynthesis and the helium abundance, and by the embers of the Cosmic Microwave Background, and additional technical results. Are small extra dimensions a problem? No! The curled up dimensions contain lots of information that implies testable predictions for the compactified theories, particularly determining the forces and particles.

• Do string/M-theories exist? Can anyone define what they are? This red herring should not be taken seriously - recall that some of the main successes of quantum theory in the mid 1920’s were achieved before rigorous definitions of quantum theory were given.

• Sometimes people say wrongly that the Standard Model offers no path forward. In fact it tells us to focus on theories beyond the Standard Model that contain Yang-Mills gauge forces, quarks and leptons with hierarchal masses, one and only one fermion with a large Yukawa coupling of order gauge couplings, gravity, etc.
• Is string/M-theory "the only game in town", Dawid’s NAA? It’s important to only consider games that are comprehensive and include all the issues – not only gravity, but all the Standard Model forces, existence of quarks and leptons, dark matter, a cosmic matter asymmetry, electroweak symmetry breaking, a stable hierarchy of the right size between atoms and the Planck scale, etc. Compactified string/M-theories are known to address all these issues, and indeed nothing else is known to do that, not even close.

• Dawid’s unexpected explanatory power argument is very strong. One of the best examples is supersymmetry, which was introduced for theoretical reasons, but turned out to provide possible explanations for the hierarchy problem, electroweak symmetry breaking, dark matter, matter asymmetry and more. The unexpected explanatory power of string theory is impressive too – look at the issues addressed by the compactified M-theory above.

• One can think of Dawid’s book as describing how physicists use theory assessment at a given stage in order to decide what to work on. It does that very well. Or, one could think of it as describing how non-physicists might evaluate the work of physicists (from the general public to philosophers). Then one could imagine controversy. It holds up well, with much of the confusion arising from books and articles and blogs that don’t understand the string/M-theories, and that don’t understand that only compactified theories can make contact with our world.

Acknowledgements

I’m grateful to my collaborators over the past decade on compactified M-theory, particularly Bobby Acharya and Piyush Kumar as well as Konstantin Bobkov, Sebastian Ellis, Eric Kuflik, Ran Lu, Jing Shao, Scott Watson, and Bob Zheng; to David Gross, Brent Nelson, Malcolm Perry, Joe Polchinski and others for discussions; and to Richard Dawid, Slava Mukhanov, and Gia Dvali for their hospitality at the meeting.