

Connecting String Theory and Phenomenology

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Abstract

To make progress in learning the underlying fundamental theory, it will be necessary to combine bottom-up phenomenology and top-down analysis — in particular, top-down is unlikely to succeed alone. Here I elaborate on the role of both, and describe obstacles that need to be overcome to help data point toward the underlying theory, as well as approaches that might help to bypass full systematic treatments. I also summarize arguments that superpartners are probably being produced at the Tevatron Collider.

1 Introduction — Top-Down and/or Bottom-Up?

The central problem in particle physics continues to be understanding the physics of electroweak symmetry breaking (EWSB). Basically that means finding and studying the Higgs boson(s). Equally importantly we need to confirm (or not) that weak scale supersymmetry is an essential part of our low-scale world. Then the central problems become understanding the physics of supersymmetry breaking, and learning about the underlying, more fundamental, theory at the high scale, where forces unify.

I expect there will be little progress toward these goals without experimental data. Top down approaches are seldom successful in physics. One might think that theorists only need to write down string theories, try out compactifications, get a 4D effective field theory below the Planck scale, calculate predictions for low scale phenomena, and soon have the basic answer. Unfortunately, carrying out such a process is much more difficult than it first seems to be. Essentially any prediction for data, or understanding of masses, requires knowing $\tan\beta$, the ratio of the two Higgs vevs. But $\tan\beta$ does not exist in the high scale theory. It only arises as the EW symmetry is broken, as one approaches the low scale. $\tan\beta$ must be calculated, and depends on many aspects of the high scale theory being correct. The origin of μ is equally important. In my view a major success of superstring theory is that $\mu = 0$ occurs naturally in the superpotential because μ enters as a mass term and the low-scale theory is formulated from the string zero modes. Because of the non-renormalization theorem this is stable. But once supersymmetry is broken a μ -term will be generated, perhaps by the Giudice-Masiero mechanism, or as a vev of a scalar field. In the former case the relevant contributions can occur as non-renormalizable contributions in the Superpotential or Kähler potential, terms that may not appear in lowest order and tree level. μ enters into many predictions, for the Higgs sector, for chargino and neutralino and sfermion masses and production cross sections and decay branching ratios, and more. If the origin of μ is not understood, a top-down approach will not be fruitful. In a top down approach the two equations from minimizing the Higgs

potential and requiring it be bounded from below would be used to calculate m_Z and $\tan\beta$ in terms of μ, m_{H_u}, m_{H_d} , and b , these four quantities all being determined by the underlying theory.

One might think there are sectors for which predictions might be made, such as the gluino mass, that do not depend on $\tan\beta$ or μ . But it is more complicated. Many parameters get connected by the needed RGE running, which introduces dependence on squark masses, trilinear couplings A , and b (the soft parameter coefficient of $H_u H_d$). b is very important in determining $\tan\beta$, and its RGEs depend strongly on the trilinear couplings and gaugino masses. If any of these are not known it is not possible to make useful low scale predictions. Further, many of the soft parameters can be complex, and we now know that their phases can have large effects on not only CP violating phenomena but also on mass eigenvalues, production cross sections, decay branching ratios, virtual effects, etc. So the top-down approach must also include an understanding of the phases and the origins of CP violation, not only as a matter of principle but to do practical calculations. One might think that one could calculate charged lepton masses. The electron mass is too small to be meaningfully predicted — it is sensitive to many corrections from non-renormalizable operators and loops. Conceivably an approximate calculation of the ratio m_μ/m_τ could make sense, but it has some dependence on non-renormalizable operators, $\tan\beta$, trilinears, RGEs, etc.

So top-down approaches can and will be very important for guiding thinking, but are unlikely to lead to detailed serious predictions that really test the stringy ideas, even at the level of the 4D field theory, since it will be necessary to make assumptions in order to get predictions. Then it is the assumptions that are being tested too (or mainly).

What about bottom-up? It will be very exciting when superpartners are found, and it will tell us low scale supersymmetry is indeed the right direction for increased study, which knowledge is greatly needed. But it is crucial to realize that experimenters measure only information about masses of mass eigenstates, from kinematics of particles that enter the detector, and cross sections (times branching ratios). Of all the observables that can be measured, only one occurs in the Lagrangian a theorist would write, and that only approximately (the gluino mass). The next stage is to study the pattern of superpartner properties to learn about the underlying theory. That will not be so simple — experimenters cannot communicate with string theorists, and vice versa, because they do not share a common language. Telling a string theorist a chargino mass or cross section will be of no use — those quantities are not in the theory directly, and we saw above that it is very unlikely there will be serious calculations for them. Telling an experimenter the high scale Lagrangian will not help with a comparison of theory and data.

So it will be necessary to deduce the low-scale Lagrangian from the low-scale data in order to connect experiment with theory. Unfortunately, that cannot in general be done! Every observable can be expressed in terms of a set of complex Lagrangian parameters, such as the gaugino masses, μ , squark masses, etc. There is also always a dependence on $\tan\beta$. By simply counting one can see that at any hadron collider the number of observables is always less than the number of Lagrangian parameters, so the equations cannot be inverted to solve for the parameters. Indeed, this is the most important reason why we need lepton colliders with polarized beams — with polarization one can double the number of measurements for non-zero cross sections, and add additional observables by running

at two different energies (since the coefficients in the equations relating observables and Lagrangian parameters depend on energy).

At the Tevatron, which is all we will have for at least five years from this conference, the situation is worse because the Tevatron and its detectors are luminosity-limited, even assuming Fermilab can get it to work as well as was planned. And by their very nature superpartners do not give dramatic signals because every event has two escaping LSPs, so no kinematical variable can show a dramatic peak of the sort that made W and Z discovery relatively easy. Indeed, that is a testable prediction of supersymmetry. Instead, in several channels an excess of events will slowly accumulate. Probably no single signal will be statistically significant.

Of course, the basic lesson of the introduction is that top-down and bottom-up approaches are complementary, and must be merged to make progress.

2 Learning the Low-Scale Theory

In practice we may be lucky, and find that some parameters put us in a region of parameter space where measurements are possible. For example, if $\tan\beta$ is very large it may be possible to observe $B_s \rightarrow \mu\mu$ at the Tevatron and therefore get a measurement of $\tan\beta$. Data from the Higgs sector, the way the electroweak symmetry is broken, how the hierarchy problem is solved, gauge coupling unification, the absence of LEP signals, rare decays, cold dark matter detectors, $g_\mu - 2$, proton decay, the neutrino sector, and other non-collider physics will be very important to combine with collider data to make progress.

The key point is that since supersymmetry is a real theory it is possible to calculate its predictions for many processes and use them all to constrain parameters. Because of this even at hadron colliders the situation may not be so bad. By combining information from several channels each with almost-significant excesses we can learn a lot about the parameters and, more importantly, the basic theory. For example, the following table shows how different forms of supersymmetry breaking and mediation lead to qualitatively different “inclusive signatures”.

Inclusive Signatures	\tilde{GMSB} , <u>large μ</u>	\tilde{GMSB} , <u>small μ</u>	$GMSB$, <u>low scale</u>	Unstable <u>LSP</u>	Gluino <u>Condensation</u>	<u>$\langle D \rangle$</u>
Large E_T	yes	yes	yes	no		
Prompt γ 's	no	sometimes	yes (but...)	no		
Trilepton events	yes	no	no	no		
Same-sign dileptons						
Long-lived LSP						
τ - rich						
b - rich						

One can add both rows and columns — this is work in progress. This approach also shows how to combine top-down and bottom up approaches — one uses top-down analysis to identify the columns and fill in the missing entries in the table. By simply identifying qualitative features of the channels with excesses one can focus on a few or even one

type of theory. Then detailed study can let one zoom in on the detailed structure of the underlying theory and its high energy features. With such an approach one can partly bypass the problem of not being able to fully isolate the Lagrangian explicitly. One will not be able to prove that specific superpartners are being observed with this “inclusive” analysis, but we can gamble and leave the proof for later. In this table \tilde{G} stands for gravitino, and \tilde{GMSB} for gravity-mediated supersymmetry breaking, $GMSB$ for gauge-mediated supersymmetry breaking, $\langle D \rangle$ for supersymmetry breaking by an D-term vev, etc. The key point is that each inclusive observation allows one to “carve” away part of the parameter space, and the remaining parts point toward the underlying high scale theory. One does not need to measure every soft parameter to make progress, because the patterns, the mass orderings, etc., imply much about the underlying theory — if one understands the theory.

Can we make progress while we know so little about string theory and how to find its vacuum state, and with very limited data? Perhaps history can provide guidance here. At the end of the 1960s particle physics was widely viewed as being in bad shape, with little hope for significant progress. Three years later the Standard Model existed, and most active workers were convinced it was correct. The progress was based on some seemingly isolated theoretical results, including Yang-Mills gauge theories, the Higgs mechanism, the Glashow electroweak model and the Weinberg lepton model, plus clues from the hadron spectrum. The experimental results were the knowledge that weak interactions occurred via V,A currents (rather than S,P,T), parity and charge conjugation violation (i.e. chiral fermions), knowing the weak interactions were weak, and the SLAC deep inelastic scattering data that implied constituents in the proton. It all fell into place with the proof of the renormalizability of the electroweak theory and asymptotic freedom. We may be in a similar situation once the existence of Higgs bosons and light superpartners is confirmed at the Tevatron. Sometimes people say we know too little about string theory to try to do phenomenology with it. I think it is the opposite — only if we learn from phenomenology what region of string theory space to focus on are we likely to make progress.

3 Obstacles

But there are a number of obstacles that can obscure the connection between low-scale data and low-scale theory, and the connection to the high-scale theory. These obstacles can be at least partly overcome by theoretical study — this is a fruitful area for research, particularly now that we are close to getting the data. Here I will list a number of obstacles and sometimes comment on how they might be studied.

- Most theories have intermediate scale matter[1, 2] that can affect RGE running even though the theory remains perturbative up to the high scale. We have to learn how to find ways to run up that are not sensitive to the intermediate scale matter, or find checks such as running two different ways that would give the same answer without intermediate scale matter but differ in its presence, or find other ways to either learn about such particles or bypass them. For example, some types of intermediate scale matter increase the fine-tuning needed to explain EWSB, so they can be excluded.

- We don't know at what scales to start or end RGE running. In general the supersymmetry breaking scale will be different from the mediation scale. In string theories in general the string scale is different from the unification scale or the compactification scale. Certainly the literature is not consistent on this issue. Model studies should be carried out that clarify how to proceed in practice. Phenomenological results are certainly sensitive to these scales. In general we can expect patterns to emerge that will help settle such questions.
- Infrared fixed points[3, 4] would make it difficult to deduce high-scale quantities. This occurs when a range of high-scale input parameters flow to the same low-scale value, so a measurement of the low scale value implies a range of high-scale values. An important conclusion[5] is that accurate low-scale measurements, such as can be obtained at linear colliders, will be important for deducing the high-scale theory. Further theoretical study is needed to learn how to combine measurements to avoid the ambiguities. The philosophy of fixed points is interesting. Some people view them as a good thing because one can predict or understand a low scale result even if we do not know the high scale theory. But actually it is the opposite — we want to learn the underlying high scale theory, so we need to get around fixed point behavior.
- Most soft terms can be complex[6, 7]. While there are constraints on their phases, suggesting some may be small, the phases may affect many observables such as the Higgs sector, superpartner cross sections, etc. If they are present but not included in analysis wrong conclusions will be drawn. EDM data, and the apparent success of the SM description of CP violation in the K and B systems, suggest the soft phases are small, but no known symmetry or principle implies that the soft phases should be small, so care is needed in how phases are included (or not included).
- Additional U(1) symmetries under which visible sector particles are charged may lead to D-terms[8] that affect scalar masses even though the U(1) symmetry is broken at a high scale. That can shift sfermions, and in particular $M_{H_u}^2$ and $M_{H_d}^2$, thus changing the way EWSB works, and therefore leading to changes in μ , gaugino masses, CDM relic density and detectability, etc. Conversely, from the observed pattern of scalar masses once superpartners are observed it may be possible to deduce their U(1) charges and learn about the high-scale U(1)s.
- The theory may have an extended gauge group, i.e. a grand unification, and/or extra U(1)s. This can also lead to extra soft terms, larger mass matrices for neutralinos and for the Higgs sector, new gauge couplings, kinetic mixing, etc. If one does not include the larger gauge group in the analysis (because one does not know about it) the result may be misinterpretation of low-scale data and its implications. For example, the trace of the neutralino mass matrix is the sum of its eigenvalues. If it is 5x5 instead of 4x4, with an extra soft term M'_1 , then the true trace would be $M'_1 + M_1 + M_2$ but this would be interpreted as just $M_1 + M_2$, so one would deduce incorrect values for M_1 and perhaps for M_2 . One can develop consistency checks to detect such departures from the simplest theories.

- High scale threshold corrections must be made, but of course cannot be made until the high scale spectrum is known. So their effects must be included in a way that allows them to be determined and does not lead to wrong conclusions about the implications of low energy phenomena.
- In general there will be non-renormalizable operators that affect small Yukawa couplings and therefore the CKM phase, calculation of $\sin^2 \theta_W$ and other precision data, etc. If such operators are present it will be necessary to rescale gauge couplings and gaugino masses and even the ratio M_a/g_a^2 , if the gauge kinetic function and the Kähler potential have such operators.
- The Kähler potential can have flavor-dependent contributions that affect Yukawa couplings and thus the CKM angles and phase, and trilinear couplings, and thus the analysis of rare decays and lepton flavor-violating effects.

More obstacles can be listed. Perhaps it is best to think of them not as obstacles but as opportunities for research. By proceeding with a judicious combination of study of patterns in data and clues, plus models and top-down analysis, it may be possible to deal with the obstacles so they do not prevent progress toward learning the underlying theory.

4 Superpartners

If we are sure that low energy supersymmetry is part of the description of nature, the absence of effects in some processes contains a huge amount of information. So once direct evidence for the light Higgs sector and a few superpartners is obtained, we can draw many conclusions about the form of supersymmetry breaking and mediation, and the structure of the underlying theory and its stringy nature, not only from what is explicitly seen but also what is absent. Where are the superpartners? Is there reason to expect them to be found experimentally? This is of course an old question, which we revisit. We are motivated by the absence of superpartners at LEP on the one hand, and by increased theoretical understanding of supersymmetry theory on the other.

Should superpartners have been observed at LEP, or in Run I at the Tevatron? What emerges from study of modern models is that superpartners might have reasonably been in the LEP or Run I parameter region, but we would have been lucky if they were, in the sense that much of the reasonable parameter space puts the superpartners somewhat above those regions — for LEP it is the energy cutoff, while for the Tevatron it is the luminosity that was and is limited.

What do we know that can set a mass scale for superpartner masses? From a purely theoretical side we would have to understand supersymmetry breaking to set that scale, and our knowledge of the mass spectrum that would result from supersymmetry breaking is far from implying any particular mass scale for superpartners. We must use some physics input. We could of course just ignore the question and wait, but our view of what masses to expect can significantly affect what resources are available for the search, and what methods are used.

What physics do we know that is relevant? First, the value of m_h^2 is sensitive to the scale of new physics and essentially rises to that scale. Qualitatively this is the hierarchy problem, and tells us that the new physics, presumably the superpartner masses, are “around a TeV”, rather than tens of TeV or much higher, but is not quantitative enough to distinguish a TeV from 100 GeV.

Second, gauge coupling unification implies light superpartner masses and small μ . The latter is sometimes forgotten, but μ enters chargino and neutralino and squark and Higgs masses, so it significantly affects the gauge coupling running and the location of the thresholds where the supersymmetry beta functions enter the running. But again the results are not quantitative enough to pin down the superpartner masses within an order of magnitude. If the LSP is indeed the CDM then getting the right relic density provides constraints on the soft parameters, but there is a large range of parameters that give the right relic density, and we do not know how much of the relic density is the LSP.

It turns out that the only thing we know that quantitatively relates the soft masses to a measured number is radiative electroweak symmetry breaking, REWSB. *IF* supersymmetry indeed provides the explanation for how the electroweak symmetry is broken, to allow fermion and gauge boson masses, then it provides an equation relating M_Z to soft masses,

$$M_Z^2 = -2\mu^2 + 2 \left(\frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} \right) \quad (1)$$

at tree level. This is the only presently known connection of the supersymmetry parameters to data that is precise enough to be useful, and is extremely important, though not yet well understood. One can rewrite this in a useful form by expressing the quantities on the right hand side, which are here evaluated at the weak scale, in terms of high scale input. We do that in the general MSSM, with the full soft Lagrangian and no assumptions about gaugino or squark mass degeneracies, obtaining[12]

$$M_Z^2 = -1.9\mu^2 + 6.9M_3^2 - 0.3M_2^2 + 0.01M_1^2 - 1.2m_{H_u}^2 + 1.6M_Q^2 + \dots \quad (2)$$

Here the soft masses (and μ) are evaluated at the unification scale. This equation is written for $\tan \beta = 5$.

IF supersymmetry does indeed explain the origin of M_Z , we would naively expect none of the terms on the right hand side to be much larger than M_Z^2 . Accidental cancellations do not explain basic results in physics. That implies upper limits on M_3 , μ , etc. The limits are a little soft, but it turns out that because the coefficients are large even letting each term be a few M_Z^2 still leads to important upper limits on the superpartner masses. In the past people have gone through such reasoning and deduced that very light superpartners should exist. When they were not found at LEP people got confused about the arguments. But the past arguments were based on using assumed degeneracies. If the three gaugino masses are taken equal, $M_3 = M_2 = M_1 = M_{1/2}$, then the first three terms combine into $6.6 M_{1/2}^2$ so that $M_{1/2}$ is expected to be quite small, implying very light charginos and neutralinos that do not exist. Here we see that without the degeneracy assumption there

are essentially no restrictions on M_1 and M_2 , so the absence of charginos and neutralinos at LEP should not be thought to be evidence against the argument based on REWSB, but rather evidence against gaugino mass degeneracy.

Sometimes people think gaugino mass degeneracy is implied by gauge coupling unification. But that is not so. Our best theoretical guide[2, 9] to such questions is to ask what happens in string theory. While tree level gaugino masses are often degenerate, they are often suppressed in string theories (see[9] and references therein). The one-loop corrections are typically not degenerate and then lead to non-degenerate gaugino masses. At the same time, the gauge coupling leading contributions are not suppressed, so loop effects are small, and the leading contributions unify. More theoretically, M_a and g_a^2 arise from vevs of different components of the dilaton multiplet, so there is no general connection at all. Sometimes people argue that the RGE invariance of M_a/g_a^2 implies gaugino mass degeneracy, but again it only holds at tree level. Phenomenologically one can make a strong statement. As remarked above, gaugino mass degeneracy plus some constraints on fine tuning imply that M_1 and M_2 are light enough to be inconsistent with the absence of charginos and neutralinos at LEP. Thus gaugino mass degeneracy requires large fine tuning.

Are there possible loopholes that would allow one to evade the conclusion from equation 2 that M_3 and μ must be at most about M_Z in size? We[2] have recently pursued this question, both by examining models and by looking at how stringy approaches behave. It seems sensible to make stringy models by making plausible assumptions when needed, and examine how they explain EW symmetry breaking. Basically we find that μ and the various soft masses arise in such different ways physically that cancellations are extremely unlikely even in very general frameworks. One can see that the variation with m_{top} is small, and the variation with $\tan\beta$ is mild for $\tan\beta \gtrsim 4$. There are essentially four possibilities to discuss.

1. Could μ and M_3 be related so that their contributions cancel in the calculation of M_Z ? Answering that requires an understanding of how μ arises. One of the phenomenological successes of supersymmetric string theory is in setting μ to zero naturally at the unification scale. Then μ can arise by a Giudice-Masiero like mechanism, from terms in the Kähler potential or non-renormalizable terms in the superpotential, or alternatively μ can arise from NMSSM type models where a scalar gets a vev, or stringy generalizations where scalars in non-renormalizable operators get vevs. Either way if one writes examples one sees that μ depends on very different physics from M_3 . Particularly when one looks in examples with gauge coupling unification one finds that it is extremely hard to imagine any robust cancellation between M_3 and μ .
2. Could there be cancellations among soft terms, either among gaugino masses or between gaugino masses and scalars? A cancellation among gaugino masses would require a huge non-degeneracy since the sizes of their contributions to M_Z are so different. If the sizes are made less different by reducing M_3 that would give a light gluino as needed. What about the scalars and M_3 ? Again, that would require a large scalar non-degeneracy. More generally, one can see that the soft parameters are affected by supersymmetry breaking and by how the breaking is transmitted,

introducing at least two mass scales. Or one can think of it in terms of dilaton dynamics (which strongly affects gaugino masses) and moduli dynamics (which strongly affects scalar masses). To have a significant cancellation would require special relations among these separate parts of the theory. If one thinks in terms of parameters, there would have to be a special relation among $m_{3/2}$, dilaton vevs, and moduli vevs.

3. Can the coefficients be made smaller? Yes. For example, one can run down from a lower scale, in which case the coefficient of M_3 is smaller. Or include various amounts of intermediate scale matter in such a way as to reduce the coefficients. But first, the coefficients do not get small, just smaller. More important, examining any particular approach that reduces the coefficients shows that the same physics also leads to lighter superpartner masses. For example, in the MSSM run down from the usual unification scale one finds the physical gluino mass $m_{\tilde{g}} \approx 3M_3^{UNIF}$, while if one reduces the coefficient of M_3 from 6.9 by a factor of 10, allowing a larger M_3 for a given amount of fine tuning, the physical gluino mass in the reduced coefficient case turns out to be $m_{\tilde{g}} \approx 0.4M_3^{UNIF}$. Thus the physical gluino is again light.
4. Another argument that superpartners are heavy compared to what is detectable at the Tevatron, or even at a 500 GeV linear collider, has emerged with the construction of so-called benchmark models in recent years. For example, only one of the widely publicized Snowmass models[10] has superpartners light enough so they may possibly be detectable at the Tevatron. If such a result is generic it would be important. Fortunately, it is not generic. We[9] have constructed some models that are well-motivated theoretically, based on the heterotic string. Of course one cannot yet derive the needed compactifications or deduce how supersymmetry is broken, but one can assume plausible mechanisms that could happen, and specialize to concrete models. We find sets of models that have less fine tuning than the minimal SUGRA type Snowmass or CERN[11] models, and in particular have light enough gauginos so that some can always be detected at the Tevatron (and at a 500 GeV linear collider). The bottom line is that the concrete models that have been previously constructed are, for historical reasons, a very special set. They can only accommodate EWSB by having large cancellations, which casts doubt on their relevance. They may also be misleading for their implications for collider signatures and background studies. They do not imply that nature's superpartners are heavy compared to what can be seen at the Tevatron.

5 Summary

From the points made here we can conclude that if superpartners are not produced at the Tevatron it is rather unlikely that supersymmetry and the usual radiative mechanism is the actual explanation for electroweak symmetry breaking. Then the constraints on superpartner masses are very weak. Gauge coupling unification depends on the same conditions as radiative EWSB, requiring μ and soft masses at the TeV scale, though it depends on the masses logarithmically rather than quadratically. Nevertheless, if super-

partners are not produced at the Tevatron it is interesting to consider what arguments imply they should be seen at LHC.

If superpartners are observed at the Tevatron as should be expected, then considerable analysis and good thinking will be needed to deduce the Lagrangian at the weak scale from the measured masses and cross sections and branching ratios. Further innovative thinking and analysis will be needed to learn the unification scale Lagrangian, and to deduce properties of supersymmetry breaking and mediation from the low scale information. In both cases there are important research opportunities. Combining inclusive analysis of collider signals with information from rare decays, dark matter, neutrino physics, proton decay, baryogenesis, dipole moments and more may allow us to bypass many apparent obstacles. One can imagine that it will be possible to guess the supersymmetric Standard Model from the resulting analysis, then the 4D effective string field theory, and perhaps even the 10D string theory.

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