Exciting Implications of LHC Higgs Boson Data

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Abstract

Naively, the LHC Higgs boson looks like a Standard Model Higgs boson, with no guidance to physics beyond the Standard Model, as has often been remarked. The data show that what was discovered is the true Higgs boson. If one includes the full information available, experimental and theoretical, there are actually four significant clues implied by data. They point toward a supersymmetric two-doublet decoupling theory, and a hierarchy problem solution via TeV scale supersymmetry. That in turn suggests an underlying compactified string/M theory with a de Sitter vacuum, so we can be confident that the low scale model has an ultraviolet completion.

1 INTRODUCTION

Nature has played an amusing and challenging trick on us. The Higgs boson discovered at LHC in 2012 seems to be a Standard Model one, if one looks at it’s decay branching ratios (at the current level of precision). But of course it cannot be a Standard Model one because of the hierarchy problem. Fortunately, there is a well-known supersymmetric model that looks like the Standard Model. For those who actually want to figure out what the Higgs boson is telling us, there are four major clues.

Before listing the clues, it is worth making some remarks. Most importantly, we know that what was discovered is the actual Higgs boson, because the decays $h \to ZZ$ and $h \to W^+W^-$ are observed at full strength. Both decays are forbidden in the Standard Mode, (because the $Z$ and $W$ are in electroweak triplet states, while $h$ is in an electroweak doublet, and two triplet states cannot be combined to make a doublet). The true vertex must be $hhZZ$ or $hhWW$,

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with one $h$ getting a vacuum expectation value (vev). The production rates are also full strength. Thus we learn that the Higgs mechanism is operating, and the size of the Higgs vev is full strength. None of the vev is distributed among other Higgs states. Of course, the data has error bars, so the quantitative remarks should be qualified by waiting for the data on $ZZ$ and $WW$ branching ratios to improve.

It did not have to come out that way. There could have been several Higgs states sharing the Higgs vacuum values. Perhaps they would have been directly seen, or the $ZZ$ or $WW$ branching ratios would have been somewhat smaller. Current error bars still allow some sharing. There could have been light Higgs partners observed.

Clue 1. In the minimal supersymmetric world there is an upper limit on the Higgs boson mass of at most about 130 GeV, which is satisfied for the observed Higgs mass. The tree level lightest eigenstate is less than $M_Z$ and with top loop radiative corrections its mass increases up to about 130 GeV. The observed Higgs boson mass is indeed lighter than that limit.

Clue 2. In a supersymmetry world with low scale superpartners the hierarchy problem is solved. That would hold here if gauginos were around the TeV scale. That is still a possible result.

Clue 3. The well-known model \[1,2\] with large soft Higgs mass terms and two Higgs doublets, satisfying the electroweak symmetry breaking conditions, has one light Higgs eigenstate, two heavy neutral states, and a heavy charged pair. It automatically has decay branching ratios that are very close to the Standard Model ones, just as the data does. This is called the decoupling solution, and has been familiar for over two decades. Such a solution arises naturally in some UV complete theories, as we will briefly discuss below.

Clue 4. The fourth clue is more subtle. For a single Standard Model Higgs boson the effective Higgs potential is $V = \mu^2 h^2 + \lambda h^4$. In the Standard Model $\lambda$ can run to go negative at larger scales, so the potential becomes unbounded from below, and there is no resulting world. Most people reacting to this situation have shrugged and said probably the universe would be long lived so the instability can be ignored. But it was pointed out \[3-7\] that without vacuum stability, fluctuations in the Higgs field during inflation and in the hot early universe would have taken most of the universe into an anti-De Sitter phase, giving a massive collapse, and the expansion of the universe would never have occurred. The point was basically raised explicitly in 2008, and there was some uncertainty in how to properly calculate, over several years. Probably it was settled by the significant paper \[7\] in 2017. The result is that for generic expectations for the Hubble parameter during inflation, the Higgs field fluctuations generated during inflation, or the hot, high density early universe, probe the instability region, take most of the universe into the unstable AdS phase, so the usual expansion of the universe fails to occur. Thus the message is that the apparent instability is not acceptable, and new physics must arise to stabilize the vacuum. In supersymmetry $\lambda$ is determined by the gauge couplings $\lambda = (g_1^2 + g_2^2)/8$, and is positive definite, so the vacuum stability is automatic.
2 IMPLICATIONS - LOW SCALE THEORY

First, it is important to realize that there is a phenomenological Higgs sector that behaves in a way consistent with the above clues. It is the Higgs sector expected in a two Higgs doublet supersymmetric world, and has long been known [1,2] to have these features. In a world with the terms of the soft-breaking Lagrangian large, and thus the terms of the Higgs potential large, and also the electroweak symmetry breaking conditions (needed for allowing mass and for describing Z and W masses correctly) satisfied, the Higgs boson mass is calculable and the Higgs decay branching ratios are predicted to be very close to the Standard Model ones. Actually, it is the ratio of the Higgs boson mass to the Z mass that is calculable with precision. The electroweak symmetry breaking conditions for two doublets implies that \( M_h \lesssim M_Z \).

The one top loop quantum corrections raise the Higgs boson mass to about 125 GeV for heavy soft-breaking terms. In the supersymmetric case the coefficient of the quadratic term in the potential, \( \lambda \), is calculable in terms of the gauge couplings and is positive definite, so there is no vacuum stability issue. The hierarchy problem is solved as usual in a supersymmetric theory. It’s well known that the two doublets rearrange into one effective doublet that decouples, and one that is like the Standard Model doublet.

It’s very encouraging that a simple low-scale model exists that describes the data well without any adjustable parameters, reported before the LHC data [8]. It predicts four extra states, a heavy charged pair, a second heavier CP even state, and a heavier CP odd state. None of them could be detectable at planned electron-positron colliders or LHC upgrades, but they could probably be seen at a future hadron collider with an energy several times that of LHC. The model predicts that there are deviations from the Standard Model h decay branching ratios, but they are at most a few per cent in size, coming from chargino loops, so they are probably too small to detect.

The value of the Higgs boson mass is an interesting topic. The mass is measured very well (\( M_h \approx 125.11 \pm 0.35 \text{GeV} \)) depending on how one combines errors. That is better than one can ever hope to calculate it theoretically. When we calculate it [8] we first work at the high scale, string scale or unification scale. We calculate the soft breaking Lagrangian and the resulting Higgs potential, and therefore the coefficient \( \lambda \) of the quartic term. We match that to the effective theory at an appropriate scale, e.g. the geometric mean of the stop mass eigenstates, integrate out heavier scalar states, and run to the top scale. The squark masses are required to be a few tens of TeV by the compactified theory. People have calculated two loop threshold corrections, and three loop beta functions. We had a small workshop in December 2013 at the MCTP with some experts to study how to do the matching and running, particularly with the heavy scalars expected in good theories. Perhaps one can hope to calculate the Higgs mass from a theory to nearly 1% eventually, but that is optimistic. There will be an additional scale uncertainty of about a percent from doubling or halving the gravitino mass. Because the Higgs mass is written at the compactification scale, followed by the running to the low scale,
it is not possible to show a simple, elegant formula for $M_h$.

Given the decoupling model and vacuum stability, one could ask if there was significance to finding ourselves in the metastable region. The value of $M_h$ is fixed by the electroweak breaking and the large soft terms implied by the compactified theory. The top mass is fixed by the Higgs vev and the top Yukawa coupling. The Yukawa coupling is determined by the superpotential, a completely separate part of the theory. There is not yet an understanding of why there should be one and only one large quark Yukawa coupling, but it seems that being in the metastable region is a coincidence.

3 ULTRAVIOLET COMPLETION?

It is thought that almost all low scale models for Higgs sectors, dark matter, LHC physics, etc., do not have a ultraviolet (UV) completion. That is, they could not have originated from a theory that included a quantum theory of gravity. Such models/theories are said by Cumran Vafa to live in the "swampland". Vafa in his TASI lectures [9] suggests some criteria, but it is hard to know if a low scale model is in the swampland. By far the best way to be confident that a low scale model has a UV completion, which is of course necessary if we hope it is relevant to describing our world, is to start with a 10 or 11 dimensional string/M-theory, and compactify it to 4 dimensions.

So we ask if our two-doublet Higgs sector with large soft-breaking terms arises from a compactified string/M theory? The answer is yes, it has been demonstrated [10] that compactifying M-theory on a manifold with $G_2$ holonomy necessarily gives a 4-dimensional supersymmetric quantum field theory. Moduli are all stabilized, in a de Sitter vacuum. Vafa [9] states that the resulting vacuum is not de Sitter, which is true for his assumptions. But including hidden sector charged matter (which is generically present and which he did not include) gives a deS vacuum, via the additional F-terms - their contribution cancels the $-3W^2$ term in the scalar potential, giving a positive energy [10]. So the full theory does have a de Sitter vacuum.

The resulting theory automatically implies the supersymmetry is softly-broken via gravity mediation, and generically satisfies the conditions for electroweak symmetry breaking, with a Higgs mass about equal to the observed one. The compactified M-theory has been shown to have Yang-Mills gauge theories like the Standard Model [11] and chiral quarks and leptons like the Standard Model [12]. It solves the hierarchy problem, and it can support grand unification [13] and has axions, and a solution to the strong CP problem [14].

It has two dark matter candidates, axions and hidden sector stable matter. The theory does not have adjustable parameters, though our present inability to calculate some things means some results are poorly known. With all these successful tests we can be rather confident that our Higgs sector qualifies as a realistic one. One such example is sufficient to be satisfied that the low scale description can arise in an underlying theory that is consistent with also having quantum gravity [15].
3.1 FINAL REMARKS - A DREAM FULLFILED, NOT A NIGHTMARE

Old fashioned people could view the Higgs physics in a traditional way - the compactified M-theory predicted the Higgs boson and its mass (ratio to the Z mass) and its decay branching ratios, without free parameters, and experiment has confirmed them, which helps validate the theory. The compactified theory also predicts additional tests: it predicts that gluinos are in the LHC range before any major upgrades if it collects enough luminosity, that the $g \mu - 2$ experiment at Fermilab should not see significant deviations from the Standard Model, that electric dipole moments are smaller than the current limits but not much smaller [16], and more.

People sometimes say that the situation after LHC could be the nightmare one with only a Standard Model Higgs boson and no guidance as to how to proceed. Sometimes people say Higgs physics is a mystery. Those statements are wrong, and arise from ignorance about or ignoring information and clues. It is not surprising that the Higgs boson branching ratios are like the Standard Model ones, because such a situation occurs naturally in well-known robust models, and those models have possible ultraviolet completions (as a model must to not be in the swampland). The Higgs boson whose field breaks the electroweak symmetry has been found, and the data do provide information that is helpful in guiding us toward how to extend the Standard Model. Higgs physics is not a mystery.

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