Higgs Mass and other Generic Predictions for Realistic String Vacua

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Higgs Workshop
University of Michigan, Ann Arbor

Based on:
1112.1059 (Kane, P.K., Lu, Zheng)
1204.2795 (Acharya, Kane, P.K.)
Plan of the Talk

- Introduction & Motivation.
- Summary.
- Details
  - “Model-independent” predictions.
  - Specific Predictions.
    - Higgs, BSM physics, DM, Precision

  Focus on this, briefly mention others if time.

- Conclusions
Higgs Physics may soon become Experimental Science!

– Until now, only existed in the realm of theory.

– Reason for this meeting
– Generated a lot of interest in the theory community.

Have heard (will hear) many talks trying to make sense of this from the Electroweak scale point of view.
Here, focus on Top-Down Approach
(but include Exp. constraints)

Emphasis laid on solving the “Big Hierarchy” problem
Motivation

The “Big Hierarchy” problem consists of two problems:
– Higgs technical naturalness problem (TeV scale susy keeps Higgs mass stable)
– Origin of the Electroweak Scale itself – how does it arise from microscopic theory?

String Theory

Why is $M_{EW}$ so much smaller than the fundamental scale, the String scale in String theory?

Usually $M_{\text{string}}$ close to $M_{\text{planck}}$

Also assume $M_{KK} \sim M_{\text{string}}$ (have to be checked self-consistently, dynamically)

• To solve “Big Hierarchy”, have to generate $\sim$ TeV scale SUSY dynamically.
Summary

Study solutions of compactified string/M-theories having the following properties:

1) Supergravity approx. valid  
2) Moduli are stabilized.

3) Spontaneously broken SUSY with ~ TeV superpartners.

Within solutions in this class satisfying all current experimental and observational constraints, make predictions for BSM physics:

- **Essentially Model-Independent**  
  \[ m_{3/2} \gtrsim 30 \text{ TeV} \] \[ \sqrt{F} \] has to be “High”

- Predictions
  - Scalars very heavy – should not be seen at the LHC.
  - Non-thermal cosmological history before BBN.
  - O(1) fraction of DM in the form of axions.

- **MSSM matter and gauge**

  Spectrum below \( M_{\text{GUT}} \) (w/ R-parity)

  - Compute \( M_H/M_Z \) precisely.
  
  \[ M_H \sim 125 \text{ GeV for } \tan \beta \gtrsim 6. \]

  - H virtually indistinguishable from SM Higgs.
  - Gluino pair production should be seen.
  - Next gen. DM & EDM experiments should see signal
Why is String theory relevant for Particle Physics?

Extra dimensions manifest themselves through presence of “moduli” fields in 4D.

Modes of “X-dim graviton”

Moduli must be “stabilized”, & given sufficiently large masses, for two reasons:

1) Satisfy fifth force constraints

2) All low-energy physics couplings determined from their vevs. (eg. $\alpha_{\text{EM}}$)

Crucial difference between a general EFT and EFT arising from a String compactification – Presence of Moduli

Moduli affect low-energy physics in important ways, indirectly.
In recent years, significant progress in moduli stabilization in string theory.

**Type IIB :**


**Type IIA :**


**M-theory :**

B. S. Acharya, hep-th/0212294.


**Heterotic:**


Moduli Stabilization and SUSY breaking entwined

Want moduli stabilization mechanisms which can give rise to $\sim$ TeV scale SUSY.
Hence could give rise to realistic 4D vacua.

– Of course other kinds of vacua possible, but not interested in those.

PHILOSOPHY

Assuming our Universe is a solution of String Theory,
what “generic” features would one expect for BSM physics?
Throwing Darts on the String Landscape

“Barren” Landscape

“Fertile” Landscape

SM at low energies

~TeV scale susy, GUT

Look for Generic BSM Features in these Vacua
Getting to the “Fertile” part of the Landscape

Stabilizing Hierarchies and Moduli

Type IIB: Denef, Douglas, Florea, Grassi, Kachru hep-th/0503124; Bobkov, Braun, P.K., Raby 1003.1982

M Theory: Acharya, Bobkov, Kane, P.K., Shao hep-th/0701034; Acharya, Bobkov 0810.3285

Basically, realize the old idea of Witten

— Dimensional Transmutation can generate exponentially suppressed scales naturally.

— But now also stabilize moduli

\[ m_{3/2} \sim \frac{\Lambda^3}{M_{pl}^2}; \quad \Lambda \sim e^{-\frac{2\pi}{\alpha_h b}} M_{pl}, \quad \alpha_h^{-1} = \sum_i N^i S_i \]

Only dimensionful scale \( M_{pl} \)!

\( m_{3/2} \) order parameter of susy breaking (with zero CC).
**Crucial Result**: For generic moduli Super- & Kahler- potentials,

\[ M_{\text{modulus}}^{\text{min}} = O(1) m^{3/2} \]

*Explicit examples with more than one moduli satisfy it. Also borne out by general analysis*

- **Two ways to show this:**
  - **I) General SUGRA result** Acharya, Kane, Kuflik 1006.3272
    
    (Denef, Douglas; Scrucca, Gomez-Reino)
    
    \[ M_{\text{min}}^2 < \zeta^+ M^2 \zeta \] for any unit vector \( \zeta \)
    
    **Choosing** \( \zeta \) **in the sGoldstino direction, can show**
    
    \[ M_{\text{min}}^2 = m^{3/2} \left( 2 + \frac{|r|}{M_{\text{pl}}^2} \right) \]
    
    \( r = \text{curvature in moduli space} \)
    
    For models in which only one scale present – \( m^{3/2} \) (itself, arising from \( M_{\text{pl}} \))
    
    \[ \frac{|r|}{M_{\text{pl}}^2} = O(1) \quad \Rightarrow \quad M_{\text{min}} = O(1) m^{3/2} \]
II) Even when more than one scale present can show that for realistic cases which generate Hierarchy

\[ M_{\text{min}} = O(1) m^{3/2} \]

\textit{Acharya, Kane, P.K. 1204.2795}

\textit{P.K. (To appear)}

– At least some moduli stabilized by Kahler potential effects

– Geometric Moduli stabilized close to a supersymmetric point.

– Dynamics stabilizing moduli \( \leftrightarrow \) Dynamics of supersymmetry breaking.

Due to vanishingly small C.C.

Since generic result for large classes of realistic vacua (with mild assumptions) \( \leftrightarrow \) Make general statements about all such vacua.
Generic Predictions

- With rather mild assumptions, essentially:
  a) Validity of SUGRA approximation.
  b) $H_{\text{inflation}} > m_{3/2}$

(complete set of assumptions carefully explained in the review: Acharya, Kane, P.K. 1204.2795)

- Implies that $M_{\text{mod}}^{\text{min}} = O(1) m_{3/2} > \sim 30$ TeV due to BBN constraints.

- Universe has a “non-thermal” history before BBN.
- $m_{3/2} \sim \frac{F}{M_{\text{pl}}}$ so, $\sqrt{F}$ should be “high”, as in gravity mediation.
- Axions form an $O(1)$ abundance of DM. (slightly subtle)

Mechanisms which stabilize many moduli, naturally keep most axions light

One of which can naturally be the QCD axion (solves strong CP with moduli stabilization)

Abundance computed within non-thermal cosmology

$\mathbf{f_a} \sim \mathbf{M_{GUT}}$ requires only $\sim 1$-10% tuning

Acharya, Bobkov, P.K. 1004.5138
Generically, \( m_{\text{sm-charged}} = O(1) m^{3/2} \) in general SUGRA.

Is \( m_{\text{sm-charged}} \ll m^{3/2} \) (“sequestering”) possible, in special cases?

- To date has not been shown to exist in a viable manner with moduli stabilization
- M-theory and Type IIA – no pheno. viable sequestering present.
- Type IIB – Argued that “maybe” present Kachru, McAllister, Sundrum th/0703105

After moduli stabilization, “superpotential de-sequestering” ruins it Berg, Marsh, McAllister, Pajer 1012.1858

So, rather conservative assumption: **NO sequestering** \( (M_{\text{scalar}}, A = O(1) m^{3/2}) \)

None of the SM-charged scalars (except the lightest Higgs scalar) should be seen at the LHC!
What about gaugino masses?

- Although scalars heavy, gauginos need not be.
  
  Suppressed if
  
  - F-term of modulus determining gauge coupling $<\ll$ Dominant F-term.
  
  - Happens in M-theory examples as well as many Type IIB examples.


Specific Predictions

- Assume matter and gauge spectrum below $M_{KK} = \text{MSSM}$ precisely.
  - Motivated by gauge unification and radiative EWSB in MSSM.

Focus on vacua with the following properties:

- $M_{\text{scalar}}, A \approx m^{3/2}$, Gaugino masses suppressed.

- $\mu$ - both “large” $O(m^{3/2})$, & “Small” possible in different vacua

  \text{Acharya, Kane, Kuflik, Lu 1102.0556} \quad \text{Giudice, Masiero PLB 206 480, Casas, Munoz ph/9303227}

  \mu \text{ generated by string instantons in some constructions, so both “small” and “large” } \mu \text{ possible}

  \text{Cvetic, Halverson, Richter 0905.3379; Heckman, Vafa 0809.3452}
Higgs Mass
(The lightest CP-even neutral scalar - nondecoupling)

PROCEDURE

- Compute soft susy breaking parameters at \( M_{KK} \sim M_{GUT} \) in the class of vacua. Find:

  \[
  M_a \text{ (Gaugino masses)} \sim 0.01-0.1 \, m_{3/2}^3, \quad A_0/M_0 = O(1), \quad M_0 \approx m_{3/2}
  \]

- \( \tan \beta \) should in principle be predictable, but imperfect understanding of \( \mu \) (B\( \mu \)) only allows us to constrain \( \tan \beta \). However correlation between \( \tan \beta \) and \( \mu \)

  “Small” \( \mu \) \quad \leftrightarrow \quad \tan \beta > \sim 5 \quad \text{& vice versa}

- RGE Evolution – gives rise to radiative EWSB

- Match on to EFT with gauginos and scalars at \( Msusy = \sqrt{m_{\text{stop}1}m_{\text{stop}2}} \sim m_{3/2} \)

- Then compute Quartic (\( \lambda_H \)) in the EFT below Msusy via 2-loop RGEs, taking all relevant LL and finite thresholds into account.

Similar to:

Haber, Hempfling ph/9307201, Carena et al ph/0001002, Giudice, Strumia 1108.6077; Binger ph/0408240; Bernal, Djouadi, Slavich 0705.1496
Higgs Mass Prediction

Higgs mass prediction (at two loops) for three values of $m_{3/2} = 25, 50, 100$ TeV

Expect: $25$ TeV $< m_{3/2} < 100$ TeV

Uncertainty in the Higgs mass prediction for a given $m_{3/2}$ and $\tan \beta$

<table>
<thead>
<tr>
<th>Case</th>
<th>Variation of Input</th>
<th>$\Delta M_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Small” $\mu$</td>
<td>Theoretical</td>
<td>±0.5</td>
</tr>
<tr>
<td>$.05 m_{3/2} \leq \mu \leq .15 m_{3/2}$</td>
<td>Theoretical + Experimental</td>
<td>±1.1</td>
</tr>
<tr>
<td>“Large” $\mu$</td>
<td>Theoretical</td>
<td>±0.5</td>
</tr>
<tr>
<td>$.05 m_{3/2} \leq \mu \leq .15 m_{3/2}$</td>
<td>Theoretical + Experimental</td>
<td>±1.25</td>
</tr>
</tbody>
</table>

Data favors “Small $\mu$” (Black points) $\tan \beta > 6$

$122$ GeV $< M_h < 129$ GeV
Higgs Properties

- **Decoupling Limit**
  - Higgs behaves very similar to the SM Higgs.

- **How similar?**
  - Production (by gluon fusion) virtually the same since $m_{\text{stop}} \gg m_{\text{top}}$.
  - Decays could be different due to effects from light gauginos and higgsinos.

![Graph showing deviation in h -> b bar decay width]

Deviation in $h \rightarrow b \bar{b}$ decay width by at most ~1 % from the SM width.

So, total width hardly changes

$\tan\beta = 20$

$\tan\beta = 10$
\[ h \rightarrow \gamma \gamma \] very close to that for SM. 
Same for \[ h \rightarrow Z \gamma \]

\[ M_{3/2} = 50 \text{ TeV} \]

\[
\frac{\Gamma_{\gamma\gamma}^{\text{SUSY}} - \Gamma_{\gamma\gamma}^{\text{SM}}}{\Gamma_{\gamma\gamma}^{\text{SM}}}
\]

Diaz, Perez hep-ph/0412066

LHC Signatures of the Higgs should be indistinguishable from 
that of the SM Higgs
Correlated Falsifiable Predictions

- Higgs Mass Result strictly valid only when gauginos are light ($<\sim$ TeV)

- So, should see them at the LHC!
  
  $\sim g \sim g$ followed by decay preferentially to 3rd gen. Quarks via off-shell 3rd gen Squarks

  Acharya, Grajek, Kane, Kuflik, Suruliz, Wang 0901.3367, Kane, Kuflik, Lu, Wang 1101.1963

  $\tilde{g} \rightarrow tt + \chi, \tilde{g} \rightarrow bb + \chi, \text{ and } \tilde{g} \rightarrow tb + \chi.$

Recent searches by ATLAS, CMS (saw talks yesterday)

$1l+\geq 1b$ jets $+\geq 4$ jets $+\text{Missing ET}$ $M_{\text{gluino}} \sim 700-750$ GeV

- Should also see disappearing charged tracks from decays of charginos ($\sim W^+ \rightarrow \sim W^0$)

- Depending upon the accuracy of $M_h$ measurement, get insight about $m_{3/2}$ and tan $\beta$.

  - Use as a consistency check with other measurements.
Typical Spectrum
• “Dark” Frontier:

Wino-like LSP DM candidate with EW scale mass.
– Naturally $O(1)$ fraction of DM in LSPs within non-thermal history

Acharya, Kane, P.K., Watson 0908.2430
(Remember, remaining in axions) Acharya, Bobkov, Kane, P.K., Shao, Watson 0804.0863

– Indirect-detection FERMI, AMS 02 should see signals.
– Direct-detection naturally evade current XENON bounds, but next generation expts should see a signal.
  (if $\mu$ not too large, favored by Higgs mass)

– Axions Other astrophysical signals (to study)

• Precision Frontier:

– EDM measurements improve by few orders of magnitude

Should be able to probe the framework Kane, P.K., Shao 0905.2986
Kadota et al 1107.3105
CONCLUSIONS

In this data-rich era, ultimate scientific metric for the viability of any theory

How does it compare with Experiment?

- We have studied Generic features for BSM physics for compactified string theories giving rise to realistic 4D vacua

  (with rather mild assumptions)  
  - solve the Hierarchy problem.
  - consistent with particle and cosmological constraints.

Pragmatic Approach – Many testable predictions.
• Approach very useful even if results do NOT agree with data.

  – Depending on the nature of data, could tell us which assumption(s) need to be relaxed?

  – Provide a lot of useful insight about nature of microscopic theory.
An Example

If squarks/sleptons observed at the LHC:

– contradiction with some of the basic assumptions/results of the framework.

• Imply one of the following possibilities:
  
  a) Moduli Super- and Kahler- Potential non-generic (very special).
  
  b) $H_{\text{inflation}} \lesssim m_{3/2}$.  

  c) Late period of Thermal Inflation.

  d) Some form of sequestering is realized.

  Provide very useful insight about Theory!

  None of these possibilities realized naturally within String constructions yet.

• Would be a challenge to realize any one of the above within a string theory framework, consistent with experimental constraints.
Of course, if data agrees with the predictions from various experiments,

- Provide great opportunity to learn more about the string vacuum

We live in.
Extra Slides
Comparison to Split-SUSY

Top-Down Approach

- Dynamical solution to Big Hierarchy
- EWSB dynamically occurs
  (Correlation between $\mu$ and $\tan\beta$)

Split-SUSY (anthropic in many cases

Huge fine-tuning by assumption for large $M_{\text{susy}}$

For smaller $M_{\text{susy}}$, have to explain that scale

($M_h \sim 125 \text{ GeV} \text{ rules out } M_{\text{susy}} > 10^8 \text{ GeV}$)

Giudice, Strumia 1108.6077

No EWSB constraint imposed.

Technical

- Only gauginos suppressed, not trilinears
- Suppression by Dynamics
- Suppression only by 1-2 orders of magnitude
- No long-lived gluinos.
- Higgs mass prediction different in principle for the two cases (even for same $M_{\text{susy}}$).

- Both gauginos and trilinears suppressed.
- Suppression by $(R)$-symmetry
- Suppression essentially arbitrary.
- Long-lived gluinos – defining feature (at least in original models)
Higgs Mass Comparison
Little Hierarchy/ Fine-Tuning

Notion of Fine-tuning quite subtle

**EW Naturalness**  – Fine-tuning mitigated compared to what is naively expected for such heavy scalars. From EW point of view, some fine-tuning still remains

But Top-Down Approach  →  Another possibility

The fine-tuning at Low scale may just be “Apparent”, caused by “Imperfect understanding” of Microscopic Theory.

If know the theory completely, just compute – no fine-tuning by definition.
Detailed Argument

- EW Naturalness requires
  \[ |\mu|, |m_{H_u}| \text{ (EW)} \sim M_Z \]
  \[ \frac{1}{2} m_Z^2 = -\mu^2 - \frac{m_{H_u}^2 \tan^2 \beta - m_{H_d}^2}{\tan^2 \beta - 1} \sim -\mu^2 - m_{H_u}^2, \]

- For scalar masses \( \sim 30 \text{ TeV} \), naively have severe fine-tuning

- However, not quite true when \( \mu \) suppressed

- Intersection Point Regime.

- So, natural values \( A_0/M_0 \sim 1 \) (at \( M_{\text{GUT}} \))

- \( m_{H_u}^2(t) \sim f_{M_0}(t) M_0^2 - f_{A_0}(t) A_0^2 + R(t) \)

- So, if \( |\mu| \sim 0.1 \text{ m}_{3/2} \)

  Fine-Tuning Mitigated

  possible in string theory constructions, and favored by Higgs mass.

  Feldman, Kane, Kuflik, Lu 1105.3765
Possibility of No-fine-tuning

- If for some underlying reason (which we don't know yet)
  a) $A_0/M_0$ close to 1.2,
  b) $\mu \sim 3 \times 10^{-2} \text{ m}_{3/2}

\[ |m_{H_u}|^2 (\text{EW}) \sim 10^{-2} \text{ m}_{3/2}^2 \]

- Region Plot for $M_Z^2$
\[ m_h^2 = 2v^2[\lambda(Q) + \delta\lambda(Q) + \tilde{\delta}\lambda(Q)], \quad m_t = \frac{g_t(Q)v}{1 + \delta_t(Q) + \tilde{\delta}_t(Q)}, \] (19)

where \( v = 2^{-3/4}G_F^{-1/2} = 174.1 \text{ GeV} \) is extracted from the Fermi constant for muon decay, \( G_F \).

Here \( \delta\lambda \) [11] and \( \delta_t \) [12] are the well-known corrections due to SM particles:

\[ \delta\lambda = -\frac{\lambda G_F M_Z^2}{8\pi^2\sqrt{2}} (\xi F_1 + F_0 + F_3/\xi) \approx 0.0075\lambda \] (20)

\[ \delta_t = \delta_t^{\text{QCD}} + \delta_t^{\text{EW}} \approx -0.0602 - 0.0002 \] (21)

\[ \delta_t^{\text{QCD}}(m_t) = -\frac{4}{3\pi} \alpha_3(m_t) - 2.64\alpha_3^2(m_t) - 0.92\alpha_3^3(m_t) \] (22)

Higher order corrections to \( \delta\lambda \) may add an uncertainty of \( \sim 1 \text{ GeV} \)

\[ + 3g_t^4 \left[ 2X_t F\left(\frac{m_Q}{m_U}\right) - \frac{X_t^2}{6} G\left(\frac{m_Q}{m_U}\right) \right] + \frac{3}{4} X_t g_t^2 \left[ g_2^2 H_2\left(\frac{m_Q}{m_U}\right) + \frac{3}{5} g_1^2 H_1\left(\frac{m_Q}{m_U}\right) \right] \cos 2\beta \]
\[ \mu^2 = -M_Z^2/2 + \frac{\tilde{m}^2_{H_u} - \tilde{m}^2_{H_d} \tan^2 \beta}{\tan^2 \beta - 1} \]

\[ B\mu = \frac{1}{2} \sin 2\beta(\tilde{m}^2_{H_u} + \tilde{m}^2_{H_d} + 2\mu^2) , \]

\[ m^2_{H_u} \sim 10^{-2} M_{3/2}^2 \sim \mathcal{O}(\text{TeV}^2) \]

\[ \text{Solve}\left[ \left\{ 2 \left( -\mu^2 + \frac{m_{H_d}^2}{\tan \beta - 1} - \frac{m_{H_u} \tan^2 \beta}{\tan \beta - 1} \right) \right\} / \cdot \{ m_{H_d} \rightarrow m_{32}, m_{H_u} \rightarrow a \cdot m_{32}^2, \mu \rightarrow b \cdot m_{32}, B \rightarrow c \cdot m_{32} \} / . \right. \]

\[ \left\{ \begin{array}{l} c \rightarrow 1.7, a \rightarrow 0.01 \end{array} \right\} = 9.3 \times 10^{-6} m_{32}^2, \]

\[ \frac{2 \tan \beta}{1 + \tan \beta^2} + \frac{2 B \mu}{m_{H_d}^2 + m_{H_u} + 2 \mu^2} / . \{ m_{H_d} \rightarrow m_{32}, m_{H_u} \rightarrow a \cdot m_{32}^2, \mu \rightarrow b \cdot m_{32}, B \rightarrow c \cdot m_{32} \} / . \]

\[ \left\{ \begin{array}{l} c \rightarrow 1.7, a \rightarrow 0.01 \end{array} \right\} = 0 }}, \{ \tan \beta, b \}, \text{Reals} \]

\[ \text{Solve::ratnz : Solve was unable to solve the system with inexact coefficients. The answer was obtained by solving a corresponding exact system and numericizing the result.} \]

\[ \{ \tan \beta \rightarrow -8.09516, b \rightarrow 0.0730525 \}, \{ \tan \beta \rightarrow -1.23503, b \rightarrow 1.36918 \}, \{ \tan \beta \rightarrow 1.23503, b \rightarrow -1.36918 \}, \{ \tan \beta \rightarrow 8.09516, b \rightarrow -0.0730525 \} \]
Flavor

- Well known that without any underlying structure, gravity mediation too large predictions for Flavor observables.
- But flavor is a really ill-understood problem – even the origin of fermion masses and mixings not known.
- Additional structures in the underlying theory could be naturally present.

Find that quasi-degenerate and heavy scalars ~ 30 TeV consistent with all flavor bounds Kadota et al 1107.3105

Quasi-degenerate scalars could arise from;

a) Flavor symmetries present in many string constructions.

b) Moduli dynamics and mediation of susy breaking could provide further suppression.

- Focus on b) in the following, but should be aware that a) could provide further suppression.
In non-canonical basis:

\[ m_{\alpha\beta}^2 = m_{3/2}^2 \tilde{K}_{\alpha\beta} - \Gamma_{\alpha\beta} \]

Using homogeneity properties of moduli space, show

* Acharya, Bobkov 0810.3285

\[ \Gamma_{\alpha\beta} \propto \tilde{K}_{\alpha\beta} + \text{higher order corrections} \]

corrections assumed to be small – not derived, but expected to be true if SUGRA approx. is valid

Then, going to the canonical basis, find

\[ \hat{m}_{\alpha\beta}^2 \simeq m_{3/2}^2 \delta_{\alpha\beta} \]
Predicted range for the Higgs mass

- $\tan\beta = 50$
- $\tan\beta = 4$
- $\tan\beta = 2$
- $\tan\beta = 1$

Split SUSY

High-Scale SUSY

Experimentally favored

Supersymmetry breaking scale in GeV

Higgs mass $m_h$ in GeV