String Inspired Low Energy Phenomenology

Tianjun Li
Institute of Theoretical Physics, Chinese Academy of Sciences

I. Introduction

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ICTS, USTC, Hefei,   May 17, 2007

I. Introduction

String Theory

- String theory is the only known theory which might correctly describe quantum gravity
- Boson string theory: 26 dimensions
- Superstring theory: 10 dimensions
- The observed world is 4-dimensional
- Calabi-Yau compactifications for extra 6 dimensions
- Preserving the 4-dimensional $N = 1$ supersymmetry

Implication of String Theory:

- Cosmology [a]
- Particle Physics

Hints in the model building and at the LHC and ILC

[a] Y. F. Cai, M. Z. Li, J. X. Lu, Y. S. Piao, T. T. Qiu and X. M. Zhang, arXiv:hep-th/0701016.

Hints in the model building:

- Problem: Doublet-triplet splitting problem in GUTs

  Higgs representations: H_u and H_d in the MSSM while $\mathbf{5}$ and $\overline{\mathbf{5}}$ in $SU(5)$

- Solution: the Wilson line gauge symmetry breaking in the heterotic string model building or the D-brane splitting in the Type II orientifold models.

- The MSSM μ problem.

$$W \supset \mu H_d H_u \ .$$

The problems in the model building might not exist in the string models.

String Scale Gauge Coupling Unification:

- $M_{\rm String}$ in weakly coupled heterotic string theory is [a]

$$M_{\rm String} = g_{\rm string} \times 5.3 \times 10^{17} \ {\rm GeV} \ .$$

- MSSM unification scale: $M_{\rm GUT} \sim 2.4 \times 10^{16}$ GeV

Little Hierarchy between $M_{\rm String}$ and $M_{\rm GUT}$.

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[a] K. Dienes.

Superpotential at stringy tree level:

$$W = y_\phi \phi_1 \phi_2 \phi_3 \, .$$

- Chern-Simmons terms in the heterotic string compactification with standard spin connection embedding [a].
- Instanton effects in Type IIA intersecting D6-brane models [b].

Implication in Particle Physics Model Building

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[a] E. Witten; TL, J. Lopez and D. V. Nanopoulos.

[b] D. Cremades, L. E. Ibanez and F. Marchesano; M. Cvetic and I. Papadimitriou; S. A. Abel and A. W. Owen.

II. STRING SCALE GAUGE COUPLING UNIFICATION

- Gauge couplings unify at string scale [a]
- Testable flipped $SU(5) \times U(1)_X$ model [b]

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[a] V. Barger, J. Jiang, P. Langacker and TL, hep-ph/0612206.

[b] J. Jiang, TL and D. V. Nanopoulos, hep-ph/0610054.

Gauge couplings unify at string scale:

- $SU(3)_C$ and $SU(2)_L$ unify at $M_{\rm String}$: vector-like particles with $\Delta b_2 < \Delta b_3$

$$\Delta b_3 - \Delta b_2 = 1, \quad M_V \sim 2 \times 10^{13} \text{ GeV} ,$$
$$\Delta b_3 - \Delta b_2 = 2, \quad M_V \sim 3 \times 10^{15} \text{ GeV} ,$$
$$\Delta b_3 - \Delta b_2 = 3, \quad M_V \sim 2 \times 10^{16} \text{ GeV} .$$

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ unify at $M_{\rm String}$: additional vector-like particles with masses at TeV scale and $\Delta b_3 = \Delta b_2 \neq \Delta b_1$, or non-canonical $U(1)_Y$ normalization.

Testable Flipped $SU(5) \times U(1)_X$ Models:

- $SU(3)_C$ and $SU(2)_L$ unify at $M_{\rm GUT}$
- $SU(5)$ and $U(1)_X$ unify at $M_{\rm String}$
- All the vector-like particles at the TeV scale form complete $SU(5) \times U(1)_X$ multiplets

$$XF = (\mathbf{10}, \mathbf{1}) \ , \ \overline{XF} = (\overline{\mathbf{10}}, -\mathbf{1}) \ ; \quad Xl = (\mathbf{1}, -\mathbf{5}) \ , \ \overline{Xl} = (\mathbf{1}, \mathbf{5}) \ ,$$
$$(XQ, \overline{XQ}) \ , \quad (XD, \overline{XD}) \ , \quad (XN, \overline{XN}) \ , \quad (XE, \overline{XE}) \ .$$

Testable at the LHC

III. String Inspired Singlet Extensions of the Minimal Supersymmetric Standard Model (SEMSSM)

The Standard Model

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry and classical gravity
- Three families of SM fermions
- One Higgs doublet

The SM explains existing experimental data very well, including electroweak precision tests.

Major Problems in the SM

- Fine-tuning Problems
- Aesthetic Problems

Fine-tuning Problems:

- Cosmological constant problem: $\Lambda_{\rm CC} \sim 10^{-122} M_{\rm Pl}^4$?
- Gauge hierarchy problem
- Strong CP probelm
- SM fermion masses and mixings

Aesthetic Problems:

- Interaction unification
- Fermion unification
- Gauge coupling unification
- Charge quantization
- Too many parameters

Minimal Supersymmetric Standard Model

- Solving the gauge hierarchy problem: SUSY
- Gauge coupling unification
- Radiatively electroweak symmetry breaking

  Large top quark mass
- Natural dark matter candidates: R parity

  Neutralino, sneutrino, gravitino, ...
- Electroweak baryogenesis: light stop scenario
- Electroweak precision: R parity

Problems in the MSSM:

- μ problem

  $\mu H_u H_d$

- Fine-tuning for the lightest CP-even Higgs boson mass:

  $m_{h^0} = M_Z \cos 2\beta$

- CP violations in SUSY breaking soft terms

  The EDMs of electron, neutron, and ^{199}Hg

- FCNC

- Dimension-5 proton decays

$$W = \frac{QQQL}{M_{\rm Pl}} + \frac{U^c D^c U^c E^c}{M_{\rm Pl}} .$$

Next to the MSSM (NMSSM):

- S and Z_3 symmetry: $\phi \to w\phi$
- Solution to the μ problem: No $\mu H_d H_u$

$$W = hSH_dH_u + \frac{\kappa}{3}S^3 \,.$$

- Additional F-term contribution to the Higgs quartic couplings

  Lifting the Higgs boson mass

- Invisible Higgs decays: $h \to aa$

  Higgs is light and about 100 GeV

- Electroweak baryogenesis: $A_h hSH_dH_u$

Implication of String Theory:

- The $\mu H_d H_u$ term in the MSSM and the $\kappa S^3/3!$ term in the NMSSM do not exist at stringy tree level in the string derived models.
- Only the superpotential term hSH_dH_u is allowed.
- Problem: one global $U(1)$ symmetry, and one massless Goldstone boson (axion)
- Solution: breaking global $U(1)$ symmetry by additional superpotential terms or supersymmetry breaking soft terms.

Implication of String Theory:

- Superpotential terms $\mu H_d H_u$, $\mu' S^2/2!$, and $\kappa S^3/3!$ can be generated due to the instanton effects [a]

$$\mu \simeq M_{\rm string} e^{-A}, \quad \mu' \sim M_{\rm string} e^{-A'} .$$

- $A \sim A' \sim 33$
- Solution to μ problem in the MSSM.
- κ from instanton effects may be negligible.

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[a] R. Blumenhagen, M. Cvetic and T. Weigand; L. E. Ibanez and A. M. Uranga.

The most general SEMSSM [a]:

Superpotential

$$W = hSH_dH_u + \mu H_dH_u + m^2 S + \frac{\mu'}{2!}S^2 + \frac{\kappa}{3!}S^3 \ .$$

F-term scalar potential

$$V_F = |hH_dH_u + m^2 + \mu' S + \frac{\kappa}{2!}S^2|^2 + |hS+\mu|^2|H_u|^2 + |hS+\mu|^2|H_d|^2 \ .$$

D-term scalar potential

$$V_D = \frac{g_Y^2 + g_2^2}{8}\left(|H_u|^2 - |H_d|^2\right)^2 \ .$$

[a] TL, hep-ph/0612359.

Supersymmetry breaking soft terms V^I_{soft} and V^{II}_{soft}

$$
\begin{aligned}
V^I_{soft} &= m^2_{H_d}|H_d|^2 + m^2_{H_u}|H_u|^2 + m^2_S|S|^2 \ , \\
V^{II}_{soft} &= -\Big(A_h h S H_d H_u + B\mu_B H_d H_u + A_X m^2_X S \\
&\qquad + \frac{1}{2!}B'\mu'_B S^2 + \frac{1}{3!}A_\kappa \kappa_X S^3 + \text{H.C.}\Big) \ .
\end{aligned}
$$

If $\mu \neq 0$, $m^2 \neq 0$, $\mu' \neq 0$, or $\kappa \neq 0$, we assume $\mu_B = \mu$, $m^2_X = m^2$, $\mu'_B = \mu'$, or $\kappa_X = \kappa$, respectively. However, even if $\mu = 0$, $m^2 = 0$, $\mu' = 0$, or $\kappa = 0$, we can show that μ_B, m^2_X, μ'_B, or κ_X might not be zero in general.

The global $U(1)$ symmetry in the Higgs potential can be broken by the supersymmetry breaking soft terms.

Model Building:

- Forbidden some terms.
- All the relevant mass parameters should be around $1\ \mathrm{TeV}$.
- Forbidden quantum gravity effects.

Anomalous $U(1)_A$ gauge symmetry

Anomalous $U(1)_A$ gauge symmetry:

- One anomalous $U(1)_A$ gauge symmetry in the heterotic string model building or up to four in the Type II orientifold model building

- The corresponding anomalies are cancelled by the (generalized) Green-Schwarz mechanism.

- Fayet-Iliopoulos term

$$\Lambda_{FI}^2 = \frac{g_{\rm String}^2 M_{\rm Pl} A_{GGX}}{192\pi^2} ~.$$

- A SM singlet field ϕ with $U(1)_A$ charge -1

$$D_A = -\phi^2 + \Lambda_{FI}^2 \ .$$

$$\langle\phi\rangle = \Lambda_{FI} \ , \quad \frac{\langle\phi\rangle}{M_{\rm Pl}} \sim 0.171 - 0.221 \ .$$

- The $U(1)_A$ D-flatness and supersymmetry can be preserved.
- Hidden sector superfields Z and Z' :

$$\langle F_Z\rangle \sim 10^{21}\ {\rm GeV}^2 \ , \quad \langle F_{Z'}\rangle \sim 10^{21}\ {\rm GeV}^2 \ .$$

- The $U(1)_A$ charges for S and Z are $n + p/q$ and $m + p'/q'$.

- Soft masses:

$$\int d^4x d^2\theta d^2\overline{\theta}\frac{\overline{Z}Z}{M_{\rm Pl}^2}\left(|S|^2+|H_d|^2+|H_u|^2\right)\ .$$

- Gaugino masses and the $A_h hSH_dH_u$ term

$$\int d^4x d^2\theta\frac{Z\ (\text{or } Z')}{M_{\rm Pl}}W^\alpha W_\alpha+\frac{Z\ (\text{or } Z')}{M_{\rm Pl}}hSH_dH_u+\text{H.C.}\ .$$

Model A:

- $U(1)_A$ charges for S and Z

$$m+n \ = \ 47, \ \ p/q \ = \ 1/5\,, \ \ p'/q' = 4/5\,.$$

- Relevant additional operator

$$\int d^4x d^2\theta M_{\rm String} Z S \left(\frac{\phi}{M_{\rm Pl}}\right)^{48} + {\rm H.C.}\,.$$

Superpotential:

$$W = hSH_dH_u \, .$$

Supersymmetry breaking soft terms

$$V_{soft}^{II} = -\left(A_h hSH_dH_u + A_X m_X^2 S + \mathrm{H.C.}\right) \, ,$$

The global $U(1)$ symmetry in the Higgs potential is indeed broken by the supersymmetry breaking soft term $A_X m_X^2 S$.

Model B:

- $U(1)_A$ charges for S and Z

$$n = -22,\ \ p/q \ = \ 0\ ,\ \ m = 0,\ \ p'/q' = 0\ .$$

- Relevant additional operators

$$\int d^4x d^2\theta \,(M_{\rm String} H_d H_u + Z H_d H_u) \left(\frac{\phi}{M_{\rm Pl}}\right)^{22}$$
$$+ \int d^4x d^2\theta d^2\overline{\theta} \left(\overline{Z} S + \frac{\overline{Z} Z S}{M_{\rm Pl}}\right) \left(\frac{\overline{\phi}}{M_{\rm Pl}}\right)^{22} + {\rm H.C.}\ .$$

Superpotential:

$$W = hSH_dH_u + \mu H_dH_u + m^2S \, .$$

Supersymmetry breaking soft terms

$$V^{II}_{soft} = -\left(A_h hSH_dH_u + B\mu_B H_dH_u + A_X m_X^2 S + \text{H.C.}\right) \, .$$

Model C:

In Model B, we consider the gauge mediated supersymmetry breaking scenario where $\langle F_Z \rangle \sim 10^{10}$ GeV^2.

Superpotential:

$$W = hSH_dH_u + \mu H_dH_u \ .$$

Supersymmetry breaking soft terms

$$V_{soft}^{II} = -\left(A_h hSH_dH_u + B\mu_B H_dH_u + \mathrm{H.C.}\right) \ .$$

Model C can also be considered as the string derived models with hSH_dH_u superpotential term where the extra μH_dH_u term arises from instanton effects.

Model D:

- $U(1)_A$ charges for S and Z

$$n = 11, \;\; p/q \; = \; 1/2 \; , \;\; m = 0, \;\; p'/q' = 0 \; .$$

- Relevant additional operators

$$\int d^4x d^2\theta \left(M_{\rm string} S^2 + Z S^2 \right) \left(\frac{\phi}{M_{\rm Pl}} \right)^{23} + {\rm H.C.} \; .$$

Superpotential:

$$W \;=\; hSH_dH_u + \frac{\mu'}{2!}S^2 \;.$$

Supersymmetry breaking soft terms

$$V_{soft}^{II} = -\left(A_h hSH_dH_u + \frac{1}{2!}B'\mu'_B S^2 + \text{H.C.}\right)\;.$$

Model D can be considered as the string derived models with hSH_dH_u superpotential term where the extra $\mu' S^2/2!$ term arises from instanton effects.

There exists Z_4 symmetry in Model D, where H_d and H_u have charge 1, and S has charge 2. To avoid the domain wall problem after symmetry breaking, we can turn on tiny instanton effects to break the Z_4 symmetry by generating small high-dimensional operators, and then we can dissolve the domain wall.

Numerical Results for the Higgs boson masses, the chargino and neutralino masses at tree level.

- The input parameters with dimensions of mass or mass-squared are chosen in arbitrary units.
- After finding an acceptable minimum, we require

$$\sqrt{\langle H_d^0 \rangle^2 + \langle H_u^0 \rangle^2} \simeq 174.1 \text{ GeV} .$$

- (1) $M_1 = 150$ GeV, and $M_2 = 300$ GeV; (2) $M_1 = -150$ GeV, and $M_2 = -300$ GeV.

For Model A, we choose: $h = 0.7$, $m_{H_d}^2 = -0.1$, $m_{H_u}^2 = -0.2$, $m_S^2 = 0.1$, $A_h = 1.0$, $A_X = 0.68$, $m_X^2 = 0.6$. And the VEVs for the Higgs fields at the minimum are $\langle H_d^0 \rangle = 0.7031$, $\langle H_u^0 \rangle = 0.75$, and $\langle S \rangle = 1.2563$. For Model B, we choose: $h = 0.7$, $\mu = -0.2$, $m^2 = -0.3$, $m_{H_d}^2 = -0.1$, $m_{H_u}^2 = -0.1$, $m_S^2 = 0.1$, $A_h = 0.6$, $B = -0.1$, $\mu_B = -0.2$, $A_X = -1.9$, $m_X^2 = -0.3$. And the VEVs for the Higgs fields at the minimum are $\langle H_d^0 \rangle = 0.8625$, $\langle H_u^0 \rangle = 0.8625$, and $\langle S \rangle = 1.3156$.

For Model C, we choose: $h = 0.7$, $\mu = -0.1$, $m_{H_d}^2 = -0.1$, $m_{H_u}^2 = -0.1$, $m_S^2 = -0.6$, $A_h = 2.0$, $B = -0.6$, $\mu_B = -0.1$. And the VEVs for the Higgs fields at the minimum are $\langle H_d^0 \rangle = 1.5875$, $\langle H_u^0 \rangle = 1.5875$, and $\langle S \rangle = 2.075$. For Model D, we choose: $h = 0.7$, $\mu' = -0.3$, $m_{H_d}^2 = -0.1$, $m_{H_u}^2 = -0.4$, $m_S^2 = -0.68$, $A_h = 2.0$, $B' = -0.6$, $\mu'_B = -0.3$. And the VEVs for the Higgs fields at the minimum are $\langle H_d^0 \rangle = 1.6375$, $\langle H_u^0 \rangle = 1.7203$, and $\langle S \rangle = 2.275$.

Table 1: The Higgs VEVs, and the charged, CP-even, and CP-odd Higgs masses in GeV at tree level.

Model	$\langle H_d^0 \rangle$	$\langle H_u^0 \rangle$	$\langle S \rangle$	$H^\pm$	H_1^0	H_2^0	H_3^0	A_1^0	A_2^0
A	119	127	213	205	67	196	210	127	251
B	123	123	188	179	45	184	206	142	214
C	123	123	161	165	66	148	171	31	214
D	120	126	167	176	67	145	181	39	225

Table 2: The chargino and neutralino masses in GeV.

Model	M_i	$\tilde{\chi}_1^\pm$	$\tilde{\chi}_2^\pm$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{\chi}_5^0$
A	> 0	115	334	68	88	175	217	336
A	< 0	163	314	68	156	169	217	314
B	> 0	75	328	56	81	167	184	330
B	< 0	118	315	81	125	156	184	316
C	> 0	76	329	58	80	167	185	330
C	< 0	120	315	80	127	156	185	316
D	> 0	87	330	60	68	169	200	331
D	< 0	132	315	61	138	156	200	315

Higgs Physics (Model C as an example):

$$
\begin{aligned}
H_1^0 &= -0.445481 H_d^0 - 0.445481 H_u^0 + 0.776590 S \ , \\
H_2^0 &= 0.549132 H_d^0 + 0.549132 H_u^0 + 0.630006 S \ , \\
H_3^0 &= 0.707107 H_d^0 - 0.707107 H_u^0 \ .
\end{aligned}
$$

Only H_3^0 can couple to Z boson.

Higgs search is different from the MSSM and the traditional NMSSM.

Current Projects:

- Higgs search at the LHC and ILC [a].
- The Higgs boson masses at one loop, and comprehensive study for the chargino and neutralino mass matrices [b].
- Comprehensive study for the productions and decays of the Higgs particles, charginos and neutralinos at the LHC [c].

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[a] J. Jiang and TL, in preparation.
[b] J. Jiang, TL and Y. R. Wang, in preparation.
[c] J. Jiang, TL and Y. R. Wang, in preparation.

IV. SUMMARY

String scale gauge coupling unification in the weakly coupled heterotic string theory might imply TeV-scale vector-like particles.

String inspired SEMSSM with new Higgs physics.