Stringy Predictions for Particle Physics

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The material I will present here is based on work
I have done with Jonathan Heckman.
Some of them include additional colleagues
(Chris Beasley, Vincent Bouchard, Sergio Cecotti,
Miranda Cheng, Clay Cordova , Gordon Kane, Piyush Kumar,
Joseph Marsano, Natalia Saulina, Jihye Seo,
Sakura Schafer-Nameki, Jing Shao, Yuji Tachikawa ,
Alireza Tavanfar and Brian Wecht)

String theory has a vast landscape of potential vacua

Which one is ours?

How can string theory make a prediction for particle physics without resolving this question?

I will not resolve this issue. Yet I indicate how one can nevertheless make some qualitative and semi-quantitative predictions about particle physics from reasonable assumptions.

Supersymmetry:

A basic principle of string theory at the Planck or GUT scale

What scale is it broken?

1-Much higher scale than weak scale

2-Near the weak scale

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A basic principle of string theory at the Planck or GUT scale

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1-Much higher scale than weak scale
  predictions for flavor physics
2-Near the weak scale
  predictions for LHC physics

The Flavor Puzzles

Why three flavors?

Why masses are so hierarchic for quarks and charged leptons?

Why less hierarchy for neutrinos?

Why the quark mixing matrix (CKM) so hierarchic?

What explains the less hierarchic mixing matrix for leptons (PMNS)?

An unexpected mass hierarchy:

$$(m_u, m_c, m_t) \sim (0.003, 1.3, 170) \times \text{GeV}$$

$$(m_d, m_s, m_b) \sim (0.005, 0.1, 4) \times \text{GeV}$$

$$(m_e, m_\mu, m_\tau) \sim (0.0005, 0.1, 1.8) \times \text{GeV}$$

Ideas From Particle Physics

1-Why more than 1 flavor? There is no good explanation of this from the viewpoint of particle theory

2-Why hierarchic structure in masses? The best idea from particle theory to explain this comes from the work of Froggatt-Nielsen: One postulates the existence of additional U(1) symmetries which are broken only very weakly:

If U(1)xU(1)’ symmetry is an exact symmetry, all the entries of the matrix which transform non-trivially under either one will vanish. Thus in this limit the mass matrix would look like:

To get more realistic, one assumes that the U(1)xU(1)’ symmetry is violated by small amounts, captured by

Then we can estimate the order of vanishing of the entries of the mass matrix based on the corresponding charges:

Similarly the CKM matrix comes out hierarchical if the same U(1) symmetries explain the hierarchy of the masses of u-quarks and d-quarks :

Simple as these ideas sound, it does not offer a complete picture: What is the meaning of these U(1)'s, why are they violated, and what sets the size of this violation. Also what sets the charges of flavors under these U(1)'s?

Clearly to answer these questions, and also to understand why there is more than one flavor, we need a better picture!

The Main Assumption: String Theory!

Moreover:

1) Gravity should decouple from questions of particle physics.

2) Local description of extra dimensions.

The phenomenological restrictions lead to a corner of string landscape: F-Theory.

Gauge interactions are localized on small 7-branes of type IIB, or more precisely its strong coupling limit, F-theory.

Branes, Matter and Interactions in F-theory

Branes come in different types, labeled by A-D-E group, carrying the corresponding gauge group.

On the intersection of branes, which is a 2-dimensional Riemann surface, lives matter charged under the gauge symmetry of the pair of branes:

This leads to 6d matter living on space-time times a Riemann surface. For the 4d matter spectrum all we have to do is find the zero modes of the Dirac operator, taking into account flux on the 7-branes:

Flavors and F-theory

For each matter curve, 10, 5*:

To understand mass hierarchy we need to know why is hierarchic.

To leading order approximation for overlap of wave-functions

$$\lambda_{i\bar{j}} = \psi_i(P)\psi_{\bar{j}}(P)H(P)$$

which manifestly has rank 1, as it is given by outer product of two vectors!

This rank one matrix can be organized as follows:

However, the U(1) symmetries are approximate rotational symmetries: Curvatures and fluxes break the U(1)’s.

The relevant breaking turns out to be a 3-form flux:

The wave functions get modified and the overlap of wave functions become non-zero:

F-theory and CKM Hierarchy

The hierarchy of CKM matrix, also receives a natural interpretation:

$$V_{CKM}^{F-th} \sim \begin{pmatrix} 1 & \alpha_{GUT}^{1/2} & \alpha_{GUT}^{3/2} \\ \alpha_{GUT}^{1/2} & 1 & \alpha_{GUT} \\ \alpha_{GUT}^{3/2} & \alpha_{GUT} & 1 \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.008 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

$$|V_{CKM}(M_{weak})| \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.99 \end{pmatrix}$$

Very close indeed! It also predicts no fourth generation.

Neutrino Masses and Lepton Mixing Matrix

Both Majorana and Dirac Scenarios can be easily implemented:

For Dirac scenario:

$$\frac{1}{M_{GUT}} \int d^4\theta H_d^\dagger L N_R$$

arises by integrating massive KK modes on the Higgs curve. For Majorana scenario:

$$\int d^2\theta \frac{(H_u L)^2}{M_{GUT}}$$

is generated by integrating out massive right-handed neutrinos which are KK modes.

Due to the fact that in either scenario KK modes get involved, and the KK modes are not zero modes, it means that they are not holomorphic, i.e. they do not respect the U(1) FN symmetries. Leads to dilution of mass and mixing hierarchy.

This is close to current estimates for PMNS.

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arXiv:0904.1419

F-theory and Neutrinos: Kaluza-Klein Dilution of Flavor Hierarchy

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Abstract

We study minimal implementations of Majorana and Dirac neutrino scenarios in F-theory GUT models. In both cases the mass scale of the neutrinos $m_\nu \sim M_{\text{weak}}^2/\Lambda_{\text{UV}}$ arises from integrating out Kaluza-Klein modes, where Λ_{UV} is close to the GUT scale. The participation of non-holomorphic Kaluza-Klein mode wave functions dilutes the mass hierarchy in comparison to the quark and charged lepton sectors, in agreement with experimentally measured mass splittings. The neutrinos are predicted to exhibit a "normal" mass hierarchy, with masses $(m_3, m_2, m_1) \sim .05 \times (1, \alpha_{GUT}^{1/2}, \alpha_{GUT})$ eV. When the interactions of the neutrino and charged lepton sectors geometrically unify, the neutrino mixing matrix exhibits a mild hierarchical structure such that the mixing angles θ_{23} and θ_{12} are large and comparable, while θ_{13} is expected to be smaller and close to the Cabibbo angle: $\theta_{13} \sim \theta_C \sim \alpha_{GUT}^{1/2} \sim 0.2$. This suggests that θ_{13} should be near the current experimental upper bound.

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For the U(1) Froggatt-Nielsen symmetry to exaplain both Flavor and CKM hierarchy we need that there is a point In the internal geometry where all matter curves meet and That point should enjoy an E8 symmetry.

What if SUSY persists all the way down to the weak scale?

(slightly modified) GMSB

GM-mechanism generates mu-term
PQ symmetry important

Leads to: Gravitino LSP, 10-100 MeV
NLSP stau (or possibly Bino)
Mass depends on details of the model.
NLSP relatively long lived (sec-hour)

Furthermore, the fact that there is a point of E8 symmetry, suggests a novel approach to Higgs field (related to an additional conformal sector one can introduce through D3 branes probing this point).

This has led to a new model for modifying MSSM (DSSM) which naturally leads to more massive Higgs, and alleviates the mini-hierarchy problem in SUSY models.

We will wait to see if SUSY plays any role at the weak scale!