String Phenomenology

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Chalk and Cheese?

Figure: String theory and phenomenology?

String Theory

- String theory is where one is led by studying quantised relativistic strings.
- It encompasses lots of areas (black holes, quantum field theory, quantum gravity, mathematics, particle physics....) and is studied by lots of different people.
- This talk is on string phenomenology - the part of string theory that aims at connecting to the Standard Model and its extensions.
- It aims to provide a (brief) overview of this area. (cf Angel Uranga's plenary talk)

String Theory

- For technical reasons string theory is consistent in ten dimensions.
- Six dimensions must be compactified.
- $$\text{Ten} \qquad = \qquad (\text{Four}) \qquad + \qquad (\text{Six})$$
- $$\text{Spacetime} \qquad = \qquad (\mathbb{M}_4) + \text{Calabi-Yau Space}$$
- All scales, matter, particle spectra and couplings come from the geometry of the extra dimensions.
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Model Building

Various approaches in string theory to realising Standard Model-like spectra:

- $E_8 \times E_8$ heterotic string with gauge bundles
- Type I string with gauge bundles
- IIA/IIB D-brane constructions
- Heterotic M-Theory
- M-Theory on G2 manifolds

Heterotic String

Start with an $E_{8,vis} \times E_{8,hid}$ gauge group in ten dimensions.

The gauge group is broken and chiral matter generated by an appropriate choice of gauge field in the Calabi-Yau.

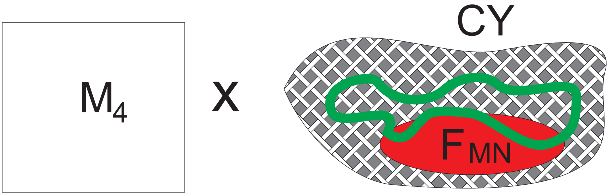
$$E_{8,vis} \times E_{8,hid} \rightarrow SU(5)_{vis} \times E_{8,hid}, E_{6,vis} \times E_{8,hid}$$

Further Wilson lines are needed to break to the Standard Model.

Requires a holomorphic, stable vector bundle in order to carry out the breaking.

At a technical level, requires the mathematics of bundle stability (James Gray's talk).

Heterotic String



Schematic of heterotic compactification: the gauge bundle F_{MN} breaks the $E_8 \times E_8$ gauge group and sources chiral zero modes, which extend throughout the bulk space.

Heterotic String

Weakly coupled heterotic string is a global construction.

Gauge fields propagate on the bulk of the Calabi-Yau.

$$\alpha_{GUT} \sim \frac{1}{\mathcal{V}}, \qquad M_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}.$$

String scale is necessarily close to the Planck scale.

Possible to construct models with Standard Model spectra, and many more with Standard-Model like spectra.

D-brane constructions

Solitonic objects (D-branes) carry worldvolume gauge fields.

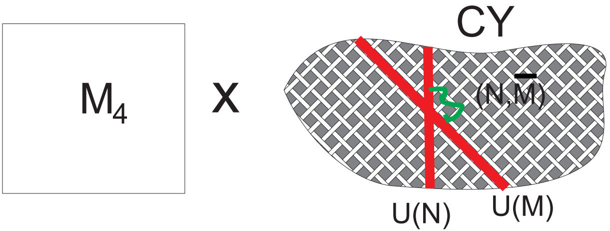
Intersections of two D-branes give chiral matter on the intersection.

Models of intersecting D-branes can give non-abelian gauge groups with chiral matter and may provide a basis for realising the Standard Model.

Stability of D-branes requires classifying special Lagrangian cycles/coherent sheaves on a Calabi-Yau.

D-brane constructions lead to non-GUT approaches to reconstructing the Standard Model spectrum.

D-brane constructions



Schematic of IIA D-brane compactification: D-branes wrap geometric cycles in the Calabi-Yau and chiral matter is supported on D-brane intersections.

D-brane constructions

- Strength of gauge group is determined by volume of cycle Σ_i wrapped by D-brane:

$$\alpha_i \sim \frac{1}{\mathrm{Vol}(\Sigma_i)}, \qquad M_s \sim \frac{M_P}{\sqrt{\mathrm{Vol}(CY)}}.$$

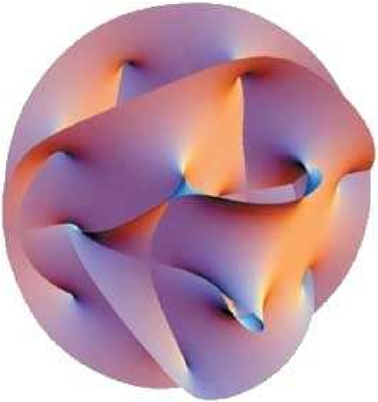
- As $\mathrm{Vol}(\Sigma_i)$ and $\mathrm{Vol}(CY)$ are not necessarily connected, string scale can be much lower than the Planck scale.
- Can imagine Standard Model constructions with string scales close to the TeV scale.

F-theory constructions

- An extension of D-brane constructions which includes certain non-perturbative effects.
- Branes are geometrised as the singularities of an 8-dimensional space: includes D-branes and also further exceptional branes.
- Shares properties of brane constructions such as localisation of gauge groups, but also naturally allows for the possibility of GUT models.
- Can also the string scale to be much lower than the Planck scale.
- But what determines the string scale? $\longrightarrow$ Moduli stabilisation

Moduli Stabilisation

Strings are compactified on Calabi-Yau manifolds.



Moduli Stabilisation

Geometric deformations of Calabi-Yau manifolds appear as (naively) massless scalars in 4 dimensions.

Calabi-Yaus have two basic deformations:

- Kähler (size) deformations: modifying the Kähler form $J = \sum t^i \omega^i$ of the Calabi-Yau.
- Complex structure (shape) deformations modifying the complex structure of the Calabi-Yau.

Kähler deformations are counted by $h^{1,1}(\mathcal{M})$ and complex structure deformations are counted by $h^{2,1}(\mathcal{M})$.

Moduli Stabilisation

It is necessary to give masses to moduli to avoid fifth forces bounds.

The process of moduli stabilisation is also closely tied to supersymmetry breaking.

Moduli stabilisation is best described in the framework of 4-dimensional supergravity.

We need to determine the

- Kähler potential, $\mathcal{K}(\Phi, \bar{\Phi})$.
- Superpotential, $W(\Phi)$.

Scalar potential is $V = e^K(\mathcal{K}^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2)$

Moduli Stabilisation

$$V = e^K (\mathcal{K}^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2)$$

Moduli potential is a potential for scalar fields.

- Can be used to try and realise inflation in string theory. (Marco Zagermann's talk)
- Also is very important for understanding supersymmetry breaking - minima of V can break supersymmetry and generate soft terms.
- We look at supersymmetry breaking in more detail.

Moduli Stabilisation (IIB)

The Kähler potential is

$$\mathcal{K} = -2 \underbrace{\ln \mathcal{V}(T + \bar{T})}_{\text{Kähler}} - \underbrace{\ln \left(i \int \Omega \wedge \bar{\Omega}(U, \bar{U}) \right)}_{\text{complex structure}} - \underbrace{\ln(S + \bar{S})}_{\text{dilaton}}$$

Three-form fluxes can stabilise the dilaton and complex structure moduli:

$$W = \int G_3 \wedge \Omega$$

Gives an effective no-scale model:

$$\begin{aligned} \mathcal{K} &= -2 \ln \mathcal{V}(T + \bar{T}), \\ W &= W_0. \end{aligned}$$

Broken supersymmetry and vanishing vacuum energy.

Moduli Stabilisation (IIB)

Non-perturbative and α' corrections can fix the remaining T moduli:

$$\begin{aligned}\mathcal{K} &= -2\ln\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right)\\ W &= W_0 + \sum_i A_i e^{-a_i T_i}.\end{aligned}$$

Can obtain a minimum at exponentially large values of the volume.

Supersymmetry breaking is similar to no-scale and is dominated by the volume modulus ($F^{T_i} \neq 0, F^U = 0$).

So what?

The MSSM Flavour Problem

The LHC hopes to discover supersymmetry.

But why should any new susy signatures occur at all?

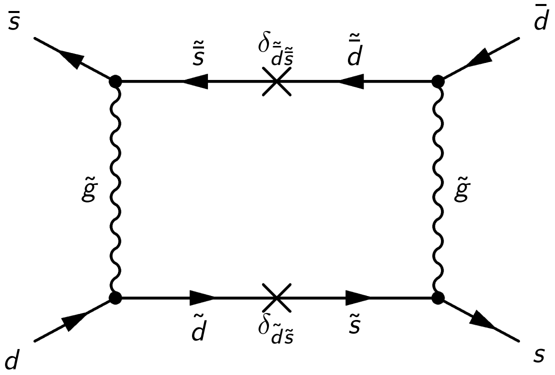
One major problem:

Why hasn't supersymmetry been discovered already?

Compare with

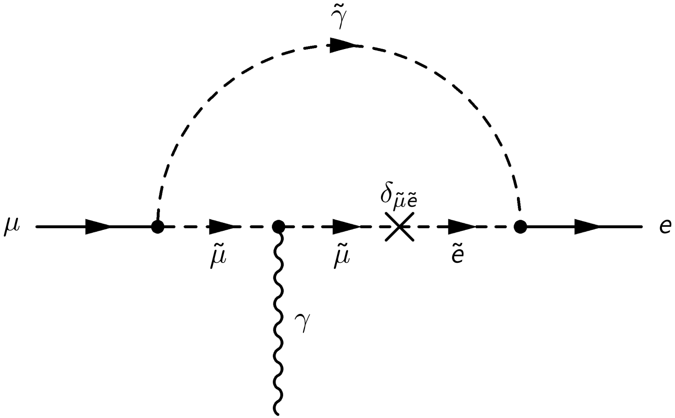
- The c quark - predicted before discovery through its contribution to FCNCs (the GIM mechanism)
- The t quark - mass predicted accurately through loop contributions at LEP I.

The MSSM Flavour Problem



The MSSM gives new contributions to $K_0 - \bar{K}_0$ mixing.

The MSSM Flavour Problem



The MSSM generates new contributions to $BR(\mu \rightarrow e\gamma)$.

The MSSM Flavour Problem

SUSY is a happy bunny if soft terms are flavour universal.

$$\begin{aligned} m^2_{Q,\alpha\bar{\beta}} &= m^2_Q, \\ A_{\alpha\beta\gamma} &= AY_{\alpha\beta\gamma}, \\ \phi_{M_1} &= \phi_{M_2} = \phi_{M_3} = \phi_A. \end{aligned}$$

Why should this be?

- Answer to flavour problem significantly affects all of susy phenomenology.
- This problem cannot be addressed purely within effective field theory - needs UV completion.

The MSSM Flavour Problem

- The flavour problem says that supersymmetry breaking cannot know about flavour physics.
- *A priori*, this is unnatural - why should the susy breaking sector be entirely ignorant of flavour?
- String theory can give a natural answer.

The size and shape fields of the Calabi-Yau are factorised

$$\Phi_{all} = \Psi_{Kahler} \oplus \chi_{complex}$$

Ψ and χ represent two distinct and decoupled sectors.

$$\mathcal{K} = -2 \underbrace{\ln \mathcal{V}(T + \bar{T})}_{\text{Kähler}} - \underbrace{\ln \left(i \int \Omega \wedge \bar{\Omega}(U, \bar{U}) \right)}_{complexstructure} - \underbrace{\ln(S + \bar{S})}_{dilaton}$$

The MSSM Flavour Problem

We have

$$\Phi_{all} = \Psi_{Kahler} \oplus \chi_{complex}$$

with Ψ and χ representing two distinct and decoupled sectors.

It turns out that

1. Ψ_{Kahler} gives rise to supersymmetry breaking.
2. $\chi_{complex}$ generates the flavour structure: $Y_{\alpha\beta\gamma} = Y_{\alpha\beta\gamma}(\chi)$.

Supersymmetry breaking and flavour physics decouple and soft terms are flavour universal!

The origin of this decoupling is the geometric properties of Calabi-Yaus.

Conclusions

- Have provided an overview of the area of string phenomenology
- Subject divides into two main areas, model building and moduli stabilisation.
- Have also described how Calabi-Yau geometry can give intrinsically stringy solutions to low energy field theory problems.