String theory and particle physics

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String theory

1. Elementary constituents are vibrating strings instead of point particles

– a quantum field theory with infinite number of fields

2. Has no ultra-violet divergence.

3. Contains gravity

4. Consistent in ten space-time dimensions

5. There are five consistent string theories, characterized by the degrees of freedom of the string

6. Has no adjustable dimensionless parameter

Even though string theory has no parameter, it has many vacua.

For example, each of the five string theories has a scalar field ϕ, known as the dilaton, with vanishing potential.

$\phi =$ c is a solution to the equations of motion for any constant c.

In quantum theory, c can be interpreted as the vacuum expectation value $\langle\phi\rangle$.

$e^{\langle\phi\rangle}$ plays the role of the coupling constant even though the theory does not have a coupling constant.

Perturbation expansion is in powers of $e^{\langle\phi\rangle}$.

Each of the five string theories also has other interesting classes of solutions

– correspond to vacuum expectation values of other fields including the metric

e.g. the ten dimensional space-time may be of the form

$$M_{d,1} \times K_{9-d}$$

$M_{d,1}$: (d+1) dimensional Minkowski space-time

K_{9-d}: An appropriate $(9-d)$ dimensional compact space such that $M_{d,1} \times K_{9-d}$ satisfies 10 dimensional Einstein equation

Shape and size of K_{9-d} are new parameters labelling this class of vacua* besides the dilaton labelling the coupling constant.

* vacua: solutions preserving Poincare symmetry / de Sitter symmetry / anti de Sitter symmetry in some dimensions

Besides the dilaton and the metric, other fields may also acquire vacuum expectation values if they satisfy the equations of motion

– depends on the details of which string theory we are considering.

e.g. the two heterotic string theories have gauge fields with gauge group $E_8 \times E_8$ and SO(32) respectively

We can switch on vacuum expectation values of these fields along K_{9-d} satisfying equations of motion.

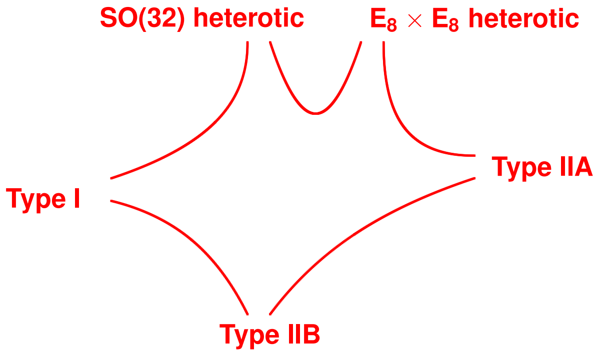
Type IIB / IIA string theory has even / odd rank anti-symmetric tensor fields.

We can switch on vacuum expectation values of these fields etc.

From the description so far, it would seem that we have five different string theories, each with many different vacua.

However discovery of duality symmetry tells us that different vacua of different string theories could describe the same physical theory.

Different string theories are different descriptions of a unified underlying theory



Different vacua are like different objects in a multi-dimensional room.

The five string theories are five windows into the room.

Coupling constant $\rightarrow$ distance of the object from the window

Does any vacuum of string theory describe the standard model at ‘low energy’?

‘Low’: TeV scale

We do not know

In the rest of the talk I’ll try to give an overview of what we know

String theory to particle physics

String theory on

$$M_{d,1} \times K_{9-d}$$

will appear as a theory in d+1 dimensional Minkowski space if K_{9-d} is sufficiently small.

For d=3 it appears as a (3+1) dimensional theory

– beginning of making contact between string theory and particle physics

Any such vacuum will have gravity since string theory contains gravity

Question: Does it have the standard model fields?

In the early days of string theory, the most successful solutions were found in the $E_8 \times E_8$ heterotic string theory on

$$M_{3,1} \times K_6$$

K_6: a six dimensional ‘Calabi-Yau manifold’

After switching on vacuum expectation values of gauge field components along K_6, we can break the gauge group spontaneously to standard model like gauge group

$$SU(3) \times SU(2) \times U(1)$$

We can also get chiral fermions and Higgs fields in the standard model like representation.

In this description, the standard model gauge group comes from one E_8.

The other E_8 could be used for accommodating unknown fields / particles, e.g. the dark matter.

It is in principle possible to get low energy phenomenology from SO(32) and type I theories but they are more complicated.

Problems:

1. The vacua considered initially had space-time supersymmetry

– not observed in nature

– must be broken

There are suggestions for breaking supersymmetry but this requires non-perturbative physics

2. The class of vacua we discussed are labelled by the vacuum expectation values of various fields

e.g. dilaton, shape and size of K_6 etc.

Since their potential is flat, these fields remain exactly massless

– known as moduli fields

– would lead to long range forces not observed in nature

Also if such fields vary with time / space the observed parameters of the standard model will change

– not observed in nature

Existence of such flat potentials is typically a consequence of supersymmetry

– should be lifted once we understand supersymmetry breaking

Question: Is there a (local) minimum of the potential?

– need this for describing standard model like vacua

This problem is known as moduli stabilization

– a universal issue that arises in all approaches to finding vacua of string theory.

Let us suppose that the moduli have been stabilized

– gives the values of all parameters, including the coupling constant

This means that if string theory leads to the standard model, it will give the model with a fixed value of the fine structure constant and other parameters

Usually we are used to using perturbation theory to study quantum field theories

We assume that the coupling constants can be adjusted at will and we can in principle make perturbation theory as good as we want by taking the coupling constants to be sufficiently small

This is not the case in moduli stabilized string theory

This means that even if we are able to stabilize the moduli, we'll not have full control over our theoretical analysis if we rely on perturbation theory

– limitation of our computational ability but not of the theory

Later we shall discuss how the problem of moduli stabilization is studied within this limitation.

Vacua of type II string theories

In the early days, type II string theories were not considered capable of producing standard model like vacua since they did not have non-abelian gauge fields in D=10

Once we have background of the form

$$M_{d,1} \times K_{9-d},$$

gravity could generate some non-abelian gauge fields using symmetries of K_{9-d}

e.g. if we could get a solution with $K_6 = S^6$ – a six dimensional sphere – then we shall have SO(7) gauge symmetry

– not big enough to accommodate the standard model.

However, discovery of duality told us that it must be possible to get bigger non-abelian gauge fields in type II theories since heterotic string theories have them

We now know of two ways of getting non-abelian gauge fields in type II theories

1. D-branes

2. Singular geometries.

Type II string theories have solutions representing extended objects called D-branes

A Dp-brane extends along p directions

D0-brane$\leftrightarrow$particle, D1-brane$\leftrightarrow$string, D2-brane$\leftrightarrow$ membrane etc

1. Type IIB theory has Dp-branes for odd p and type IIA theory has Dp-branes for even p.

2. Coincident Dp-branes have non-abelian gauge fields living on them

e.g. N coincident Dp-branes have U(N) non-abelian gauge fields in p+1 dimensions

Consider type IIA / IIB string theory on

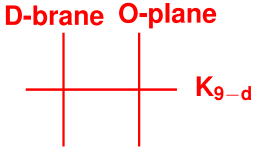
$$M_{d,1} \times K_{9-d}$$

plus N Dd branes along $M_{d,1}$, placed at some point on K_{9-d}

This configuration will have U(N) gauge fields in d+1 dimensional Minkowski space

Typically this configuration does not satisfy equations of motion.

We need to also add 'orientifold planes', extending along $M_{d,1}$ and placed at some point(s) on K_{9-d}



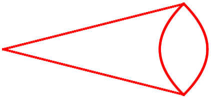
If N Dd branes are placed at the same point as the orientifold plane, the U(N) symmetry gets enhanced to SO(2N)

The second approach to getting non-abelian gauge theories in type II theories is to use singular geometries

K_{9-d} is not smooth but has singularities.

It was known from the early days of string theory that strings can propagate in some kind of singular geometries without feeling the singularity

Simple example: Tip of cones



Describing the motion of a particle through the tip of the cone leads to ambiguities but strings sense smooth geometry near the tip.

After the discovery of duality, it was realized that type II string theory in certain singular geometries can lead to non-abelian gauge fields, i.e. we take

$$M_{d,1} \times K_{9-d}$$

with singular K_{9-d}

Mechanism: Suppose we have some Dp-brane along a p dimensional subspace S_p of K_{9-d}

– can be interpreted as a particle of mass given by

$$\text{area of } S_p \times \text{(mass / unit area) of Dp-brane}$$

In the singular geometry, area of S_p may vanish for some S_p, leading to massless particles

These, together with the abelian gauge particles, generate non-abelian gauge particles

M-theory

Type IIA theory at strong coupling behaves like a 11 dimensional theory named M-theory

IIA on $M_{9,1}$ with coupling $e^{\langle\phi\rangle} \Leftrightarrow$ M-theory on $M_{9,1} \times S^1$ with $R = e^{2\langle\phi\rangle/3}$

As $\langle\phi\rangle \to \infty$, the radius of $S^1 \to \infty$ and we get $M_{10,1}$ on rhs

We do not know much about M-theory except that at low energy it behaves as a well known 11 dimensional supergravity theory

This gives

$$\text{IIA on } M_{d-1,1} \times K_{10-d} \Leftrightarrow \text{M-theory on } M_{d,1} \times K_{10-d}$$

in strong coupling limit

F-theory

IIB on $M_{d,1} \times K_{9-d}$

with ϕ varying as we move on K_{9-d}.

These vacua merge the two ways of getting non-abelian gauge theory in type IIB theory

– singular geometries and

– coincident D-branes

Both these mechanisms can be understood as singular configurations of an auxiliary $(11-d)$ dimensional space.

Typically all the vacua discussed so far have moduli fields

– scalars with no potential

We must find ways to generate potential for the scalars such that there is a local minimum of the potential

We'll discuss this in the context of type IIB vacua since these are most widely studied

Moduli stabilization

Consider electromagnetic field

$$\mathbf{F}_{\mu\nu} = \partial_\mu \mathbf{A}_\nu - \partial_\nu \mathbf{A}_\mu$$

If we have a two dimensional surface S, we can consider configurations with magnetic flux through S:

$$\int_{\mathbf{S}} \mathbf{F} \neq \mathbf{0}$$

But to ensure single valued wave-function of charged particles, the flux is quantized (Dirac quantization)

If S is contractible to a point, then $\int_{\mathbf{S}} \mathbf{F} \neq \mathbf{0}$ will requite F to diverge near that point

– magnetic monopole

If one the other hand S is a non-contractible surface inside $\mathbf{K}_6$, then $\int_{\mathbf{S}} \mathbf{F} \neq \mathbf{0}$ can be achieved with non-singular field configuration.

Type IIB string theory has two rank 2 anti-symmetric tensor fields $B_{\mu\nu}, C_{\mu\nu}$

Analog of $F_{\mu\nu}$ are rank 3 anti-symmetric tensors

$$H_{\mu\nu\rho} = \partial_\mu B_{\nu\rho} + \text{cyclic permutation}, \quad F_{\mu\nu\rho} = \partial_\mu C_{\nu\rho} + \text{cyclic permutation}$$

If K_6 has a 3 dimensional non-contractible surface S, we can switch on H and F flux through S

– generates potential for the moduli

Does the resulting potential have extrema?

Under reasonable conditions, when the quantized fluxes are not too big, we often get extrema.

In particular the modulus corresponding to the coupling constant depends on the ratio of the H and F-fluxes.

By taking the fluxes appropriately we can try to ensure that the potential has a minimum at a place where the coupling is small

– can trust perturbation theory

However since fluxes are quantized and cannot be too large, the coupling constant cannot be made arbitrarily small.

Problem: This mechanism does not produce a potential for the modulus χ corresponding to the size of K_6.

We need additional mechanism to stabilize this modulus.

1. KKLT: Non-perturbative corrections

$$V = -Ae^{-c\chi} + Be^{-2c\chi}, \quad A, B, c : \text{constants}$$

This will have an extremum where $e^{-c\chi} \sim 1$

Question: Are we justified in ignoring the order $e^{-3c\chi}$ terms?

2. LVS: Stringy + non-perturbative corrections

$$V = A\chi^{-\alpha} - Be^{-c\chi}, \quad A, \alpha, B, c : \text{constants}$$

– extremum at $\chi \sim 1$

Can we justify ignoring terms with higher powers of χ^{-1} or $e^{-c\chi}$?

In both scenarios, we typically end up with a vacuum with negative energy density

– negative cosmological constant

Our universe has positive cosmological constant.

We need to add a stack of D-branes to raise the energy density to positive value and get de Sitter universe

Why is the cosmological constant so small?

A typical K_6 has large number N of non-contractible 3 dimensional subspaces.

We can switch of F and H flux through each of them.

Suppose the quantized fluxes can take values 1,2,$\cdots$,M

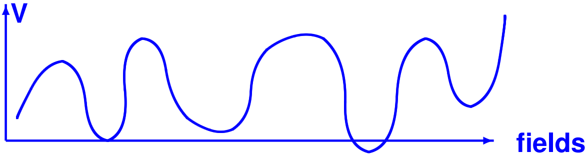
Then there are $\sim M^N \times M^N$ possible configuration of fluxes

– large number

e.g. for M=10 and N=100, we get 10^{200} possibilities with different cosmological constants

Some of them may have small cosmological constant $\sim 10^{-120}$ in natural units

One can give a simplified picture of the many vacua by imagining a theory with many scalar fields with complicated potential with many extrema.



String landscape

If string theory is the correct description of nature, then one of these minima with positive potential should describe us.

But what is special about that one?

Multiverse and anthropic principle

Different regions of the universe may be in different vacua

Most of them have cosmological constants ~ 1

– either collapses too fast or expands too fast

– not good for development of life in the form we know

A small fraction of the universe may be in a phase with low cosmological constant

We live inside one of them.

The swampland

From the discussion so far it should be clear that in order to predict the parameters of the standard model, we need to find the vacuum that describes us

– a difficult task

Swampland program examines the known vacua,

and conjectures that properties shared by all known vacua are general principles that hold for all vacua.

Values of low energy parameters that do not satisfy these relations are said to be in the Swampland

– outside the string landscape

Danger of this program:

The vacua we know and can study well are those with unfixed moduli.

Otherwise we do not have fully controllable perturbation expansion that we can use.

General lessons based on these vacua may not hold for the ones where all moduli are fixed

– the ones relevant for our universe

With this caveat in mind we'll now describe some of the conjectures in this program

Weak gravity conjecture:

In any string theory vacua with U(1) gauge fields, there is a charged particle for which the long range gravitational force is weaker than the electromagnetic force.

– true in our world, with electrons, protons, W-bosons etc. providing examples

– true in known vacua of string theory

Distance conjecture:

If there are scalars with nearly flat potential, then as we travel a distance of order one in Planck scale in the scalar field space, infinite tower of states become massless

– original low energy description breaks down

This is relevant for inflation since there we make use of scalars with almost flat potential.

Lyth bound requires the inflaton to roll over super-Planckian distances for producing significant tensor perturbation.

Therefore the distance conjecture seems to suggest that tensor perturbations are very small.

There is a way out of this based on ‘axion monodromy inflation’

A scalar keeps travelling round and round in the field space during inflation, thereby never travelling a distance larger than the Planck scale from the starting point.

Nevertheless the potential slowly decreases, as required by inflation, due to decrease of tension of some D-brane

– can produce measurable tensor to scalar ratio

Nevertheless, if we believe in the distance conjecture, and observe tensor to scalar ratio in the future, there will be strong constraint on the dynamics of inflation.

There are several other such conjectures, some quite wild, that we shall not discuss.

The way forward

Given that the details of moduli stabilization cannot be studied fully in the weak coupling approximation, it seems necessary to have better understanding of non-perturbative corrections.

If we have the actual coefficients appearing in the perturbative and non-perturbative corrections, we could in principle check if the terms we are ignoring remain small.

Eventually we may have to rely on expansion in $1/\pi$ instead of an adjustable parameter.

Conclusion

It should be clear from the talk that connecting particle physics to string theory remains a distant goal

Nevertheless, till now string theory remains the only candidate that can possibly accommodate gravity and other observed forces and particles into a single quantum theory