String Theory and Particle Physics

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Introduction: The Standard Model

Particle physics is based on an experimentally extremely successful theory

the Standard Model (SM)

Properties of the Standard Model:

➪ spectrum:

- matter fields: (spin = 1/2)
  3 families of quarks and leptons
  with measured masses and couplings,
- gauge bosons: (spin = 1)
  gluons, $W^{\pm}, Z^0, \gamma$ of gauge group

$$G_{SM} = SU(3) \times SU(2) \times U(1)_Y \xrightarrow{\langle H \rangle} SU(3) \times U(1)_{em}$$

- Higgs field H (spin = 0)

➪ experimental situation:

- good qualitative/quantitative agreement in $SU(3)$ sector
- impressive quantitative agreement in $SU(2) \times U(1)$ sector (electroweak precision data)
- no direct observation of Higgs boson yet
- observation of neutrino masses (first modification of SM)

➪ mathematical framework:

local quantum field theory (QFT)
with spontaneously broken non-Abelian gauge symmetry

- electroweak precision data test 'rules' of QFT
- gauge symmetry ensures consistency of quantization and fixes/constrains the couplings

SM leaves a number of open questions:

- what determines G_{SM} and the spectrum of particles ?
- many (19) free parameters: masses, couplings, ...
- what sets the weak scale ?
- what keeps it stable ?
- gravity cannot be consistently turned on
  (general relativity is not a renormalizable quantum field theory)

$\Rightarrow$ belief:

Standard Model is only an 'effective' theory above some scale $l \leq 10^{-18}m$

Below this scale: new phenomena and new theory.

The theory of gravity: General Relativity

➪ GR is the field theory of the gravitational interaction

- the gravitational field is the metric tensor $g_{\mu\nu}$ of space-time
- energy and momentum act as sources of the gravitational field
- Einstein's field equations

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G c^{-4} T_{\mu\nu}}$$

- measured constants:

  G: Newton's constant , Λ: cosmological constant

➪ GR successfully governs cosmology and astrophysics

$\Rightarrow$ Standard Model of Cosmology

GR leaves a number of open questions:

- what sets the value of G – why is gravitational interaction so weak compared to strong & electro-weak interactions?
- what sets the value of Λ – why is it so small ?
- physics of singularities (Big Bang and black holes) ?
- quantum theory of gravity ?

$\Rightarrow$ belief: GR is not a fundamental theory

$\Rightarrow$ Theories "beyond" SM and GR:

- Technicolor
- Supersymmetry/Supergravity
- Grand Unified Theories
- String Theory

Supersymmetry [Wess, Zumino]

➪ symmetry among fermions and bosons;

➪ generalization of Poincaré-algebra

$$\{Q^I, Q^{\dagger J}\} \ = \ \gamma^\mu p_\mu \, \delta^{IJ} \ , \quad I, J = 1, \ldots, N \ ,$$

Q is generator of supersymmetry transformation.

➪ Properties:

- fermions & bosons sit in the same multiplet
  $\Rightarrow$ enlargement of particle spectrum;
- quantum corrections are “tamed”
  $\Rightarrow$ light Higgs boson is ‘natural’ and predicted,
  $\Rightarrow$ strongly coupled QFT can be better controlled.
- consistent with electro-weak precision data;
- dark matter candidate: LSP
- gauge coupling unification

(super-) GUTs:

[Georgi,Glashow]

➪ Generalizes the gauge principle of the SM:

- all interactions are unified in one gauge group

$$G_{\rm GUT} \supset G_{\rm SM} = SU(3) \otimes SU(2) \otimes U(1) \ ,$$

(e.g. $G_{\rm GUT} = SU(5), SO(10), E_6$)

- quarks and leptons are in the same multiplet

necessary condition: unification of gauge couplings

$\Rightarrow$ supersymmetric GUTs at $\boxed{M_{GUT} \sim 3 \cdot 10^{16} GeV}$

➪ Properties:

- predicts decay of the proton $\Rightarrow$ instability of matter
- suggests light neutrinos

$$m_\nu \sim \frac{M_{Z^0}^2}{M_{GUT}} \sim \mathcal{O}(10^{-3}{\rm eV})$$

Supergravity

Supergravity $\equiv$ gauged (local) supersymmetry

- necessary to introduce fermionic gauge field, the gravitino $(s = 3/2)$
  forms together with graviton a supermultiplet
  $\Rightarrow$ local supersymmetry only exists when gravity is turned on
- If gravitino (& Higgs) exist all spins $0 \leq s \leq 2$ occur
- supersymmetric SM with soft supersymmetry breaking
  can be embedded into spontaneously broken supergravity
- UV-finiteness of supergravity not settled but not expected

At what scale is a quantum gravity necessary?

$$\lambda_{\text{Compton}} = \frac{\hbar}{Mc} \approx R_{Schwarz} = \frac{MG}{c^2} ,$$

Planck mass:	$M_{PL} = \sqrt{\frac{\hbar c}{G}} \approx 10^{-5} g$
Planck energy:	$E_{PL} = c^2 M_{PL} \approx 10^{19} GeV$
Planck length:	$l_{PL} = \sqrt{\frac{G\hbar}{c^3}} \approx 10^{-35} m$
Planck time:	$t_{PL} = l_{PL}/c \approx 5 \cdot 10^{-44} s$

relevant in

- history of the (very) early universe $\approx 10^{-43}$ sec after big bang
- physics of black holes of mass $M \approx M_{PL}$

conjecture:

at length scales

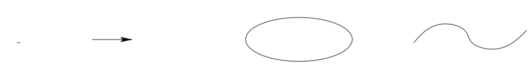
$$l \approx l_{PL} = \sqrt{\frac{\hbar G}{c^3}} \approx 10^{-35} m$$

a completely new concept is necessary to describe nature.

(Perturbative) String Theory

[Veneziano, Nambu, Goto, Susskind, . . .]

Idea: point-like objects $\longrightarrow$ strings



Strings move in D-dimensional Minkowskian background.

(perturbative) string theory is quantum theory of extended objects (strings).

Quantum excitations:

- finitely many massless excitations L:

s = 2	$\longrightarrow$	graviton
s = 3/2	$\longrightarrow$	gravitino
s = 1	$\longrightarrow$	gauge bosons
s = 1/2	$\longrightarrow$	fermions (quarks & leptons)
s = 0	$\longrightarrow$	Higgs, ...

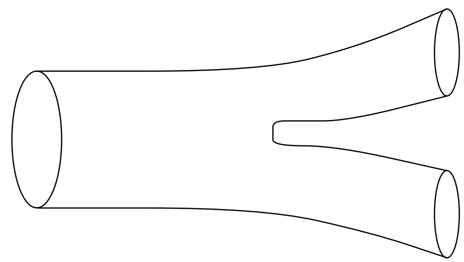
- infinitely many massive excitations H

$$M \sim n \cdot M_S$$

$M_{\rm S}$ = characteristic scale of string theory (tension of the string)

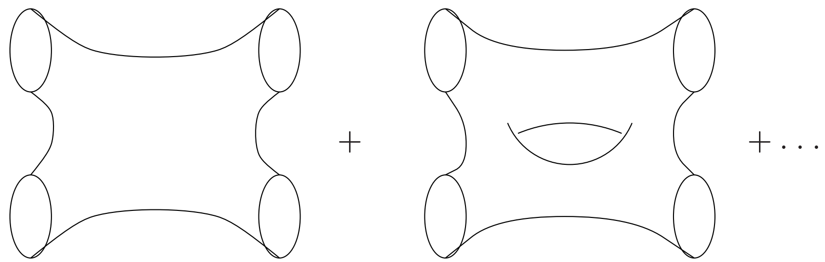
$\Rightarrow$ soft UV behavior

Interactions:



$\sim g_s$

$g_s = e^{-\langle \phi \rangle}$ is coupling constant, ϕ is scalar field (dilaton) scattering amplitudes:



quantization via "Feynman-diagrams"

scattering amplitude: $$A = \sum_{n=0}^{\infty} A^{(n)} g_s^{2+2n} \ .$$

Results:

- spectrum contains non-Abelian gauge theory with families of chiral fermions coupled to gravity
- for scattering processes with $p \ll M_S$:

$$\text{string theory} \stackrel{p \ll M_S}{\longrightarrow} \text{QFT \& GR}$$

$$A_{string} \longrightarrow A_{QFT,GR}$$

$$(\text{with } M_S \sim M_{Pl})$$

$\Rightarrow$ QFT & GR are low energy limit of string theory.

- g_s is free parameter and one can choose $g_s \ll 1$
  $\Rightarrow$ perturbative evaluation of A possible
- amplitudes $A^{(n)}$ are UV-finite ?

$\Rightarrow$ string theory is candidate for perturbative quantum gravity coupled to non-Abelian gauge theory

Properties

- spectrum is supersymmetric

  $\Rightarrow$ necessary for consistency ?

- unitarity of scattering amplitudes $\Rightarrow$ $\boxed{D \leq 10}$

  - $D = 10$: 5 different string theories: IIA, IIB, I, Het. $E_8 \times E_8$, Het. $SO(32)$

  - $D < 10$: families of theories

    geometrical compactification:

$$\mathcal{M}^{(10)} = \mathcal{M}^{(D)} \otimes K^{(10-D)}$$

consistency demands $K =$ Calabi-Yau manifold

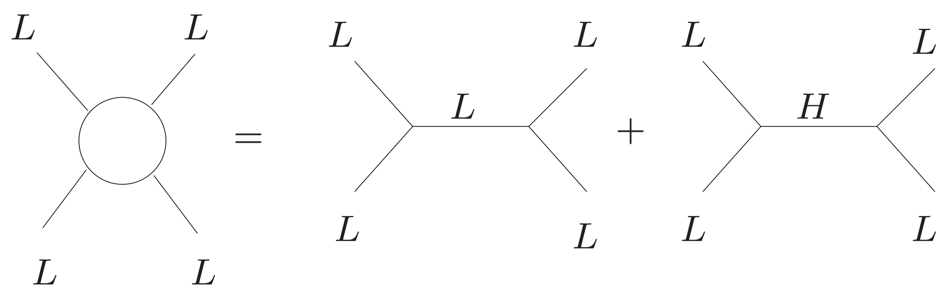
holonomy group of $K \Leftrightarrow$ number of supersymmetries

$\Rightarrow$ what chooses D ?

$\Rightarrow$ what chooses K ?

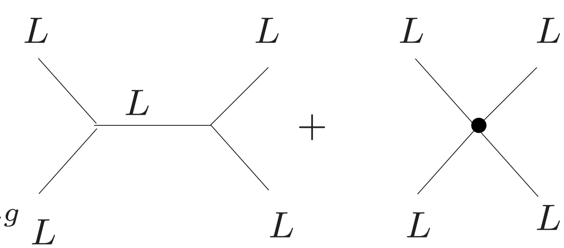
Contact with SM: The effective action

Integrating out the heavy modes H results in the low energy effective action $\mathcal{L}_{\text{eff}}(L)$ of the light modes L



$+$ t and u channels

$$\underset{p^2 \ll M^2_{string}}{=}$$



$+$ t and u channels

for $p^2 \ll M^2_{string}$: amplitudes of an effective field theory

Problems

- supersymmetry unbroken **!**
- quarks, leptons and Higgs massless, $SU(2) \times U(1)$ unbroken
  - $\Rightarrow$ what generates small masses ?
  - $\Rightarrow$ what generates the hierarchy $\frac{m_Z}{m_{Pl}} \approx 10^{-17}$
- effective potential V has flat directions (moduli T)
  - $\Rightarrow$ continuous vacuum degeneracy parameterized by $\langle T \rangle$
- Yukawa Y and gauge couplings g dynamically determined

$$Y = Y(\langle T \rangle) \; , \quad g = g(\langle T \rangle)$$

but free parameters.

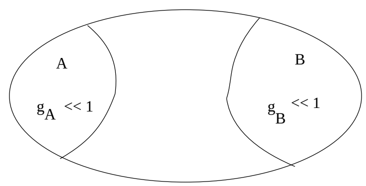
hope: cured by non-perturbative effects.

Non-perturbative Aspects of String Theory

[Hull,Townsend, Witten, . . .]

conjecture:

different string theories are dual description of one quantum theory:



perturbative spectrum A ⇔ non- perturbative spectrum B

perturbative spectrum B ⇔ non- perturbative spectrum A

difficult to prove but successful checks on 'protected' couplings !

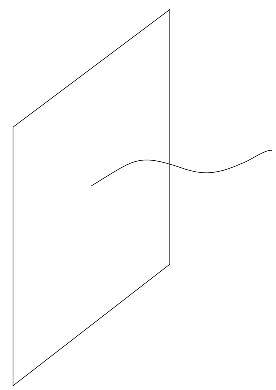
(such couplings do exist in supersymmetric theories)

Non-perturbative states of string theory: D-branes

D-Branes

[Polchinski]

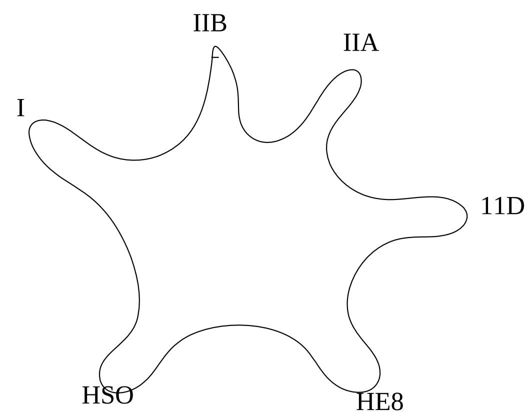
open string with Dirichlet boundary condition define hyperplane



- D-Branes are dynamical objects of string theory
- D-Branes are non-perturbative states of string theory (tension $\sim g_s^{-1}$)
- string theory is not a theory of only strings but also describes higher-dimensional objects – Branes

M-Theory

Generalization: All string theories are perturbative limits of one quantum theory



What is M-theory ?

Suggestion: theory of D-particles [Banks, Fischler, Shenker, Susskind].

$\Rightarrow$ space-time becomes non-commutative

Perspectives – where do we go from here?

➪ string theory as a fundamental theory

- conceptual
- Particle Physics
- GR/cosmology

➪ string theory as a technical tool

- QFT
- Mathematics

string theory as a fundamental theory

- conceptual
  - define and understand M-theory or
  - define and understand non-perturbative string theory
- Particle Physics
  - study compactifications of string theory and their non-perturbative properties
  - is our universe a D-brane? $\Rightarrow$ study Brane-World scenarios
- GR/Cosmology
  - study time-dependent (cosmological) string backgrounds
  - develop string scenarios for the Big Bang
  - embed de-Sitter backgrounds in string theory
  - study quantum Black Hole physics

string theory as a technical tool

➪ QFT

- use string theory to organize the Feynman perturbation theory

  [Bern, Dixon, Kosower]

- use string theory as a regulator ⇒ lessons for supersymmetric QFT

- learn about strongly coupled (supersymmetric) QFTs ⇒ (s)QCD
  - AdS/CFT correspondence ($N = 4$)
  - Seiberg/Witten ($N = 2$)
  - Dijkgraaf/Vafa ($N = 1$)

  and develop new tools

➪ string theory and Mathematics

- point-like particle ≡ probe of continuous space-time geometry
  ⇒ relation with Riemannian geometry [Einstein,Hilbert]

- string as probe: sees coarser structure
  ⇒ development of quantum geometry [Kontsevich, Manin, . . .]

  surprising results:

  – mirror symmetry in Calabi-Yau manifolds
  – computation of number of holomorphic curves on Calabi-Yau manifolds
  – development of quantum cohomology

Summary

- string theory unifies all interactions and provides perturbative quantum gravity.
- qualitative agreement with generalizations of the Standard Model but no quantitative agreement yet.
- biggest problems:
  - hierarchical supersymmetry breaking,
  - determination of the ground state,
  - cosmological constant.
- non-perturbative properties at least partially under control.
- phenomenological implications are being investigated.