Introduction to String Phenomenology

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Outline

I. The Standard Model
II. Overview
III. Heterotic model building
IV. Brane worlds
V. Flux compactifications and moduli stabilization

Bibliography

1. *String Theory and Particle Physics: An Introduction to String Phenomenology,*
   L.E. Ibáñez and A.M. Uranga, CUP 2012.

2. *A First Course in String Theory, B. Zwiebach, CUP 2009.*

3. *String Theory, Vol. 2: Superstring Theory and Beyond, J. Polchinski, CUP 1998.*

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I. The Standard Model

Basics

The SM describes electromagnetic, weak and strong interactions.
It is a quantum field theory with gauge group

(force carriers)
gauge bosons $\Longrightarrow$

$$\underbrace{SU(3)}_{\text{gluons } G^a_\mu} \times \underbrace{SU(2) \times U(1)_Y}_{W^\pm_\mu,\ Z_\mu,\ A_\mu}$$

$W^\pm$ and Z massive due to spontaneous symmetry breaking, $m_{EW} \sim 10^2$ Gev

Matter particles: quarks + leptons in 3 families

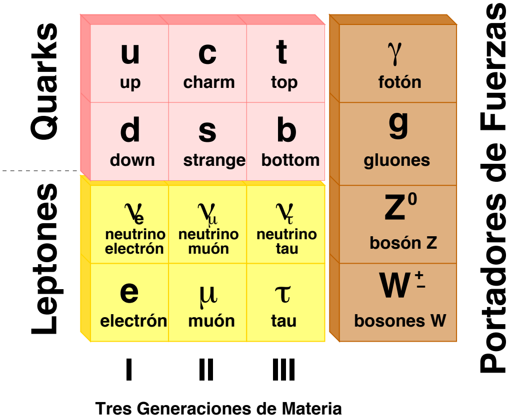
$Q^i_L = \begin{pmatrix} U^i_L \\ D^i_L \end{pmatrix}$	D^i_R	U^i_R	$L^i = \begin{pmatrix} \nu^i_L \\ E^i_L \end{pmatrix}$	E^i_R
$(\mathbf{3}, \mathbf{2})_{\frac{1}{6}}$	$(\overline{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}}$	$(\overline{\mathbf{3}}, \mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{1}, \mathbf{1})_1$

$i = 1, 2, 3$

left-handed
Weyl spinors

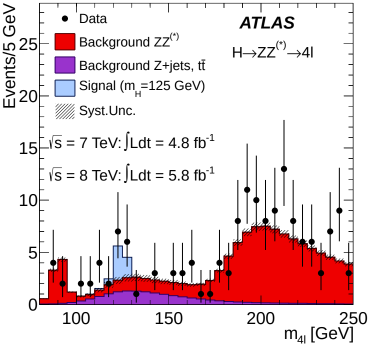
Higgs scalar $\quad H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix} \quad (\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$

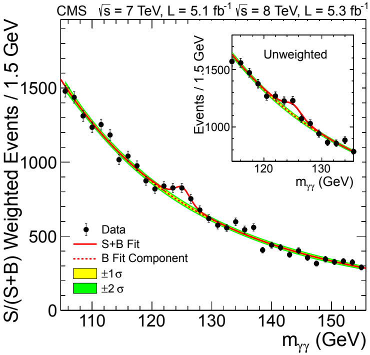
Partículas Elementales



+ Higgs

Higgs found at LHC, July 2012





$m_H \sim 125\,\text{GeV}$

SM Lagrangian

Schematically

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}^{i\,\dagger} \bar{\sigma}^{\mu} D_{\mu} \psi^{i}$$

$$+ |D_{\mu} H|^2 - V(H) \qquad \text{Higgs}$$

$$+ Y_{ij} \psi^{i} \psi^{j} H \qquad \text{Yukawa interactions}$$

only terms of mass dimension ≤ 4 $\Rightarrow$ conservation of B and L

Features of the SM

- $\langle H \rangle \neq 0 \;\Rightarrow\;$ electroweak spontaneous symmetry breaking (EW SSB)

$$SU(2) \times U(1)_Y \xrightarrow{\langle H \rangle} U(1)_{\rm EM}$$

- the fermionic spectrum is chiral, i.e. left-handed and right-handed fermions have different $SU(2) \times U(1)_Y$ quantum numbers
- chiral fermions $\Rightarrow$ Dirac masses $m\,\bar{f}_R f_L +$ h.c. not gauge invariant
- fermion masses due to EW SSB and Yukawa couplings

$$\mathcal{L}_{\rm Yuk} \;=\; Y^L_{ij} L^i E^j_R H \;+\; Y^D_{ij} Q^i_L D^j_R H \;+\; Y^U_{ij} Q^i_L U^j_R H^* + \text{h.c.}$$

$$\mathcal{L}_{\rm Yuk} \xrightarrow{\langle H \rangle} m^L_{ij}\, L^i E^j_R \;+\; m^D_{ij}\, Q^i_L D^j_R \;+\; m^U_{ij}\, Q^i_L U^j_R + \text{h.c.}$$

$$m \;=\; Y \langle H \rangle \xrightarrow{V_L m V_R^\dagger} \text{diag}(m_1, m_2, m_3)$$

- couplings of $W^\pm$ to U- and D-quarks given by

$$V_{CKM} = V^U_L V^{D\,\dagger}_L \qquad \text{Cabbibo-Kobayashi-Maskawa matrix}$$

Neutrino masses

In the SM $m_\nu = 0$

but observed neutrino oscillations require non-zero tiny $m_\nu \sim 10^{-6} m_e$.

It can be explained introducing right-handed neutrinos ν_R

transforming as $(\mathbf{1},\mathbf{1})_0$ under $SU(3) \times SU(2) \times U(1)_Y$

and implementing the *see-saw* mechanism via

$$\mathcal{L}_{\rm Yuk} \supset Y^\nu_{ij} L^i \nu^j_R H^* + M_{ij} \nu^i_R \nu^j_R + \text{h.c.}$$

with $M \gg Y^\nu \langle H \rangle$

Alternatively, without ν_R, it can be explained allowing

lepton-number violating terms $\frac{h_{ij}}{M} L^i L^j H^* H^* + \text{h.c.}$

More open questions

▷ Many free parameters, e.g. three coupling constants, quark and lepton masses.
In particular there is a flavor puzzle

observed values

quarks: $(m_u, m_c, m_t) \sim (0.003, 1.3, 170)$ GeV ; $(m_d, m_s, m_b) \sim (0.005, 0.1, 4)$ GeV

leptons: $(m_e, m_\mu, m_\tau) \sim (0.0005, 0.1, 1.8)$ GeV

$$|V_{CKM}| \sim \begin{array}{cc} \begin{array}{ccc} \text{d} & \text{s} & \text{b} \end{array} & \\ \left|\begin{array}{ccc} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.99 \end{array}\right| & \begin{array}{c} \text{u} \\ \text{c} \\ \text{t} \end{array} \end{array}$$

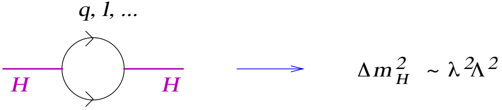
∗ large hierarchies $m_3 \ggg m_2 \gg m_1$

∗ small mixings $V_{su} \sim \epsilon, \quad V_{bc} \sim \epsilon^2, \quad V_{bu} \sim \epsilon^3$

More open questions

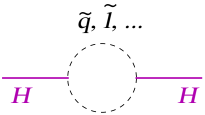
▷ EW hierarchy problem: Why is the Higgs mass m_H not modified by loop corrections ?

The problem is due to radiative corrections



and the cutoff scale Λ could be as large as the Planck mass.

Supersymmetry gives a solution. For every fermion $q, l, \cdots$ there is a scalar $\tilde{q}, \tilde{l}, \cdots$ and the above loop diagram is cancelled by



MSSM

Minimal Supersymmetric Standard Model:

extension of the SM with one additional Higgs and supersymmetric partners (gauginos, squarks, sleptons, Higgsinos).

There are dim 4 couplings violating B and L, e.g. $U_R D_R \tilde{D}$, $LL\tilde{E}$. Such couplings lead to fast proton decay. They can be forbidden imposing R-parity, a $\mathbb{Z}_2$ symmetry under which the SM particles are even and the partners are odd. R-parity ensures that the lightest supersymmetric particle is stable and is then a candidate for dark matter.

Since the superpartners have not been detected, supersymmetry must be broken above the electroweak scale but so far no evidence has been found the LHC.

More open questions

- Why $G_{\mathrm{SM}} = SU(3) \times SU(2) \times U(1)_Y$ and the specific matter representations ?

  Some simplification is achieved in Grand Unified Theories (GUTs).

  The idea is that there is a bigger symmetry group $G_{\mathrm{GUT}} \supset G_{\mathrm{SM}}$ manifest at high energy scales $M_{GUT} \sim 10^{16}$ Gev.

  The GUT idea is supported by the unification of gauge couplings g_a, obtained extrapolating the lower scale experimental values using the renormalization group equations,

$$\frac{4\pi}{g_a^2(Q^2)} = \frac{4\pi}{g_a^2(M^2)} + \frac{b_a}{4\pi} \log \frac{M^2}{Q^2}$$

  The one-loop β-function coefficients b_a depend on the group and the matter content, e.g. for $SU(3)$ $b_3 = -11 + \frac{4}{3} N_{\mathrm{gen}}$.

Gauge coupling unification

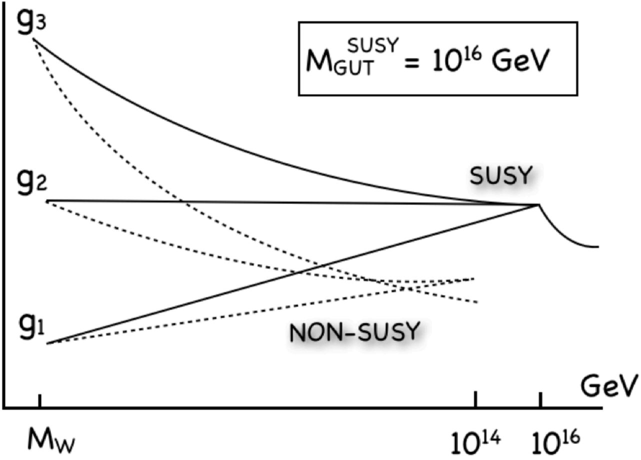


Figure from *String Theory and Particle Physics: An Introduction to String Phenomenology* L.E.Ibáñez, A.M. Uranga

GUTs

$G_{\mathrm{GUT}} = SU(5)$

1 family $= \mathbf{10} + \overline{\mathbf{5}}$

$SU(5) \supset SU(3) \times SU(2) \times U(1)_Y$

$\mathbf{10} = (\mathbf{3}, \mathbf{2})_{\frac{1}{6}} + (\overline{\mathbf{3}}, \mathbf{1})_{-\frac{2}{3}} + (\mathbf{1}, \mathbf{1})_1$

$\overline{\mathbf{5}} = (\overline{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}} + (\mathbf{2}, \mathbf{1})_{-\frac{1}{2}}$

$SU(5)$ broken to G_{SM} by Higgs in the adjoint **24**.

For EW SSB the Higgs is also in $\overline{\mathbf{5}}$. Quark and lepton masses from Yukawa couplings: $\mathbf{10} \cdot \mathbf{10} \cdot \overline{\mathbf{5}}$, $\quad \mathbf{10} \cdot \overline{\mathbf{5}} \cdot \overline{\mathbf{5}}$

The triplets in the Higgs $\overline{\mathbf{5}}$ can mediate proton decay so they must be much more massive than the doublets.This is the doublet-triplet splitting problem.

Other GUTs

$G_{\text{GUT}} = SO(10)$

1 family + ν_R= **16**

$SO(10) \supset SU(5) \times U(1)$

$\mathbf{16} = \mathbf{10} + \overline{\mathbf{5}} + \mathbf{1}$

$G_{\text{GUT}} = E_6$

1 family + ν_R + exotics= **27**

$E_6 \supset SO(10) \times U(1)$

$\mathbf{27} = \mathbf{16} + \mathbf{10}_V + \mathbf{1}$

$E_6 \supset SU(3) \times SU(3) \times SU(3)$

$\mathbf{27} = (\mathbf{3}, \overline{\mathbf{3}}, \mathbf{1}) + (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{3}) + (\mathbf{1}, \mathbf{3}, \overline{\mathbf{3}})$

More open questions

▷ How to include gravity ?

The scale at which gravitational interactions become important is the Planck mass

$$M_P = \sqrt{\frac{\hbar c}{G_N}} \sim 10^{19}\,\mathrm{Gev}$$

G_N is the fundamental constant in Newton's law $F_{grav} = G_N \frac{m_1 m_2}{r^2}$.

Since $m \sim E$, $G_N \sim 1/M_P^2$, the effective gravitational coupling is

$\alpha_{grav} = (E/M_P)^2$ which grows quadratically with energy.

The perturbative expansion of gravity diverges.

An ultraviolet (UV) completion is needed $\Longrightarrow$ Strings ?!

II. String Phenomenology overview

Aim

- Study how to embed the SM in string/M-theory and address the open questions.
  - Identify classes of constructions that realize characteristic features: chirality, family replication, EW SB, flavor structure, ...
  - Extract generic properties and look for mechanisms behind.
  - Obtain and analyze explicit models.

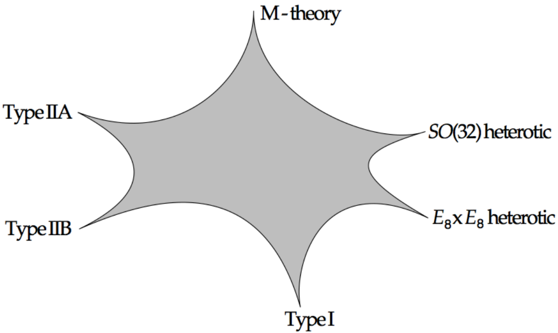
A main difference with conventional model building is that after specifying the starting setup, for instance the internal space or the D-brane content, the particle spectrum and the interactions are fixed.

String/M-theory

To begin we have the 10d string theories: $E_8 \times E_8$ heterotic, $SO(32)$ heterotic , type I, type IIA and type IIB.

There is also the 11d M-theory.

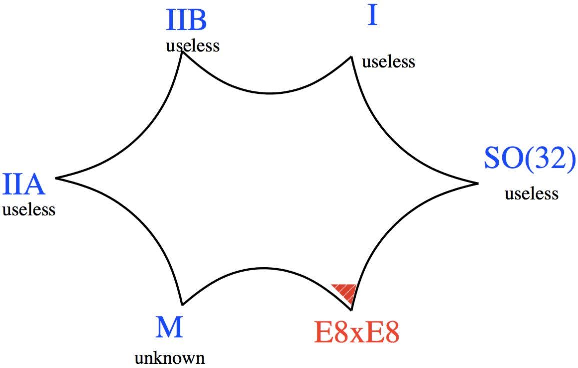
They are now thought to be all manifestations of one theory.



A brief history

In the period 1985-1995 attention mostly focused on compactifications of the $E_8 \times E_8$ heterotic.

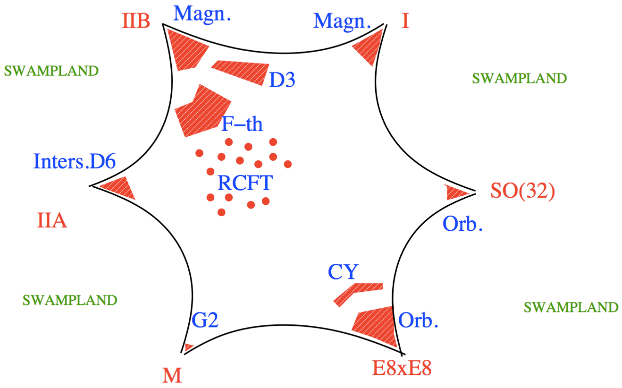
In this theory gauge multiplets are already present in 10d and give rise to e.g. E_6 GUTs and chiral fermions in 4d.



A brief history

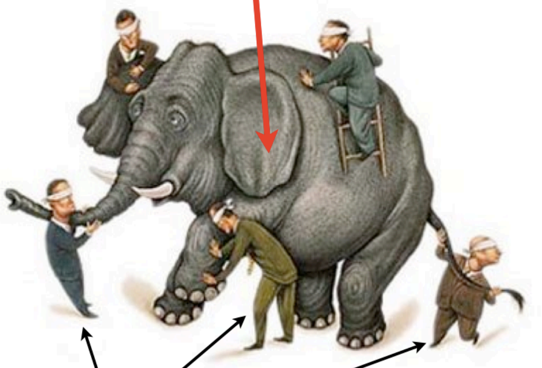
After the advent of D-branes in 1995 it was understood how the SM could be reproduced in the context of type I and type II strings.

At present all corners of the underlying theory are being explored.



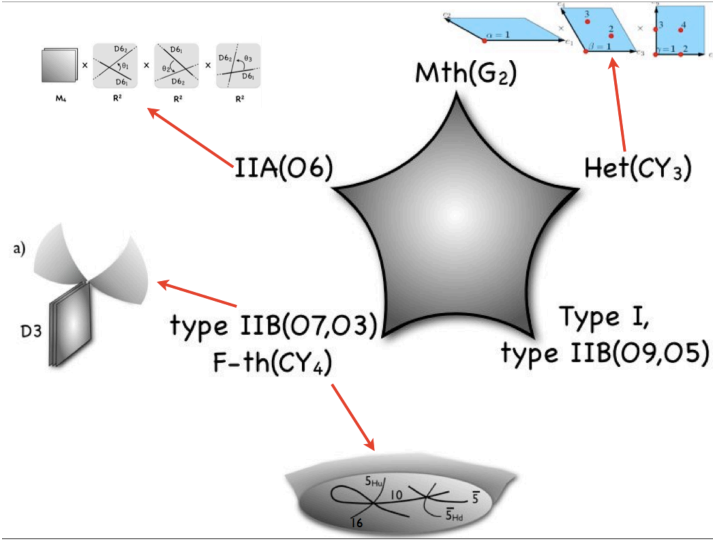
Figures from *Sumary Talk, String Pheno 2014* by L.E.Ibáñez

String/M-theory



String phenomenologists

Classes of models



Preview

In these lectures we will study realizations of the SM via:

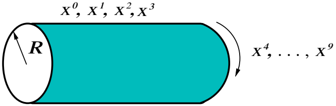
- Compactification of the heterotic string on orbifolds and Calabi-Yau (CY) manifolds.
- D-brane constructions.

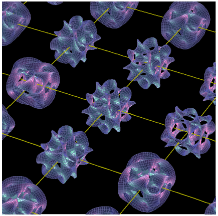
Some generic properties that are found:

- Chiral fermionic spectrum.
- Family replication.
- Gauge coupling unification, with or without GUT.
- Existence of moduli, i.e. massless scalars whose undetermined vacuum expectation values (vevs) give coupling constants.

Compactifications of the heterotic string

Kaluza-Klein idea: $\mathcal{M}_{10} = \mathcal{M}_4 \times K_6$





Gauge vectors in $10d$: A^a_M,

$M = 0, \ldots, 9, \quad a = 1, \ldots, \dim G_{\text{het}}, \quad G_{\text{het}} = E_8 \times E_8$ or $SO(32)$

Compactifying on $K_6 = \mathrm{T}^6$ gives fields in $4d$:

$A^a_\mu, \;\; \mu = 0, \ldots, 3$ gauge vectors $\oplus$ $A^a_m, \;\; m = 4, \ldots, 9$ 6 charged scalars

$10d$ gauginos give susy partners in $4d$

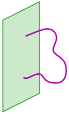
$\mathcal{N} = 4$ theory, non-chiral fermions

This problem is avoided if K_6 has $SU(3)$ holonomy as in CYs and orbifolds.

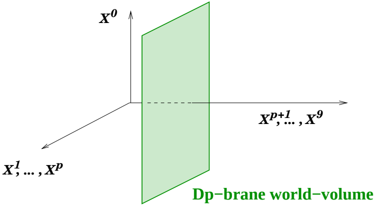
D-branes and gauge theories

1995

degrees of freedom:



open superstrings



massless states:

gauge multiplet, charged multiplets

example: susy Yang-Mills in D7-branes

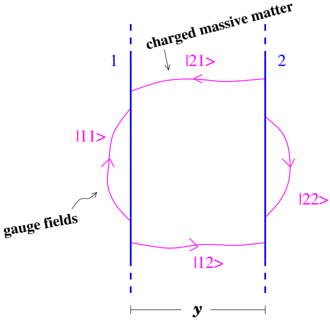
$\psi^M_{-\frac{1}{2}}|0\rangle$, $M = 0, \cdots, 7$, $\psi^8_{-\frac{1}{2}}|0\rangle$, $\psi^9_{-\frac{1}{2}}|0\rangle$

massless Neveu-Schwarz states

fields A_M, Φ, en 8 dim (Φ : complex scalar $\sim$ transverse degrees of freedom)

gauginos λ $\Leftarrow$ massless Ramond states

similar: $4d, \mathcal{N}=4$ susy Yang-Mills in D3-branes

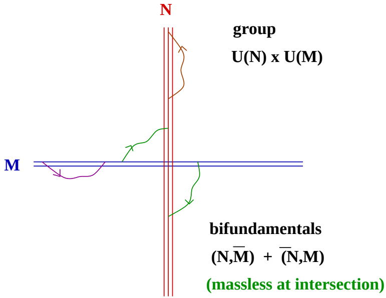


$$U(1) \times U(1) \xrightarrow{y=0} U(2)$$

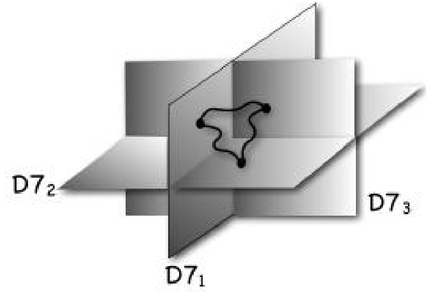
Higgs mechanism = brane separation

$$\Phi \sim y \quad \text{(transverse d.o.f.)}$$

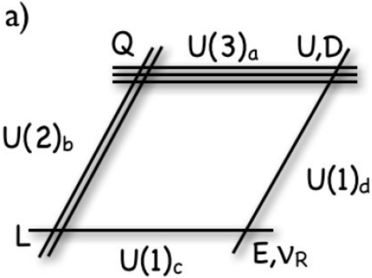
$$\langle \Phi \rangle \neq 0 \iff y \neq 0$$



Intersecting D-brane models

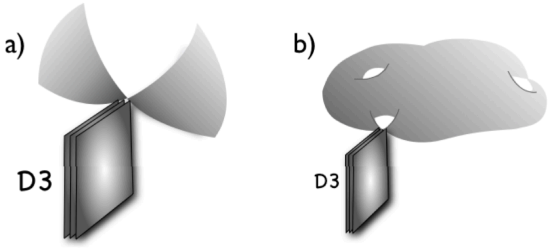


Madrid model



Global vs. local models

- Heterotic models are global. Full knowledge of the internal space is needed. All phenomenological questions have to be addressed at once.
- D-branes allow for localized SM. Questions like gauge group, chiral spectrum, Yukawa couplings, can be addressed one by one, i.e. in a bottom-up approach. In the end it is necessary to embed in full compactification.



The string scale $M_s = 1/\sqrt{\alpha'}$ and $M_P \sim 10^{19}\text{GeV}$

In perturbative heterotic

effective action in $10d$

$$S_{10} \sim M_s^8 \int d^{10}x \sqrt{-G}\, e^{-2\varphi} \left(\mathcal{R} \ + \ M_s^{-2} F_{MN}^2\right) + \cdots$$

compactification $\mathcal{M}_{10} = \mathcal{M}_4 \times K_6$ gives effective action in $4d$

$$S_4 \sim \int d^4x \sqrt{-g} \left(M_P^2 \mathcal{R}_4 \ + \ \frac{1}{g_{\rm YM}^2} F_{\mu\nu}^2\right) + \cdots$$

$$M_P^2 \sim \frac{M_s^8 V_6}{g_s^2} \qquad ; \qquad \frac{1}{g_{\rm YM}^2} \sim \frac{M_s^6 V_6}{g_s^2}$$

$V_6 = \text{Vol}(K_6)$, $g_s = e^{\langle\varphi\rangle}$

$$M_s \sim g_{\rm YM} M_P \sim 10^{18}\text{GeV}$$

In D-brane constructions

Recall that on a Dp-brane gauge fields propagate only on the $(p+1)$-dim world-surface, so they must wrap only a $(p-3)$-cycle in K_6. The relation between g_{YM} and M_s involves only the volume of this cycle. E.g. for a D3-brane

$$\frac{1}{g_{\mathrm{YM}}^2} \sim \frac{1}{g_s}$$

As before $M_P^2 \sim \dfrac{M_s^8 V_6}{g_s^2}$. Then, for a D3-brane

$$M_s^8 \sim \frac{M_P^2\, g_{\mathrm{YM}}^4}{V_6}$$

Now it is possible $M_s \ll M_P$ by having large extra dimensions transverse to the brane.