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String Theory

at

Low Energies

october 22, 2009, Bucuresti-Magurele

Outline

- Strings and D-branes
- TeV scale strings and Brane Universes

strong gravity versus string effects

- virtual graviton exchange

- contact interactions

- accelerated unification

- Intersecting branes

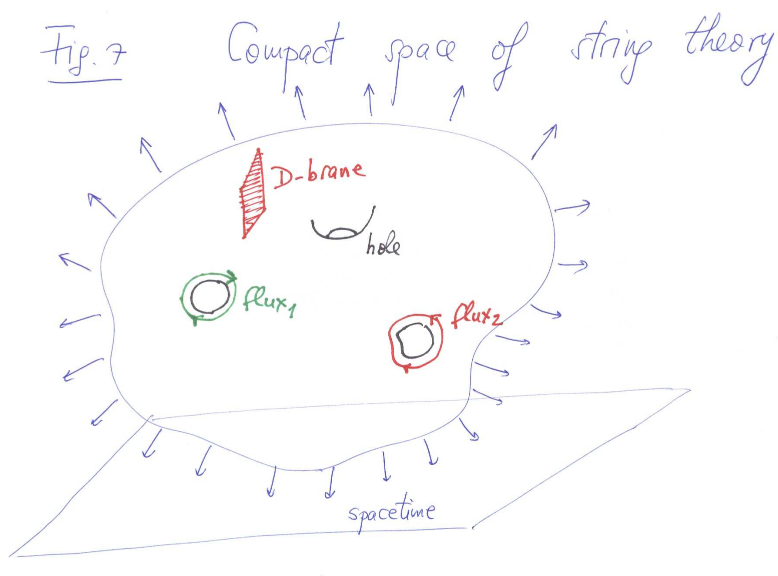
- some phenomenological properties

- Strings and their role in the LHC era

Complementary talks: B.Dobrescu, D.Ghilencea, A.Micu

1. Strings and D-branes

- Consistency conditions → 10d → six extra dimensions



Supersymmetry appears naturally → superstrings

- Superstrings are characterized by

l_s (M_s) = length (mass) of the string

$g_s = e^{\langle\phi\rangle}$ string coupling, ϕ = dilaton

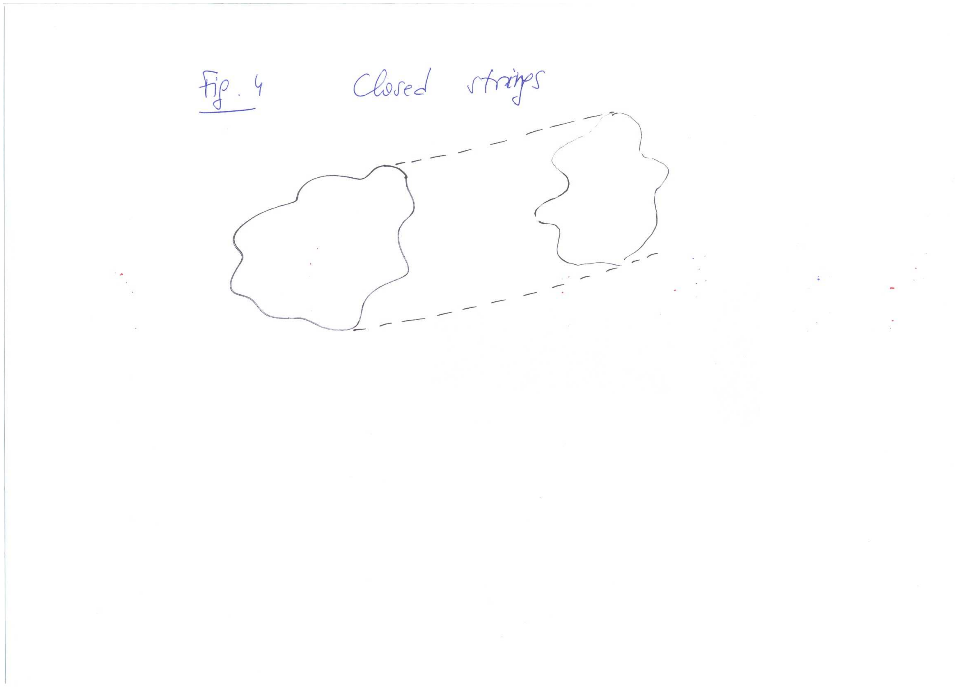
M_s is an input parameter, whereas g_s is dynamically determined.

After compactification, there are a large number of moduli fields : dilaton, volume moduli, shape moduli. Most of them are massless

$\rightarrow$ need mechanisms of moduli stabilization (talk A. Micu).

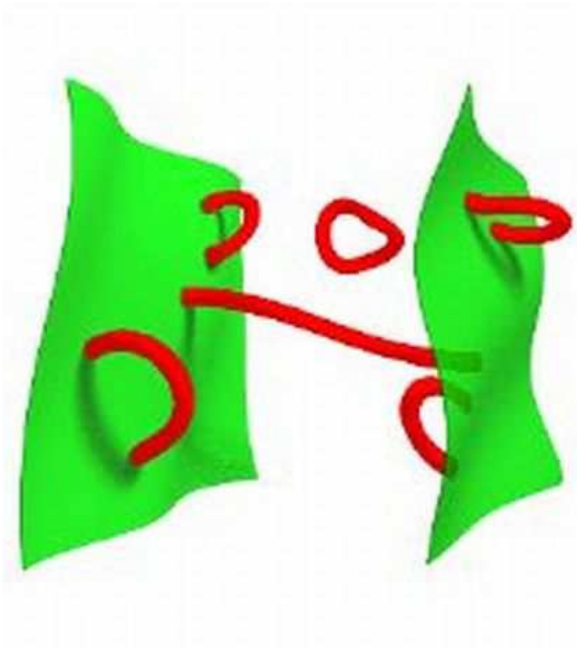
There are two types of strings :

closed strings : excitations : gravitons , etc



They propagate everywhere (in the "bulk").

open strings excitations : electrons,etc

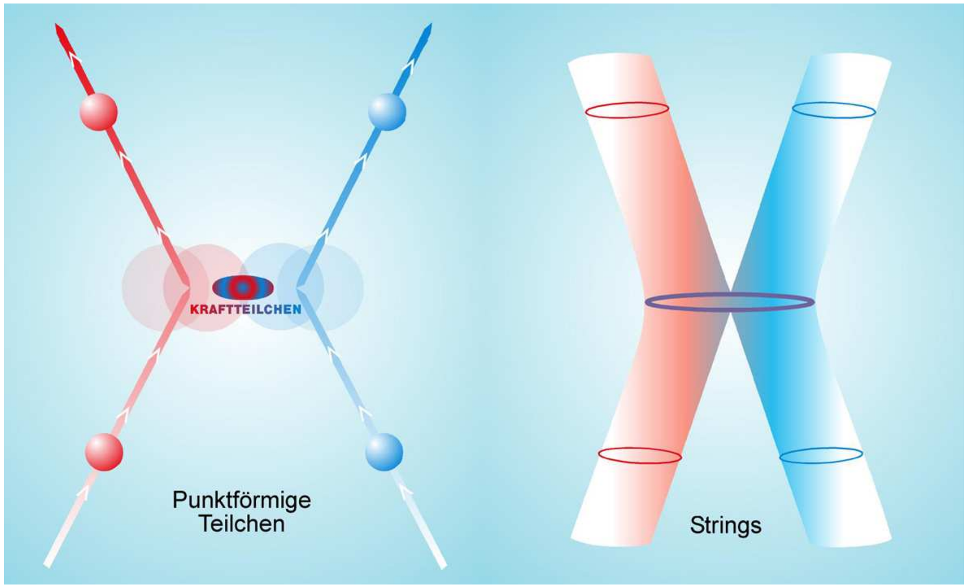


Their end points are :

- free to move : (Neumann boundary conditions)

- fixed : (Dirichlet boundary conditions)

Strings have no point-like interactions → no UV divergences !



Strings have surfaces of p space-dims. : D-branes (Polchinski, 95), which contain gauge fields (coupling g) and matter fields.

- D-branes carry mass and charges. They source gravitational fields and curve the internal space.
- Bulk (gravity) fields interact with the brane fields.

$$T^{\mu\nu}_{\text{brane}} \; g_{\mu\nu}(\mathbf{y}=0,\mathbf{x}) \;=\; \frac{1}{\sqrt{V}} T^{\mu\nu}_{\text{brane}} \; \sum_k g^{(k)}_{\mu\nu}(\mathbf{x})$$

- Branes interact via the exchange of bulk fields.

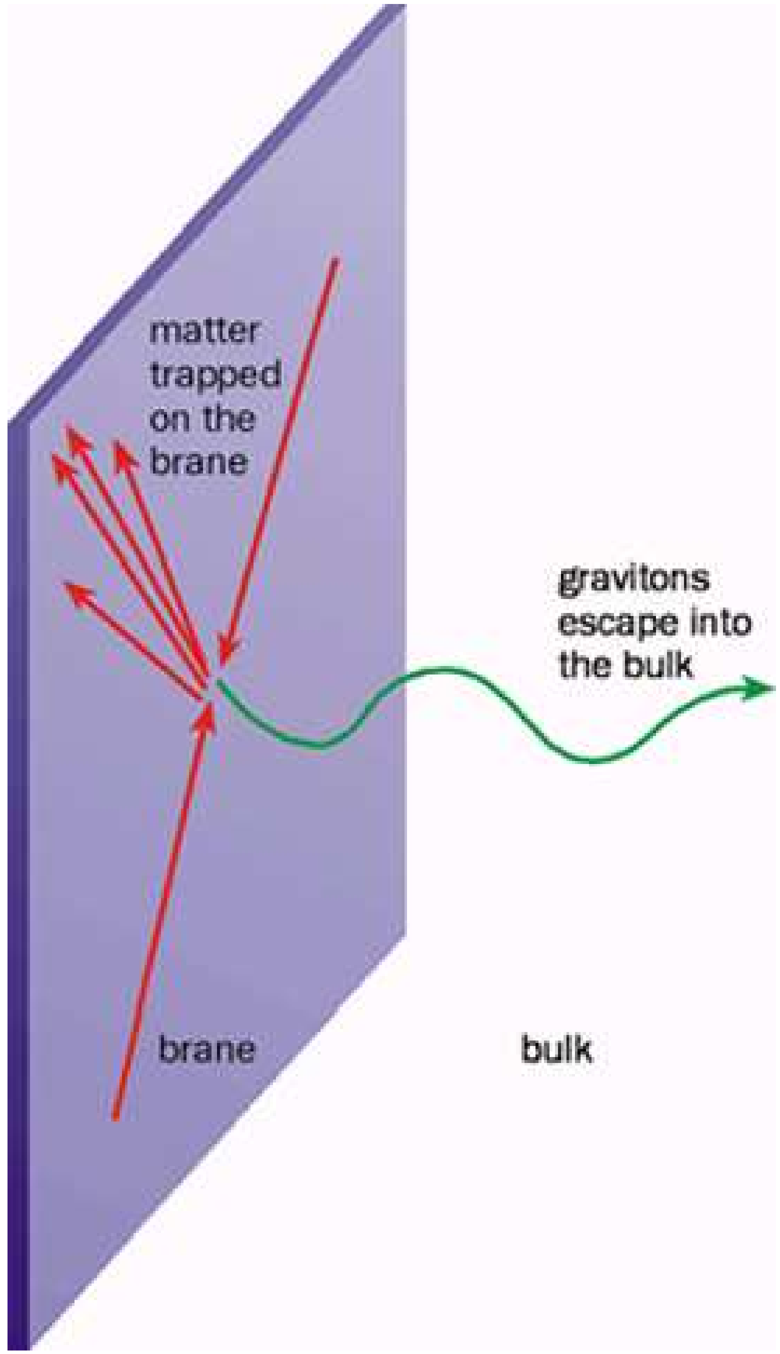
Gauge groups for N coincident Dp-branes: $U(N)$ (type II strings) or $SO(N)$ (or $USP(N)$) for orientifolds.

2. Brane universes and TeV scale strings : ADD scenario

(Arkani-Hamed,Dimopoulos,Dvali, 98)

• If SM lives on D-branes (open strings), constraints on unification and fundamental scale weaken considerably. ADD Brane Universe = the three SM gauge interactions and matter (open strings) are localized on a Dp (ex. D3) brane

The gravitation (closed strings) lives everywhere in ("in the bulk").


matter trapped on the brane
gravitons escape into the bulk
brane
bulk

The relevant effective action is

$$\int d^4x \, \left(\int d^6y \frac{M_s^8}{g_s^2} \mathcal{R} - \int d^\delta y \frac{M_s^\delta}{g_s} F_{MN}^2 \right) \, ,$$

where :

δ = parallel dimensions = $p-3$ for a Dp brane, $V_{||}$.

$n = 6 - \delta = 9 - p$ = perpendicular dimensions, $V_\perp$.

$g_s = e^\Phi$ = string coupling , M_s = string scale.

We get the relations

$$M_P^2 \; = \; \frac{1}{g_s} \, V_\perp \; M_s^{2+n} = V_\perp M_*^{2+n}$$

$$g_4^2 \; = \; g_s V_{||} \; M_s^{6-n}$$

If $M_s \sim TeV$, the hierarchy problem is solved.

The n perpendicular extra dimensions can be of macroscopic size

$$R_\perp \ \leq \ 10^{-1} \ mm \ ,$$

constraint coming from eventual deviations from Newton's law .

- If SUSY breaking on the branes, scale $M_{SUSY} \sim M_s$

$$m_{\text{bulk}-\text{moduli}} \sim \frac{M_{SUSY}^2}{M_P} \sim 10^{-3} eV$$

$\rightarrow$ also possible modifications of Newton law.

Newtonian potential between two bodies of masses m_1, m_2 is

$$V(r) = -\frac{1}{M_P^2}\frac{m_1 m_2}{r} \quad , \quad \text{for } r > R \ ,$$

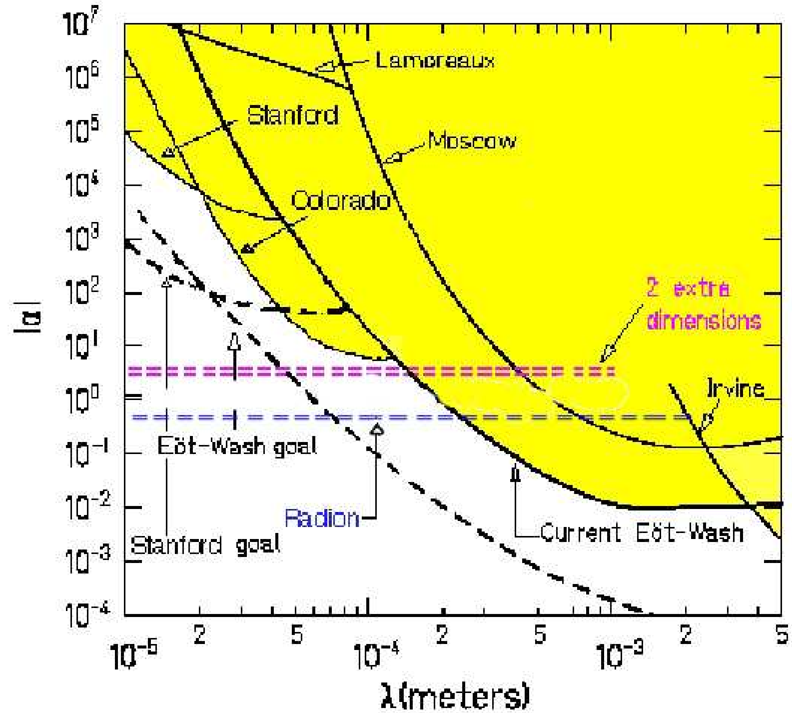
$$V(r) = -\frac{1}{M_*^{2+n}}\frac{m_1 m_2}{r^{1+n}} \quad , \quad \text{for } r < R \ .$$

Two dims. of extreme size $R_\perp \sim 10^{-1}\ mm$ give a fundamental string mass scale

$$M_s \sim 3 - 10 \quad TeV$$

$\longrightarrow$ strings could be accessible at LHC !

Hierarchy problem translated into the problem of finding a very large transverse volume.



Searches for deviations from Newton law, with

$$V(r) \;=\; G_N\,\frac{m_1 m_2}{r}\,(1 + \alpha\; e^{-r/\lambda})$$

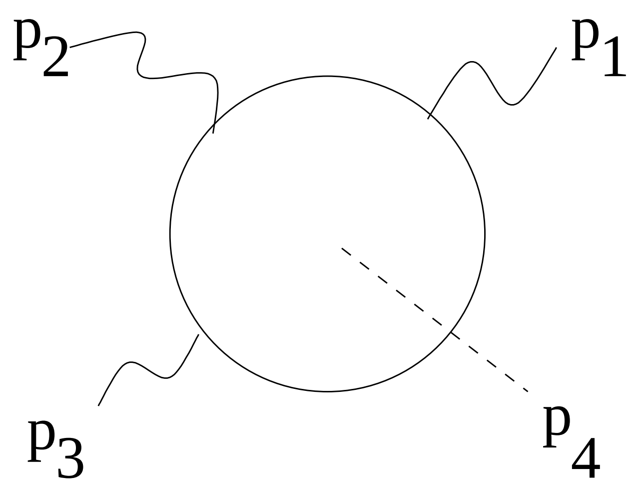
Gravity becomes strong at energies

$$M_* \;=\; (\frac{1}{g_s})^{1/(2+n)} M_s \;>\; M_s$$

$\longrightarrow$ string effects are observable in future colliders (ex. LHC in 2009), if TeV strong gravity.

Graviton emission in the bulk

three open and one closed string particles (ex: $q\bar{q} \to \gamma G$)



The inclusive cross-section

$$\sigma_{FT} \sim \frac{1}{M_P^2} \sum_{m_i=0}^{RE} \sim \frac{E^n}{M_*^{2+n}}$$

is reliable at the field-theory level.

However, string effects appear at $M_s < M_*$. By an explicit computation we find (m =graviton mass)

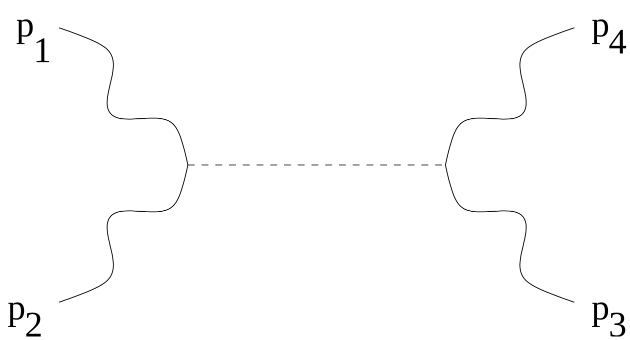
$$A_4 = \frac{2^{-\frac{m^2}{M_s^2}}}{\sqrt{\pi}} \frac{\Gamma(-\frac{m^2}{2M_s^2}+\frac{1}{2})\Gamma(1-\frac{s}{2M_s^2})\Gamma(1-\frac{t}{2M_s^2})\Gamma(1-\frac{u}{2M_s^2})}{\Gamma(1+\frac{s-m^2}{2M_s^2})\Gamma(1+\frac{t-m^2}{2M_s^2})\Gamma(1+\frac{u-m^2}{2M_s^2})} A_4^{FT}$$

which at low energy can be expanded

$$\frac{\sigma - \sigma_{FT}}{\sigma_{FT}} \sim \frac{E^4}{M_s^4}$$

Virtual graviton exchange

Another important process for the large Xtra dim. scenario: virtual graviton exchange



For $n \geq 2$ perpendicular dimensions, summation over virtual gravitons is UV divergent

$$A \sim \frac{1}{M_P^2} \sum \frac{1}{s - (m_1^2 + \cdots m_n^2)/R_\perp^2} \sim \frac{1}{M_P^2} R_\perp^2 (R_\perp \Lambda)^{n-2}$$

The result is

$$A \sim \frac{\Lambda^{n-2}}{M_*^{2+n}} \sim \frac{c^{n-2}}{M_*^4}$$

Main corrections to the four-point function is not graviton exchange, but the tree-level exchange of string oscillators (Veneziano amplitude).

$$A(1,2,3,4) \;\sim\; g^2 \; \frac{\Gamma(1-\frac{s}{M_s^2})\Gamma(1-\frac{t}{M_s^2})}{\Gamma(1-\frac{s+t}{M_s^2})} K(1,2,3,4)$$

Contact interactions

Massive string exchanges $\rightarrow$ contact interactions. Ex :

$gg \rightarrow gg \quad , \quad gg \rightarrow q\bar{q} \quad , \quad gq \rightarrow gq$

$$V(1,2,3,4) \sim \frac{\Gamma(1-\frac{s}{M_s^2})\Gamma(1-\frac{u}{M_s^2})}{\Gamma(1+\frac{t}{M_s^2})} = \frac{su}{tM_s^2} B(-s/M_s^2, -u/M_s^2)$$

leading to effective operators of the type

$$\mathcal{L}_{\text{eff}} \sim \frac{1}{M_s^4}\, trF^4 \quad , \quad \frac{1}{M_s^4}\, tr(F^2\ \bar{q}\partial q)\ , \text{etc}$$

These amplitudes are independent of the compactification details and have big luminosities at LHC.

They contain the massive Regge resonances, ex:

$$B(-s/M_s^2, -u/M_s^2) = -\sum_{n=0}^{\infty} \frac{M_s^{2-2n}}{n!} \frac{1}{s - nM_s^2} \prod_{J=1}^{n} (u + JM_s^2)$$

Four-fermion (quark) processes are more model (compactification) dependent. There are also processes with no SM background.

Ex : $qg \to q\gamma$, $gg \to g\gamma$. Corresponding amplitudes are

$$|M(qg \to q\gamma)|^2 \sim \frac{g^4}{M_s^2} \left[\frac{M_s^4 u}{(s - M_s)^2} + \frac{u^3}{(s - M_s)^2} \right] ,$$

$$|M(gg \to g\gamma)|^2 \sim \frac{g^4}{M_s^4} \left[\frac{M_s^8}{(s - M_s)^2} + \frac{u^4 + t^4}{(s - M_s)^2} \right] .$$

Analogously, for KK states :

$$\sum_{\mathbf{k}} \frac{1}{M^2 + \mathbf{k}^2/R^2} \, (\bar{\Psi}\gamma^m\Psi) \, (\bar{\Psi}\gamma^m\Psi)$$

Constraints from contact interactions give constraints of the order

$$M_s \ , \ R^{-1} \ \geq \ 2-3 \ TeV$$

• The constraints for UED are much weaker (B. Bobrescu talk).

Accelerated Unification

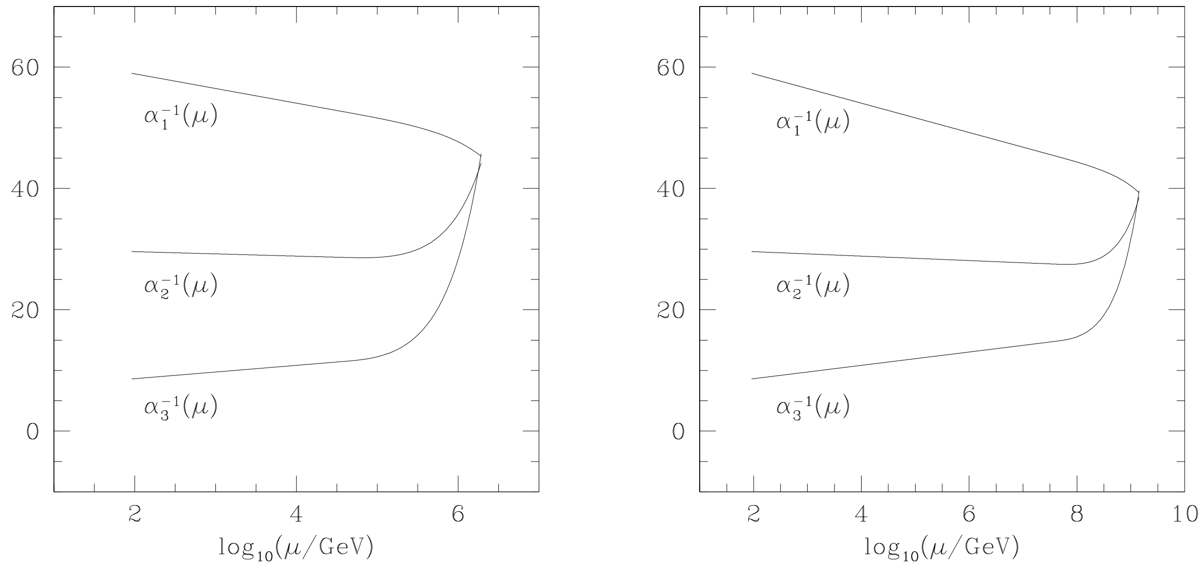
- Gauge coupling unification seems to predict a very high unification scale M_s, inaccessible to colliders.

Is there's a way to get unification at low energies ?

- Yes. The elementary particles: electron, quarks, etc propagate in TeV size extra dimensions . Their Kaluza-Klein states produce an accelerated evolution of the couplings.

$\longrightarrow$ accelerated unification .

TeV extra dims. interesting for collider (UED + dark matter, B.Dobrescu talk)

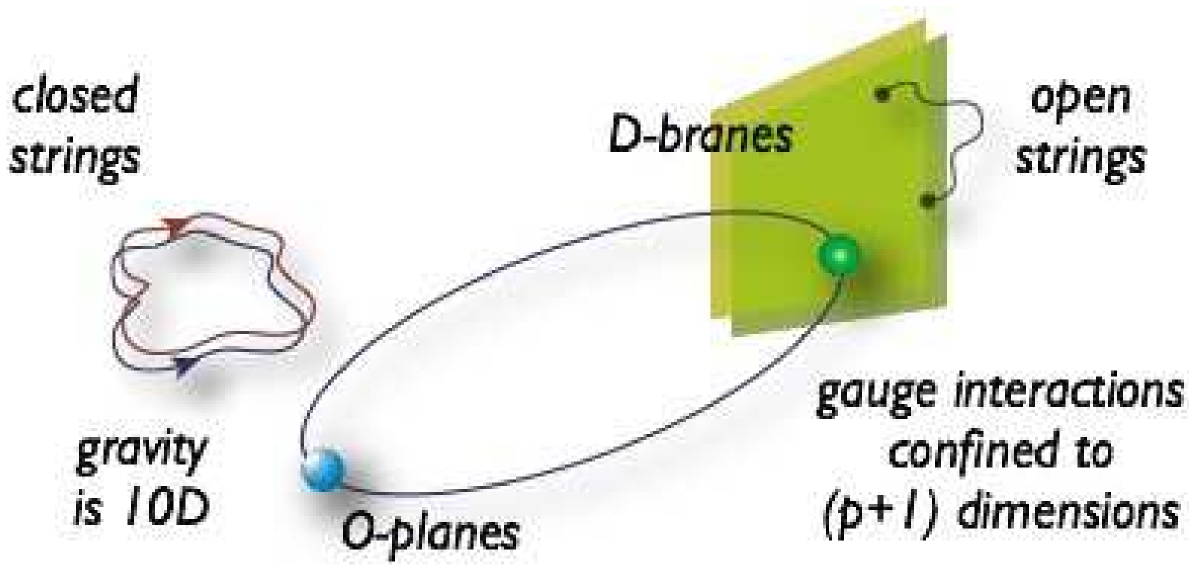


Unification of gauge couplings in the presence of extra spacetime dimensions. We consider two representative cases: $R^{-1} = 10^5$ GeV (left), $R^{-1} = 10^8$ GeV (right). In both cases we have taken $\delta = 1$ and $\eta = 0$.

3. Intersecting brane worlds

(Blumenhagen,Kors, Lust; Angelantonj,Antoniadis,E.D.,Sagnotti)

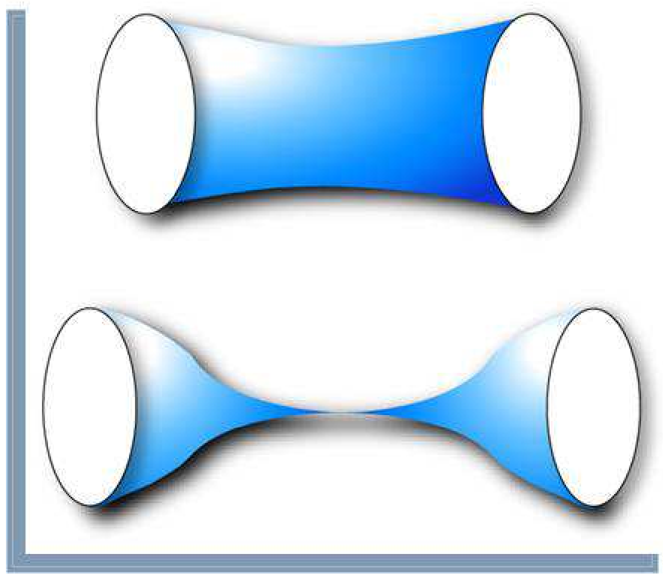
Cartoon picture of type II orientifolds : open/closed strings, Dp-branes/O-planes →



D-brane/O-planes have tension and charges (T_p, q_p).

Crucial constraint: RR tadpole constraints $\leftrightarrow$ UV finiteness $\leftrightarrow$ Gauss law in internal space

$$\sum_{Dp} q_{Dp}^{(n)} + \sum_{Op} q_{Op}^{(n)} = 0 \quad ; \quad SUSY \rightarrow T_p = q_p$$



Simple way of partially or totally breaking SUSY is by rotating the branes in the compact space.

Type IIA orientifolds : there are three angles $\theta_1, \theta_2, \theta_3$ that D6 brane(s) can make with the horizontal axis x_4, x_6, x_8 of the three torii of the compact space.

For two distinct stacks of D-branes/O-planes $D^{(1)}$ and $D^{(2)}$, relevant quantities are the relative angles

$$\theta_i^{(12)} = \theta_i^{(1)} - \theta_i^{(2)}$$

Compact space : two important additional ingredients:

• rotations of branes in the compact space are quantized, according to

$$\tan\theta_i^{(a)} = \frac{m_i^{(a)} R_{i2}}{n_i^{(a)} R_{i1}} ,$$

where $(m_i^{(a)}, n_i^{(a)})$ are the *wrapping numbers* of the brane(s) $D^{(a)}$ along the two compact directions of the compact torus T_i^2.

The total internal volume of the brane $D^{(a)}$ is then

$$V^{(a)} = (2\pi)^3 \prod_{i=1}^{3} \sqrt{m_i^{(a),2} R_{i2}^2 + n_i^{(a),2} R_{i1}^2} .$$

For two stacks of branes $D^{(a)}$ and $D^{(b)}$, the number of times they intersect in the compact torus T_i^2 is given by the *intersection number*

$$I_i^{(ab)} = m_i^{(a)} n_i^{(b)} - n_i^{(a)} m_i^{(b)} .$$

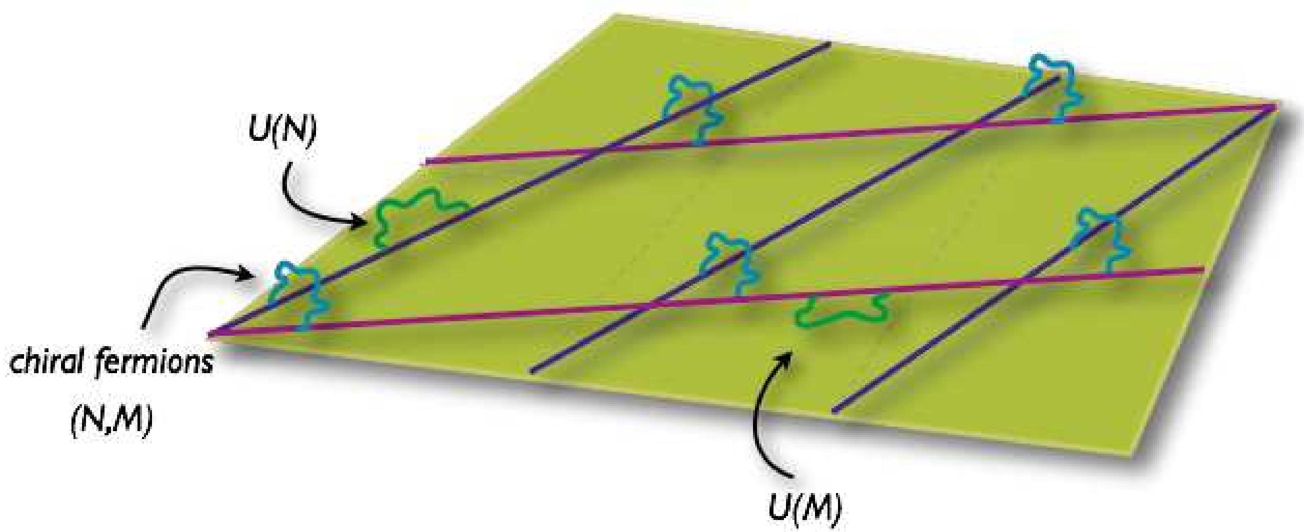
Branes at angles generate 4d chirality. Example: type IIA string with two sets of M_a coincident $D^{(a)}$ and M_b coincident $D^{(b)}$ intersecting branes in toroidal compactification :

- the gauge group is $U(M_a) \otimes U(M_b)$.

- strings stretched between the two D-branes have chiral fermions $(M_a, \bar{M}_b)$

Multiplicity equal to the total number of times the branes intersect in the compact space

$$D^{(a)}{-}D^{(b)} \quad : \quad I^{(ab)} = \prod_{i=1}^{3} I_i^{(ab)} = \prod_{i=1}^{3} (m_i^{(a)} n_i^{(b)} - n_i^{(a)} m_i^{(b)}) \, .$$



The chiral spectrum for toroidal compactification contains chiral fermions in

sector	representation	multiplicity of states
$D^{(a)} - D^{(b)}$	$(M_a, \overline{M_b})$	I_{ab}
$D^{(a)} - D^{(b')}$	(M_a, M_b)	$I_{ab'}$
$D^{(a)} - D^{(a')}$	$\frac{M_a(M_a-1)}{2}$	$\frac{1}{2}(I_{aa'} + I_{aO})$
$D^{(a)} - D^{(a')}$	$\frac{M_a(M_a+1)}{2}$	$\frac{1}{2}(I_{aa'} - I_{aO})$.

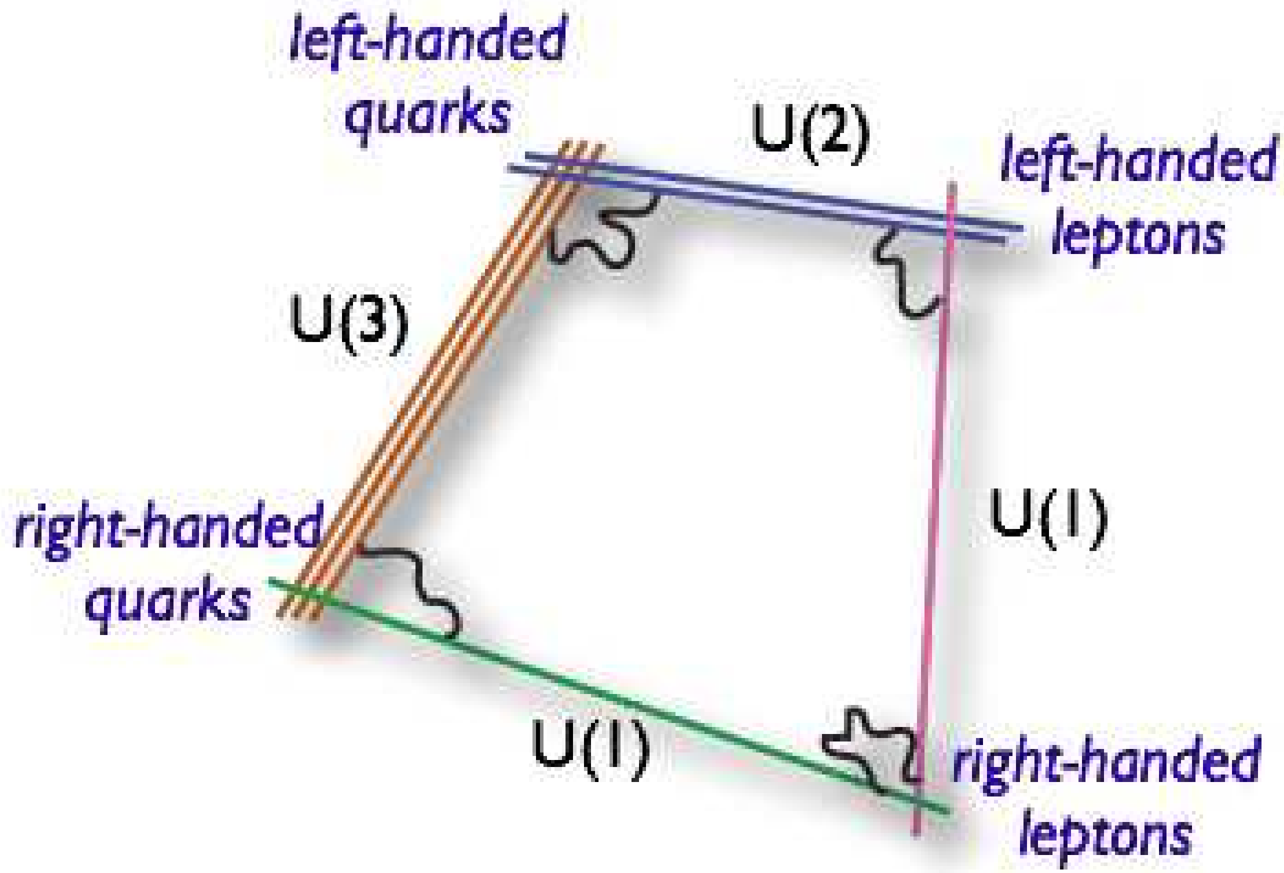
Some phenomenology of intersecting branes models

Standard Model like spectra

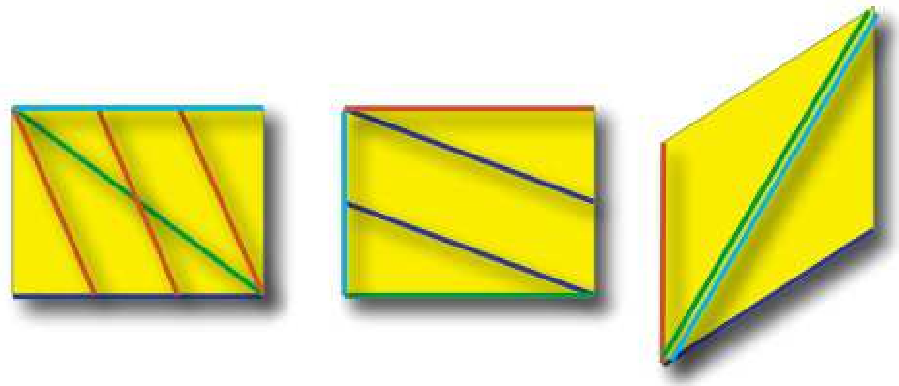
(Madrid group; Munich group)

Quasi-realistic models with intersecting were constructed in the last couple of years. The generic Standard Model type construction contains four (or more) stacks, containing D-branes with a minimal gauge group $U(3) \times U(2) \times U(1)^2 = SU(3) \times SU(2) \times U(1)^4$.

"Standard Model" quiver



Intersection pattern



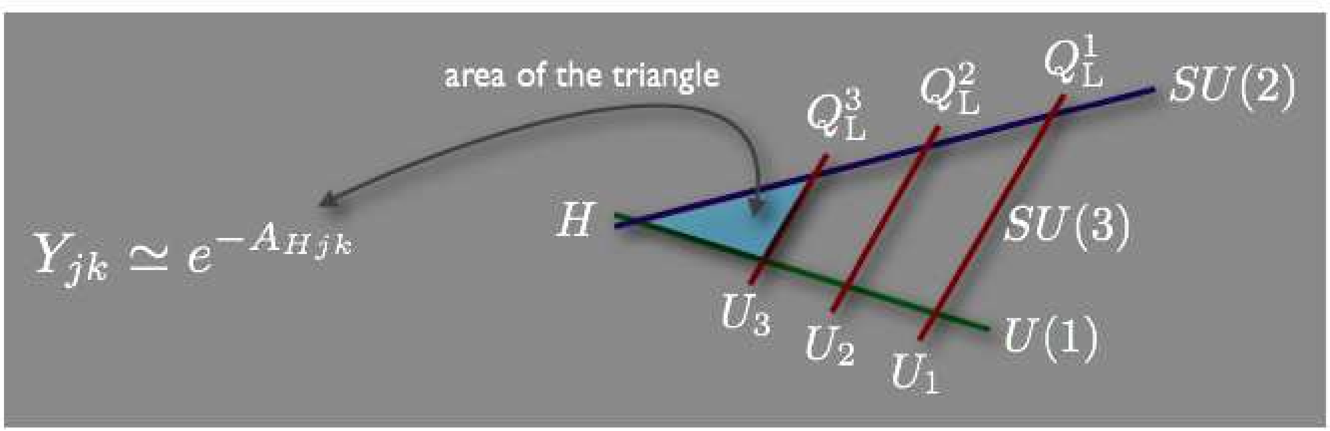
U(3)	(1,0)	(2,-1)	(1,0)
U(2)	(1,-1)	(1,0)	(1,1)
U(1)	(1,-3)	(1,0)	(0,1)
U(1)	(1,0)	(0,1)	(1,1)

Yukawa couplings

Number of Generation = number of intersections between branes.

Then Yukawa couplings have a nice geometrical intepretation of mass hierarchies

(Cremades,Ibanez,Marchesano)



• Three abelian gauge factors X_a are anomalous (massive) by Stueckelberg mixing with axions. The fourth is massless: the hypercharge Y. Anomaly cancelation à la Green-Schwarz (gauge transf. of axions):

$$Tr\ X_a\ G_a^2\ \neq\ 0 \quad , \quad Tr\ X_a\ X_b^2\ \neq\ 0$$

(Some) problems:

• SUSY realistic models (MSSM) difficult to realize.

• Gauge coupling unification is not automatic.

• For $SU(5)$ GUT's, top coupling 10 10 5_H perturbatively forbidden.

Strings : and their role in the LHC era ?

The LHC (Large Hadron Collider) era starts, with energies (2009) of 10 TeV, in searching for physics Beyond the Standard Model.

- "Stringy" Discoveries :

• Discovery low-energy SUSY :

$\longrightarrow$ if SUSY breaking transmission is gravitational (not easy to test) $\longrightarrow$ Supergravity $\longrightarrow$ Superstrings

$\longrightarrow$ try to discover signatures of moduli fields :

Anomaly cancelation a la Green-Schwarz, deviations from Newton law in table-top experiments.

• Flat (large) extra spacetime dimensions $\leftrightarrow$ string theory at a low scale $M_s \rightarrow$ spectacular effects of strings : Regge states, KK production, contact operators, strong gravity at TeV ...

• Warped (small, Randall-Sundrum like) dimensions: spin two TeV mass KK gravitons, radion.

- "Non-stringy" discoveries :

• Z' gauge bosons, fourth generation, little Higgs models...

$\rightarrow$ String theory probably not very relevant

- No discovery :

• perturbative consistency (unitarity) of the SM broken around 1 TeV

$\longrightarrow$ new nonperturbative physics (ex. technicolor) $\longrightarrow$ holographic studies based on AdS/CFT ?