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Large extra dimensions

at

low energy

Outline

1) Introduction and motivations

- the gauge hierarchy
- strings and gravity
- mass scales in heterotic string

2.) Realizations of low-scale strings (TeV)

- type I and D-branes
- type II
- duality relations to heterotic

3) Experimental predictions

- longitudinal (TeV) dimensions
- transverse (submm) dimensions

  and low scale quantum gravity
- string effects
- gravity modifications at submm

5) D-brane physics at the TeV

- the gauge hierachy revisited
- SUSY breaking
- electroweak symmetry breaking
- gauge coupling unification
- a minimal embedding of the Standard Model
- R-neutrinos from extra dimensions

Beyond the Standard Model

- electroweak symmetry breaking

why? - origin of mass and hierarchies

- include gravity

- Supersymmetry: Bosons $\leftrightarrow$ Fermions

- String theory: Quantum Mechanics + General Relativity

LHC experiment (CERN):

Discovery machine

proton - proton collider at 14 TeV $\rightarrow 10^{-17}$ cm

Window

Higgs sector: spin-0 particle

$SU(2) \times U(1) \underset{250\text{GeV}}{\longrightarrow} U(1)_{\text{el}}$

$\Rightarrow$ Mass generation

exp: no elementary scalars

th: quadratic divergences

$\Rightarrow$ Higgs mass $\sim$ highest mass scale

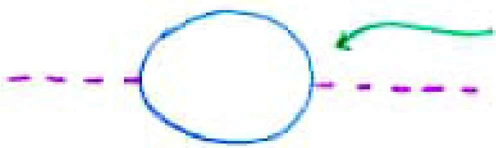
$$\delta M_H^2 \sim \Lambda^2$$

Supersymmetry

- elementary scalars: partners of fermions

- stabilizes the gauge hierarchy

$$M_W / M_P \simeq 10^{-16}$$

$$\delta M_W^2 = $$  bosons + fermions

$$= 0$$ susy exact

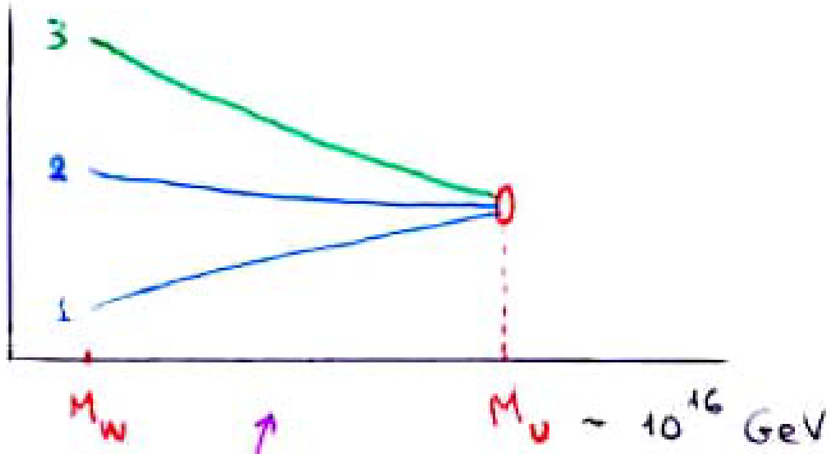
$$= \mathcal{O}(m_{SUSY}^2)$$ $m_{SUSY}^2 \neq 0$

boson-fermion mass splitting

- rich spectrum of superparticles in the TeV region

$$m_{SUSY} \sim \text{TeV}$$

Unification



Standard Model with susy

String Theory

point particle $\rightarrow$ extended objects

particles $\equiv$ string vibrations

- Quantum gravity
- Framework for unification of all interactions
- "ultimate" theory : · UV finite

  · no free parameters

string scale $M_s \leftrightarrow \ell_s$

string coupling $\lambda_s \sim e^{\langle\phi\rangle}$

· known particles $\equiv$ massless excitations

+ infinite number of massive modes at M_s

Consistent (super)strings live in 10 dimensions

freedom of compactification ≡ choice of vacuum

$D=10$: 5 theories

Heterotic	Type I SO(32)	Type IIA or IIB
SO(32) or $E_8 \times E_8$	closed + open	pure supergravity

Old picture: Heterotic most promising

$\lesssim 94$

Others uninteresting (type II) or difficult (type I)

New picture: All are equivalent

different perturbative "corners" of the same

underlying M-theory

string dualities: $\lambda \longleftrightarrow 1/\lambda$

strong weak

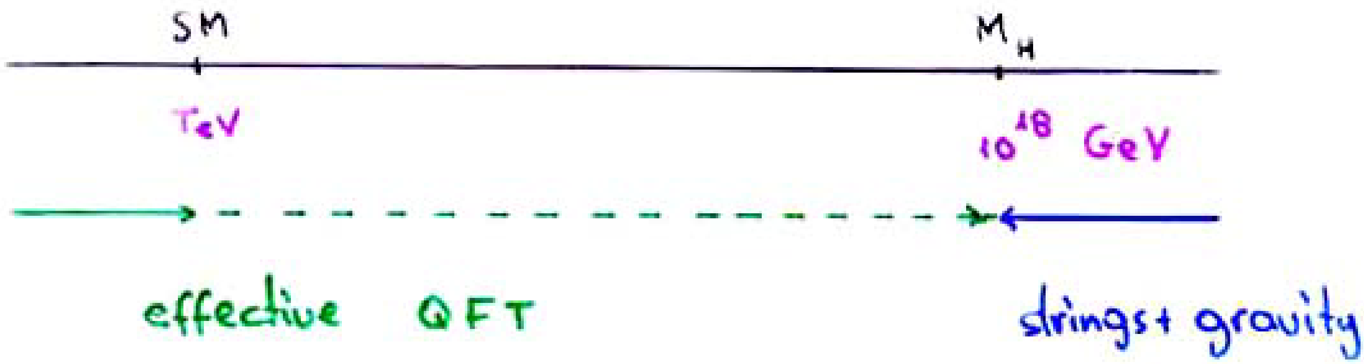
Old view (Heterotic) : near $M_p \sim 10^{19}$ GeV $(10^{-33}$ cm$)$

$$M_H \sim g\, M_p \simeq 10^{18} \text{ GeV}$$

$$\lambda_H \sim \sqrt{V}$$

weak coupling $\lambda_H < 1 \Rightarrow V \sim$ string size

separate physics in 2 regions :



However physical motivations $\Rightarrow$

large volume may be relevant

$\not{S}USY$ by compactification $\Rightarrow R \sim \text{TeV}^{-1}$ I.A. '90

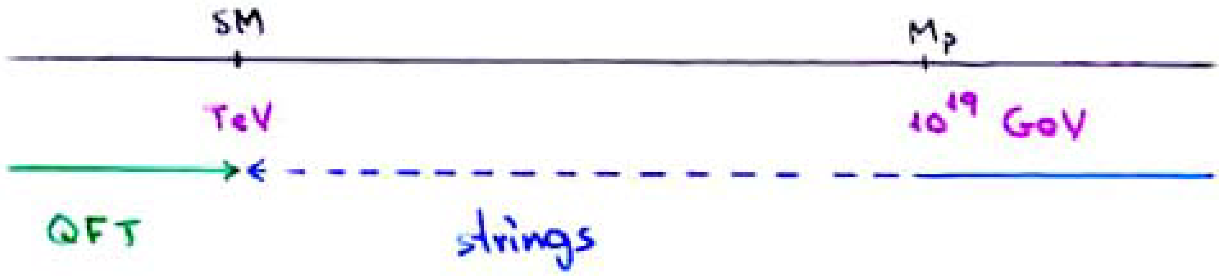
Recent view : M_s arbitrary parameter Witten '96

why not at TeV ? Lykken '97

$M_s \sim$ TeV $\Rightarrow$ nullification of gauge hierarchy

(I.A.) - Arkani Hamed - Dimopoulos - Dvali '98

I.A. - Bachas '98



- new large dimensions

- low scale quantum gravity black-holes in accelerators ?

- modification of gravitation at (sub)mm

- challenge to re-address most of the "old" problems

At what energies string theory becomes important?

Recent view: M_s arbitrary parameter Witten '96

why not at TeV? Lykken '97

$M_s \sim \text{TeV} \Rightarrow$ nullification of gauge hierarchy

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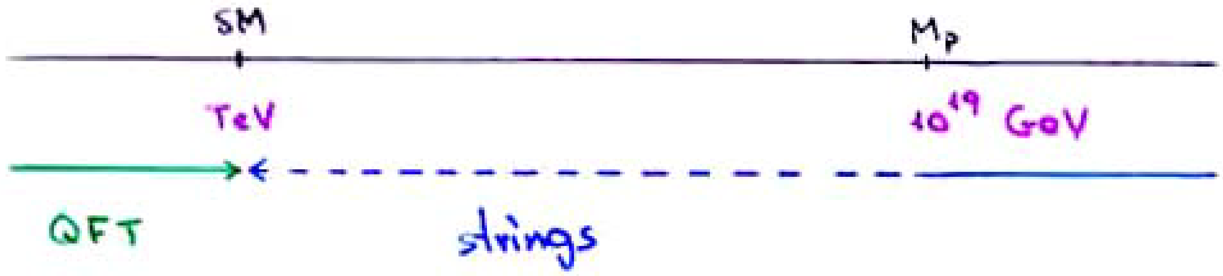

- new large dimensions

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Preliminaries

10 d parameters: $\ell_s = M_s^{-1}$, $\lambda_s = e^{\langle \phi \rangle}$

compactification on a manifold of volume V $\Rightarrow$

4 d : $M_p = \ell_p^{-1}$, g gauge coupling

10^{19} GeV $\leftrightarrow$ 10^{-33} cm $\qquad$ $1/5$

method: express ℓ_s, λ_s in terms of M_p, g, V

for every string $s = H, I, II$ or M-theory

- weak coupling condition: $\lambda_s < 1$
- $V > 1$ in ℓ_s units

otherwise T-duality to account for the light winding modes

$$\underbrace{\frac{m}{R}}_{\text{KK}} + \underbrace{n\frac{R}{\ell_s^2}}_{\text{windings}}$$

$$R \longrightarrow \tilde{R} = \ell_s^2/R$$

$$\lambda_s \longrightarrow \tilde{\lambda}_s = \lambda_s\, \ell_s/R$$

conventions: $\hbar = c = 1 = 2 = \pi$

1. Heterotic string $E_8 \times E_8$ or $SO(32)$

gauge and gravitational interactions appear at tree-level

$$S = \int d^4x \; \frac{V}{\lambda_H^2} \left(\underbrace{\frac{1}{\ell_H^8}}_{\frac{1}{\ell_P^2}} R + \underbrace{\frac{1}{\ell_H^6}}_{1/g^2} F^2 \right) + \cdots$$

$M_H = \sqrt{k}\, g\, M_P$ level of the 2d afine Lie algebra

$$\lambda_H = g \frac{\sqrt{V}}{\ell_H^3}$$

$\Rightarrow$

$M_H \gtrsim 10^{18}$ GeV

$\lambda_H < 1 \quad \Rightarrow \quad V \sim \ell_H^6$

however physical motivations suggest large volume

- unification

- susy breaking I.A. '90

spontaneous $\cancel{\text{SUSY}}$ by compactification (perturbatively)

10d $\to$ 4d on a compact 6d space

$\Rightarrow m_{3/2} \sim m_{1/2} \sim 1/R$ ← size of an internal dimension

$\Rightarrow$ $R^{-1} \sim \text{TeV}$ I.A. '90

exp: spectacular prediction

tower of KK excitations for SM particles

$X \equiv X + 2\pi R \;\Rightarrow\; p = \frac{n}{R}$ $\quad n = 0, \pm 1, \ldots$

$$m_n^2 = m_0^2 + \frac{n^2}{R^2}$$

th. problem: they contribute to β-functions for $E \gg R^{-1}$

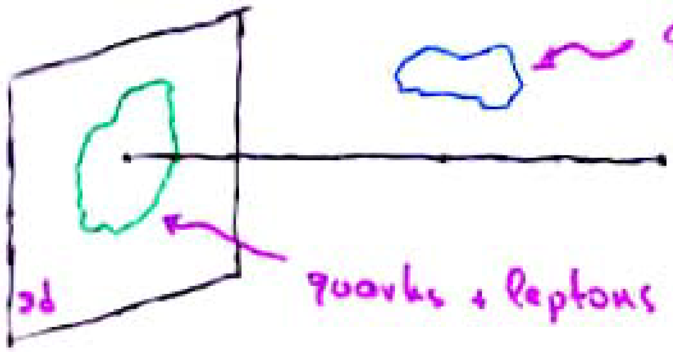
$\Rightarrow$ log evolution becomes power $g^2 R$

$\rightarrow$ very rapidly in a non-perturbative domain way out: vanishing of β-functions level by level I.A. '90

e.g. KK into $N=4$ multiplets

1 vector + 4 fermions + 6 scalars

$\Rightarrow$ special models: orbifold examples



other couplings (Yukawa's, etc) ? more conditions

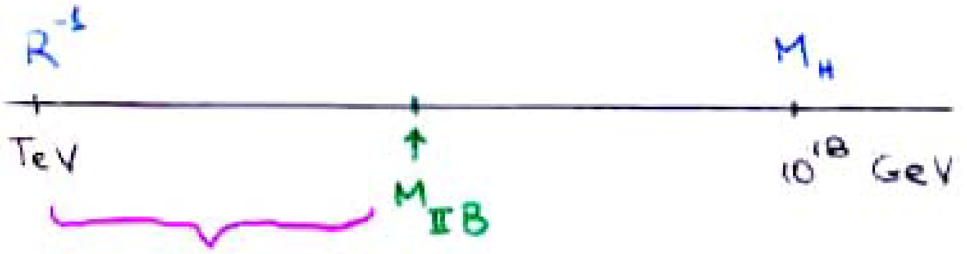
strong coupling can be addressed using string dualities '96

$$\lambda \to 1/\lambda$$

strong weak

strongly coupled heterotic: type I/I', II A/B or M-theory

- one large dim $\Rightarrow$ II B   I.A.-Pioline '99



$\lambda \lesssim 1$

non-trivial fixed-point theory: tensionless string

$\Rightarrow$ all conditions of soft UV behavior

- two or more large dims $\Rightarrow$ I/I', II A

but $M_{dual} \lesssim R^{-1} \sim$ TeV !

Realizations of TeV strings

Type I $\Rightarrow$ submm dims

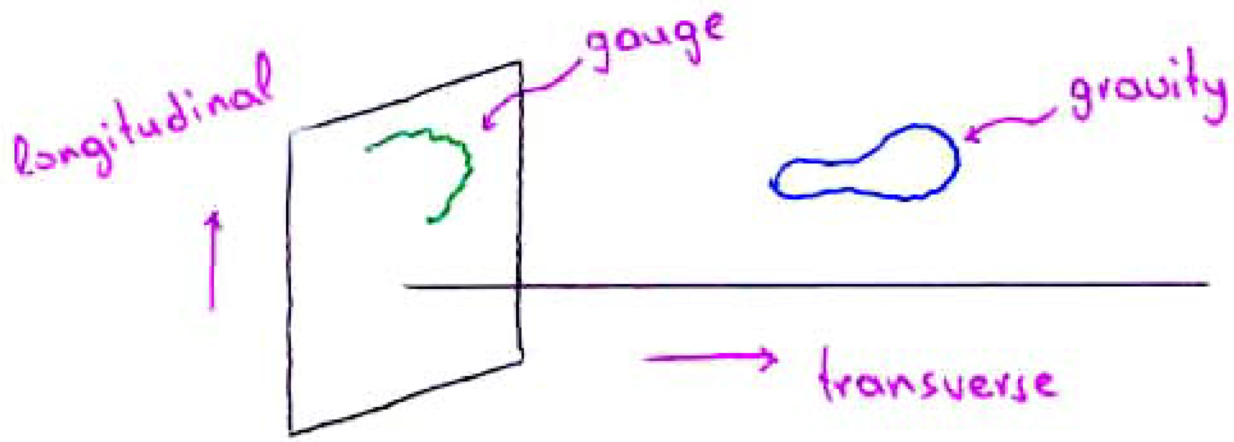
Type II $\Rightarrow$ tiny coupling

strongly coupled Heterotic SO(32) (type I)

$E_8 \times E_8$ (type II)

Type I : closed strings $\rightarrow$ gravity

open strings $\rightarrow$ gauge sector on D-branes



p-brane $\Rightarrow$ p-3 compact dims //

$\underbrace{9-p}_{n}$ " " $\perp$

weak coupling $\Rightarrow$ longitud dims $\sim$ string size

transverse dims : no constraint

n $\perp$ dims of radius r $\Rightarrow$

$$M_P^2 = \underbrace{\frac{1}{g^4} M_I^{2+n}}_{M_{P_{(4+n)}}^{2+n}} r^n$$

Planck mass of 4+n dims

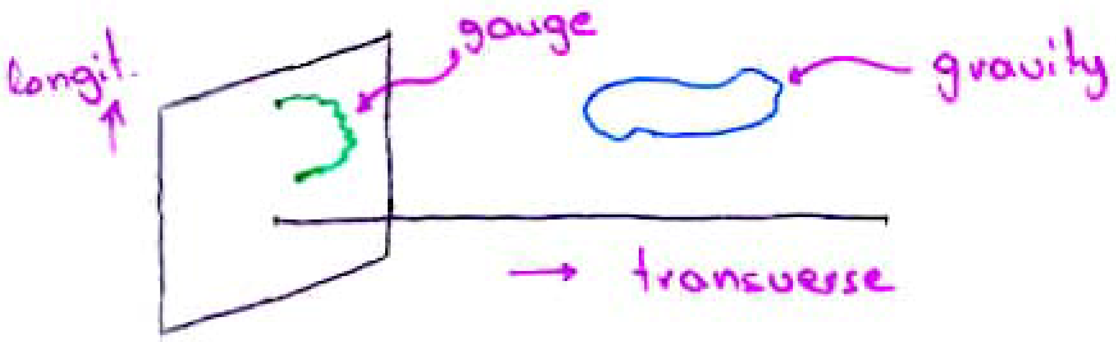
largeness of M_P / M_I $\Rightarrow$ extra-large r

- string coupling : $\lambda_I \simeq g^2$
- gravity strong at $M_{P_{(4+n)}} \sim \underset{\substack{\uparrow \\ \text{TeV} \\ 10^{-16}\text{ cm}}}{M_I} << \underset{\substack{\uparrow \\ 10^{19}\text{ GeV} \\ 10^{-33}\text{ cm}}}{M_P}$

3. Type I theory ≡ strongly coupled Het SO(32)

type I/I′ : closed strings → gravity

open strings → gauge sector on D-branes



p-brane ⇒ p-3 dims // , 9-p dims ⊥

$$S = \underbrace{\int d^{10}x}_{d^4x\, V^{\perp}_{9-p}\, V^{\parallel}_{p-3}} \ \overset{\text{sphere}}{\frac{1}{\lambda_I^2}}\ \frac{1}{\ell_I^8}\, R \ + \ \underbrace{\int d^{p+1}x}_{d^4x\, V^{\parallel}_{p-3}}\ \overset{\text{disk}}{\frac{1}{\lambda_I}}\ \frac{1}{\ell_I^{p-3}}\, F^2$$

$$\frac{1}{\ell_P^2} = \frac{1}{\lambda_I^2}\frac{V_\perp V_\parallel}{\ell_I^8} \qquad\qquad \ell_P = g\,\ell_I\left(\frac{\ell_I^{9-p}}{V_\perp}\lambda_I\right)^{1/2}$$

$$\Rightarrow$$

$$\frac{1}{g^2} = \frac{1}{\lambda_I}\frac{V_\parallel}{\ell_I^{p-3}} \qquad\qquad \lambda_I = g^2\,\frac{V_\parallel}{\ell_I^{p-3}} < 1 \ \Rightarrow\ V_\parallel \sim \ell_I^{p-3}$$

$M_{\underline{I}} \sim 1$ TeV $\Rightarrow$

$n=1 \quad \Rightarrow \quad r \simeq 10^8$ km excluded

$n=2 \quad .1$ mm $\quad 10^{-3}$ eV

$\vdots$ $\Bigg\}$ possible

$n=6 \quad .1$ fm $\quad 10$ MeV

- gravity tested up to $\gtrsim$ cm
- most severe : astrophysics + cosmology

graviton emission on cooling of supernovae $\Rightarrow$

$M_{P(6)} \gtrsim 50$ TeV $(n=2)$ A-H D D

Cullen-Perelstein '99

$M_I \simeq 10^{11}$ GeV (intermediate scale)

Benakli

Burgess - Ibanez - Quevedo

$- \; M_W \sim \frac{M_I^2}{M_P} \Rightarrow$

weak scale dual to Planck mass

$- \; m_{susy} = M_I \Rightarrow$

"minimization" of the hierarchy

$n=6 \Rightarrow r = 10^2 \, l_I$

in general $M_I \lesssim 10^{11}$ GeV to guarantee $m_{susy} \lesssim 1$ TeV

in our brane, originating from "nearby" non susy branes

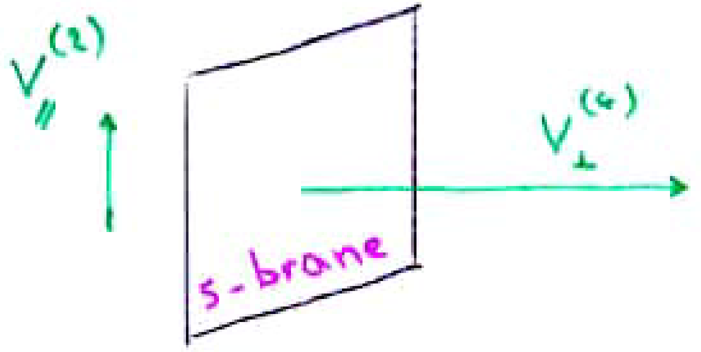
Ibanez

$m_{susy}\big|_{us} \sim M_I^2 / M_P \lesssim 1$ TeV

I.A. - Pioline '99

Type II strings

Non abelian symmetries : non-perturbative on a 5-brane localized at singularities of the internal manifold



$$M_p^2 = \frac{1}{\lambda_{II}^2} \frac{1}{g^2} M_s^{2+4} V_{\perp}^{(4)}$$

New possibility : largeness of $M_p \Rightarrow$ tiny string coupling

all radii $\sim M_s^{-1}$, $\lambda_{II} \simeq 10^{-14}$

- No strong gravity at TeV
- signal : 2 longitudinal (TeV) dims $V_{\parallel}^{(2)}$ with gauge interactions

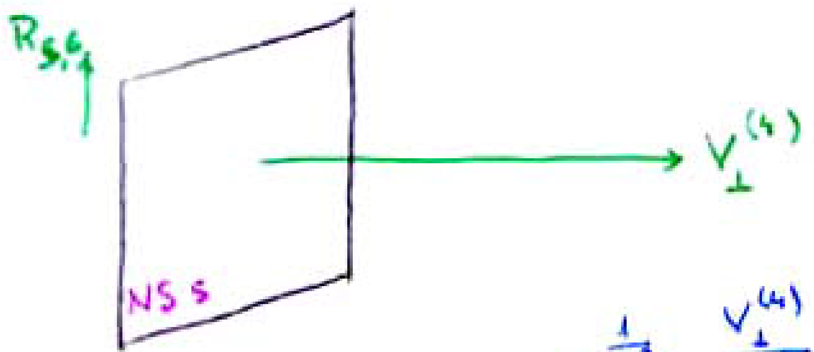
4. Type II strings

I.A. - Pioline '99

Non abelian symmetries: non-perturb on a NS 5-brane

localized at singularities of the internal manifold

4.1 Type IIA : e.g in d=6 D2 branes wrapped around collapsing 2-cycles of a singular K3



$$\frac{1}{\lambda_{IIA}^2}\,\frac{V_\perp^{(4)}}{\ell_{II}^4}$$

$$S = \int d^6x \left\{ \frac{1}{\lambda_{6A}^2}\,\frac{1}{\ell_{II}^4}\, R + \frac{1}{\ell_{II}^2}\, F^2 \right\} + \cdots$$

$d^4x \; R_5 R_6$

no dependence on λ_{II}

$$\frac{1}{g^2} = \frac{R_5 R_6}{\ell_{II}^2} \qquad\qquad \frac{1}{\ell_P^2} = \frac{1}{g^2}\,\frac{1}{\lambda_{6A}^2}\,\frac{1}{\ell_{II}^2}$$

$(M_s, \lambda_s) \rightarrow (M_P, g)$: $\boxed{M_P^2 = \frac{1}{\lambda_s^2} M_s^2 \, V}$

Het: $g = \lambda/\sqrt{V} \lesssim 1 \Rightarrow \lambda \lesssim 1 \quad V \gtrsim 1$

Type I: $g = \lambda/\sqrt{V_{\parallel}}$ $\qquad \lambda \lesssim 1 \quad V_{\parallel} \gtrsim 1 \quad V_{\perp}$ arbitrary

Type IIA: $g = 1/\sqrt{V_{\parallel}^{(2)}}$ $\qquad V_{\parallel}^{(2)} \gtrsim 1 \quad V_{\perp}^{(4)}, \lambda$ arbitrary

Type IIB: $g = R_4/R_5$ $\qquad R_4 \lesssim R_5 \quad V_{\perp}^{(4)}, \lambda, V_{\parallel}^{(2)}$ arbitrary

new possibility : large $V_{\parallel}^{(2)}$ at weak coupling

$M_P^2 \sim R^2 M_{II}^4 \Rightarrow R \sim \text{TeV}^{-1} \quad M_{II} \sim 10^{11}$ GeV

$R^{-1} \ll E \ll M_{II}$: 6d tensionless string $\Rightarrow$

non-trivial fixed-pt gauge theory

Het with small instantons: same as IIA or IIB

Benakli - Oz '99

Are there more possibilities ?

presumably No because these describe

heterotic string with any number of large dims

Heterotic with n dims at $R > \ell_H = M_H^{-1}$

$6-n$ " " ℓ_H

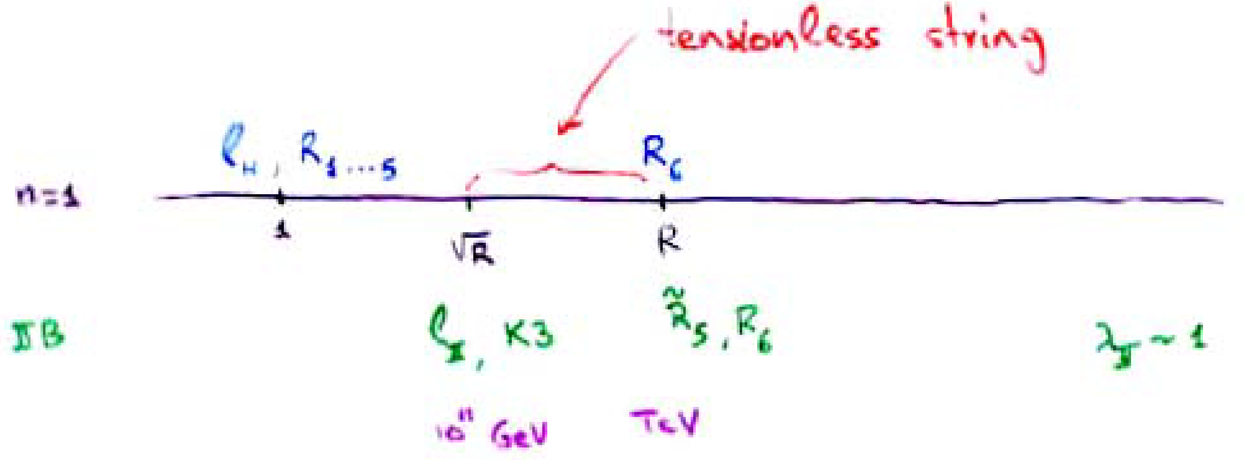
$\ell_H,\ R_{n+1,\dots,6}$ $\qquad$ $R_{1,\dots,n}$ $\qquad$ $\lambda_H \sim R^{n/2} > 1$

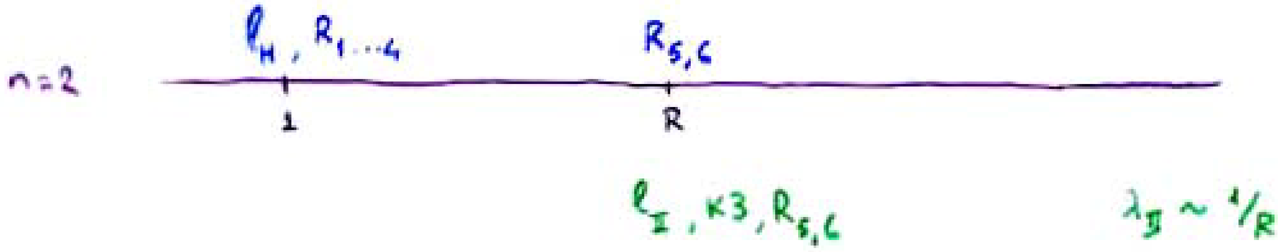
1 $\qquad$ R

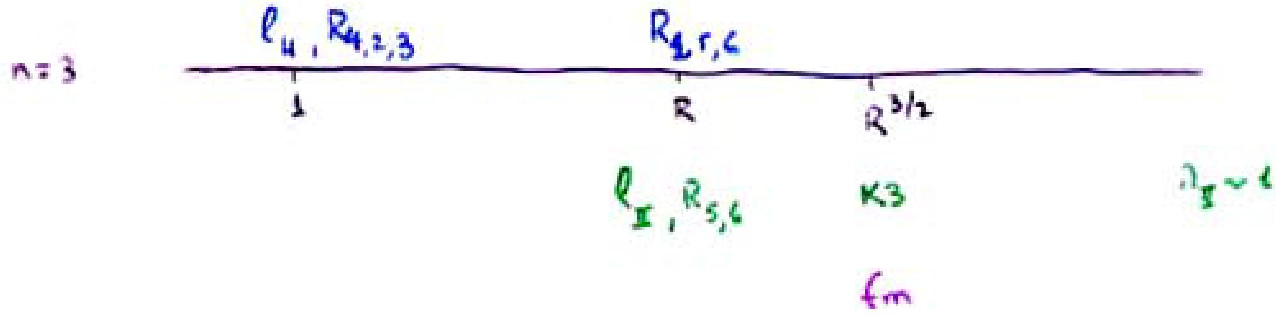
$n=1 \Rightarrow$ II B : $\ell_{II} \sim \sqrt{R}$

$n=2,3 \Rightarrow$ II A : $\ell_{II} \sim R$

$n \geq 4 \Rightarrow$ type I : $\ell_I \gtrsim R$



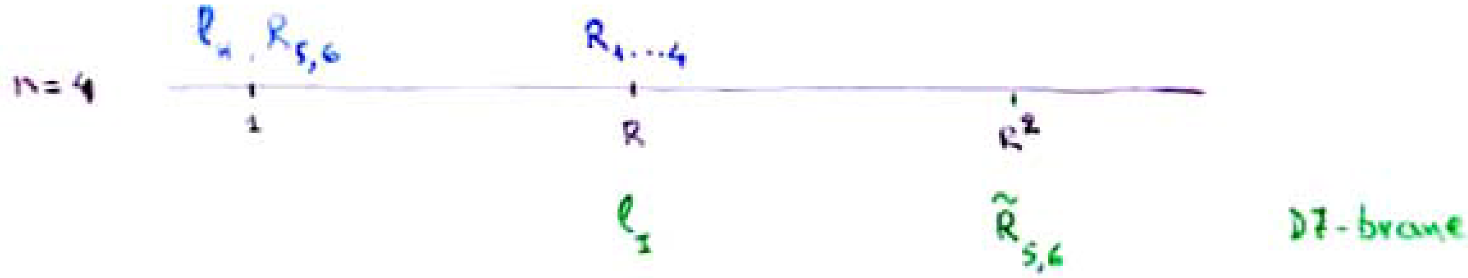


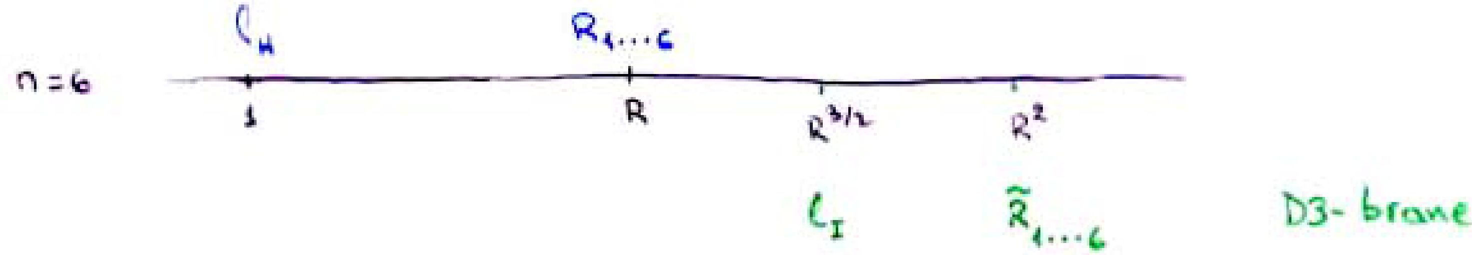


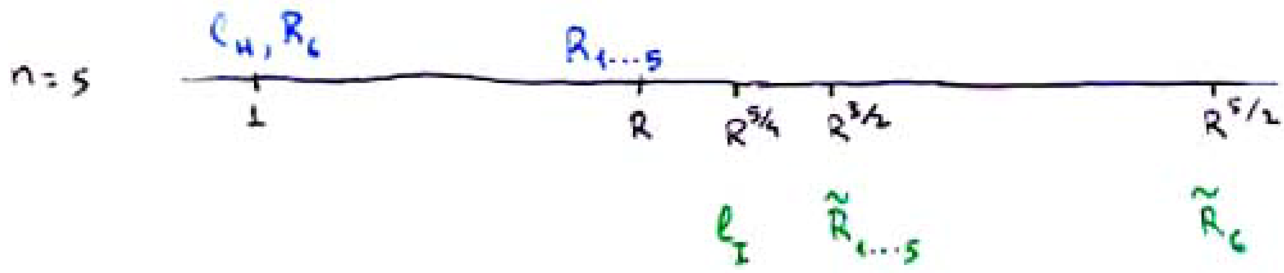
n=4 : as type I′ with $d_\perp = 2$

n=5 : strong coupling after T-duality

n=6 : as type I′ with $d_\perp = 1$







what about $n=1,2,3$?