I. Antoniadis

Physics with large extra dimensions

theoretically viable after '95

- New framework for particle physics

  dissociation of string scale M_s from M_p $\Rightarrow$

  - brane world description
  - strings in accelerators ?

- Protection of hierarchy alternative to susy :

  String scale $M_s \sim$ TeV

Outline

1) Introduction and motivations
   - the gauge hierarchy
   - string theory : state of the art
     - extra dimensions
     - the universe on a membrane

2) Mass scales in string theory (TeV strings)
   - Heterotic string
   - type I and D-branes
   - type II and NS-branes
   - duality relations

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

Bibliography

- String and D-brane Physics at Low Energy
  hep-th/0102202
  Lectures given at the string semester in
  IHP , Paris
- New Physics from New Dimensions
  Erice 2000
- Large Dimensions and String Physics
  in Future Colliders hep-ph/0007266

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

Hierarchy problem

why gravity is so weak compared to the other 3 known interactions?

Quantum theory: all masses of elementary particles $\nearrow$ $M_p \sim 10^{19}$ GeV

Supersymmetry: protection of hierarchy due to cancellations between fermions and bosons

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

TeV strings: effective ultraviolet cutoff

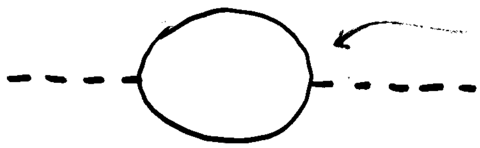
$M_s \sim \text{TeV}$

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

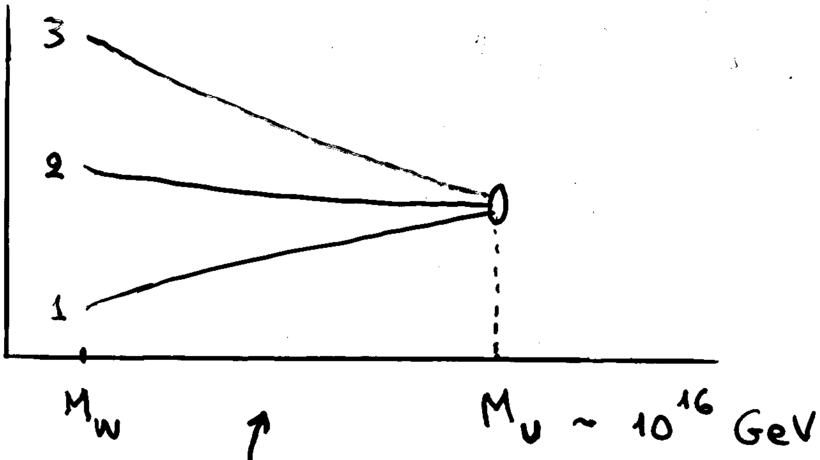
$= \mathcal{O}(m_{SUSY}^2)$ $m_{SUSY}^2 \neq 0$

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 $\longrightarrow$ 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

Two main consequences

Consistent theory $\Rightarrow$ 9 spatial dimensions !

six new dimensions of space

matter and gauge interactions may be localized

in less than 9 dimensions $\Rightarrow$

our universe on a membrane ?

Extra Dimensions

how they escape observation?

finite size R

Kaluza and Klein 1920

energy cost to send a signal:

$E > R^{-1}$ $\leftarrow$ compactification scale

experimental limits on their size

light signal $\Rightarrow$ $E \gtrsim 1$ TeV

$R \lesssim 10^{-16}$ cm

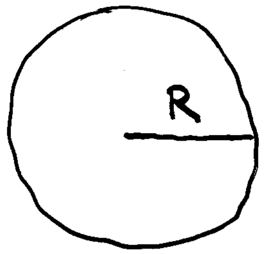
how to detect their existence?

motion in the internal space $\Rightarrow$

mass spectrum in 3d

example: - one internal circular dimension

- light signal



plane waves e^{ipy} periodic under $y \to y + 2\pi R$

$\Rightarrow$ quantization of internal momenta:

$p = \frac{n}{R}$; $n = 0, 1, 2, \ldots$

$\Rightarrow$ 3d: tower of Kaluza Klein particles

with masses $M_n = n/R$

$E >> R^{-1}$: emission of many massive photons

$\Leftrightarrow$ propagation in the internal space

Our universe on a membrane

Two types of new dimensions:

- longitudinal: along the membrane
- transverse: “hidden” dimensions

  only gravitational signal

  $\Rightarrow R_\perp \lesssim 1$ mm !

Consistent (super)strings live in 10 dimensions

freedom of compactification $\equiv$ choice of vacuum

<u>D=10 : 5 theories</u>

Heterotic	Type I SO(32)	Type II A or II B
SO(32) or $E_8 \times E_8$	closed + open	pure supergravity

<u>Old picture:</u> Heterotic most promising

$\lesssim 94$

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

<u>New picture:</u> All are equivalent

different perturbative "corners" of the same

underlying M-theory

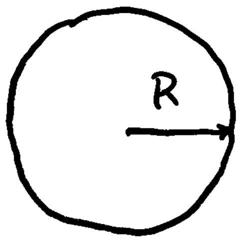
string dualities: $\lambda \longleftrightarrow 1/\lambda$

strong weak

At what energies string theory becomes important ?

- string scale : $M_s = \ell_s^{-1}$

- six compact radii : R_i



Kaluza - Klein momenta : $\frac{n}{R}$

winding modes : $m \frac{R}{\ell_s^2}$

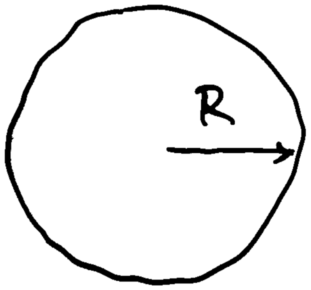
T-duality : $R \to \ell_s^2/R \qquad n \leftrightarrow m$

$\lambda_s \to \lambda_s \frac{\ell_s}{R}$

$\Rightarrow \quad R \gtrsim \ell_s$

T-duality : $R < \ell_s \quad \Rightarrow \quad \tilde{R} = \ell_s^2/R > \ell_s$

closed strings



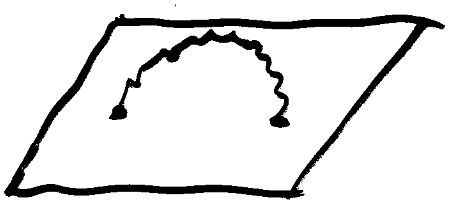
Kaluza-Klein momenta : n/R

Winding modes : mR/ℓ_s^2

symmetry : $R \to \tilde{R} \qquad n \leftrightarrow m$

$R \sim \ell_s$: classical geometry breaks down

open strings



no windings // brane $\quad n/R_\parallel$

no KK $\perp$ brane $\quad mR_\perp/\ell_s^2$

$R_\parallel < \ell_s \quad \Rightarrow \quad \tilde{R}_\parallel \equiv R_\perp > \ell_s$

$\Rightarrow$ all radii $> \ell_s$

E.F.T. : no light winding modes

At what energies string theory becomes important ?

- string scale $M_s \equiv \ell_s^{-1}$
- size of extra dimensions R_i

<u>Old view</u> (Heterotic)

$$M_H = g\, M_P \simeq 10^{18}\ \text{GeV}$$

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

but large coupling problem

<u>Recent view</u>: M_s arbitrary Witten '96, Lykken '96

$M_s \sim$ TeV $\Rightarrow$ protection of hierarchy

alternative to susy

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

Heterotic string:

gauge + gravity interactions appear at tree-level

$$S_H = \int d^{10}x \; \frac{1}{\lambda_H^2} \left(\frac{1}{\ell_H^8} R + \frac{1}{\ell_H^6} F^2 \right) + \cdots$$

$$d^4x \; \underbrace{V \qquad\qquad}_{1/\ell_P^2} \qquad\qquad \sim 1/g^2$$

$$\frac{1}{\ell_P^2} = \frac{1}{g^2} \, \frac{1}{\ell_H^2} \Rightarrow M_H = g\, M_P \sim 10^{18} \text{ GeV}$$

$$\frac{1}{g^2} = \frac{1}{\lambda_H^2} \, \frac{V}{\ell_H^6} \Rightarrow \lambda_H = g \frac{\sqrt{V}}{\ell_H^3} < 1 \Rightarrow V \sim \ell_H^6$$

Realizations of TeV strings

Type I $\Rightarrow$ submm dims

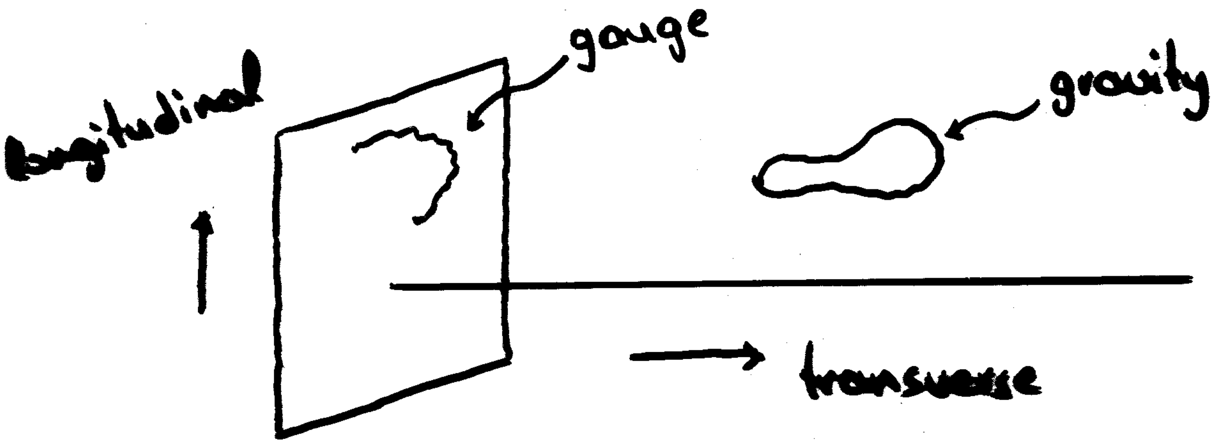
Type II $\Rightarrow$ tiny coupling

strongly coupled Heterotic SO(32) (type I)

$E_8 \times E_8$ (type II)

<u>Type I</u>: closed strings $\rightarrow$ gravity

open strings $\rightarrow$ gauge sector on <u>D-branes</u>



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

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

Dp -branes carry RR - charge

p+1 form gauge potentials

p=0 : particles charged under gauge fields

$$e \int A_\mu \, dx^\mu$$

p=1 : strings charged under 2-forms

$$\int B_{\mu\nu} \, dx^\mu \wedge dx^\nu$$

in general : $\int A_{\mu_1 \dots \mu_{p+1}} \, dx^{\mu_1} \wedge \dots \wedge dx^{\mu_{p+1}}$

compact space $\Rightarrow$ charge conservation

$\Rightarrow$ type II strings : $N - \bar{N} = 0$

number of D-branes

type I strings $\equiv$ type IIB/Ω Sagnotti '87

L↔R projection

⇒ unoriented strings ⇒

orientifold planes : non dynamical branes

- fixed under Ω at special points
- carry RR-charge

⇒ net number of D-branes

sphere   disk

$$S_I = \int d^{10}x \, \frac{1}{\lambda_I^2} \frac{1}{\ell_I^8} R + \int d^{p+1}x \, \frac{1}{\lambda_I} \frac{1}{\ell_I^{p-3}} F^2$$

$$d^4x \, \underbrace{V^{\parallel}_{p-3} \, V^{\perp}_{9-p}}_{1/\ell_p^2} \qquad\qquad d^4x \, \underbrace{V^{\parallel}_{p-3}}_{1/g^2}$$

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

$$\lambda_I \sim g^2$$

$$\frac{1}{\ell_p^2} = \frac{1}{\lambda_I^2} \frac{V_\perp V_\parallel}{\ell_I^8} \simeq \frac{1}{\lambda_I^2} \frac{V_\perp}{\ell_I^{9-p}} \frac{1}{\ell_I^2}$$

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

transverse dims : no constraint

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

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

$M_{P_{(4+n)}}^{2+n}$ 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 $M_{P_{(4+n)}} \sim M_I << M_P$

M_I: TeV, 10^{-16} cm

M_P: 10^{19} GeV, 10^{-33} cm

Supernova constraints:

cooling due to graviton production

e.g. $NN \longrightarrow NN + \text{graviton}$

number of gravitons: $\sim (Tr)^n$ $\qquad T \gg r^{-1}$

~ 10 MeV

$\rightarrow$ production rate:

$$P_g \sim \frac{1}{M_P^2}(Tr)^n \sim \frac{T^n}{M_{P(4+n)}^{2+n}}$$

$$P_g < P_{\text{neutrinos}} \underset{n=2}{\Longrightarrow} M_{P(6)} \gtrsim 50 \text{ TeV}$$

$$\rightarrow M_I \gtrsim 10 \text{ TeV}$$

$M_I \sim 1$ TeV $\Rightarrow$

$n=1$	$\Rightarrow$	$r \simeq 10^8$ km		excluded	
$n=2$		$.1$ mm	10^{-3} eV		possible
$\vdots$					
$n=6$		$.1$ fm	10 MeV		

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

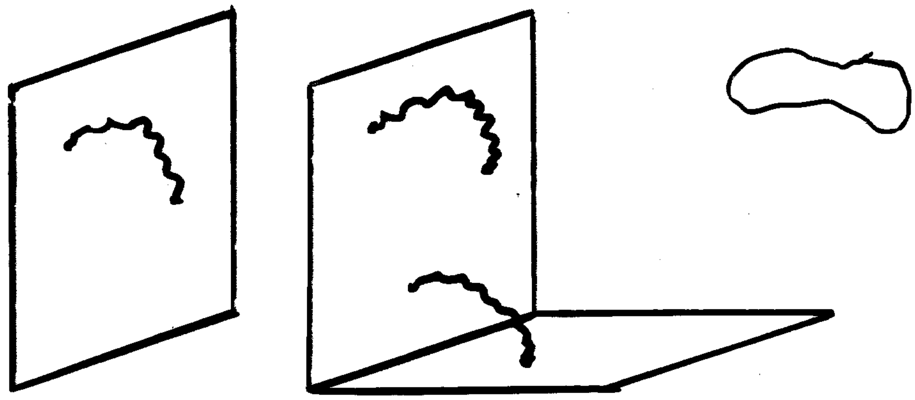
graviton emission on cooling of supernovae $\Rightarrow$

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

Cullen-Perelstein '99

Type I strings provide a perturbative framework for model building with low string scale

- gravity : closed strings (bulk)
- gauge interactions : on D-branes



A particularly attractive possibility :

- bulk is susy
- brane susy breaking

Discrete choice:

(1) Standard Model on non-susy branes

$$\Rightarrow \quad M_s \sim \text{TeV}$$

I.A. - Arkani Hamed - Dimopoulos - Dvali

(2) SM on a susy brane $\Rightarrow$

- replace hidden sector of susy by non susy branes $\Rightarrow$ $M_{susy}\big|_{hidden} = M_s$
- mediation by gravitational interactions

$$\Rightarrow \quad M_{susy}\big|_{us} \sim M_s^2 / M_p$$

$\Rightarrow M_s \sim 10^{11}$ GeV (intermediate scale)

Benakli

Burgess - Ibanez - Quevedo

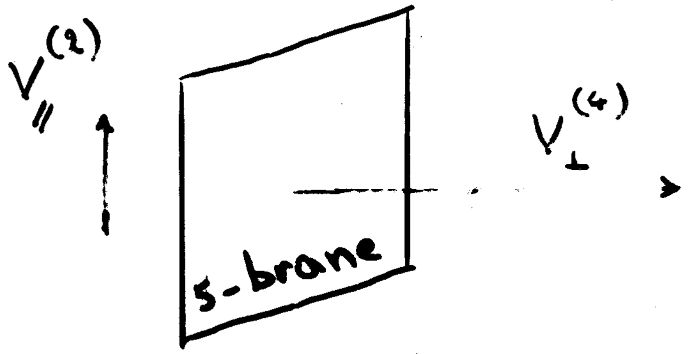
<u>Type II</u> strings

I.A. - Pioline '99

I.A. - Dimopoulos - Giveon '01

Non abelian symmetries : non-perturbative on a 5-brane $_{NS}$

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

similar in Heterotic with small instantons

Benakli - Oz

sphere

non-perturbative

$$S_{II} = \int d^{10}x \, \frac{1}{\lambda_{II}^2} \frac{1}{\ell_{II}^8} R + \int d^6x \, \frac{1}{\ell_{I}^2} F^2$$

$$d^4x \underbrace{V_\perp^{(4)} \, V_\parallel^{(2)}}_{1/\ell_p^2} \qquad\qquad d^4x \underbrace{V_\parallel^{(2)}}_{1/g^2}$$

$$\frac{1}{g^2} = \frac{V_\parallel^{(2)}}{\ell_I^2} \quad \Rightarrow \quad V_\parallel \sim \ell_I^2$$

$$\frac{1}{\ell_p^2} = \frac{1}{\lambda_I^2} \, \frac{V_\perp^{(4)} \, V_\parallel^{(2)}}{\ell_I^8} = \frac{1}{\lambda_{II}^2} \, \frac{1}{g^2} \, \frac{V_\perp^{(4)}}{\ell_I^4}$$

Gauge hierarchy

$M_P >> M_Z \Rightarrow$ why large transverse dims ?

$$r M_I \simeq \left(g^2 \, M_P/M_I\right)^{2/n} \sim \begin{cases} n=2 & 10^{15} \\ n=6 & 10^{5} \end{cases} \quad \text{or} \quad \lambda_{II} \simeq 10^{-14}$$

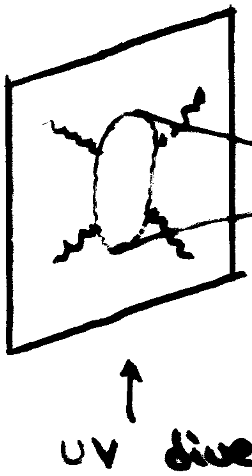
<u>Technical aspect</u>: stability in a non susy vacuum

no large corrections to SM couplings as $r M_I \to \infty$

In general no decoupling if massless bulk fields

propagate in less than 2 large transv. dims

I.A.-Bachas '98



← IR divergence : emission of massless closed string

↑ UV divergence: open string loop

$d_\perp = 1$: linear IR div $\Rightarrow$ quadratic UV $\quad r \sim M_P^2$

<u>Condition</u>: no bulk propagation in one large dim

or local tadpole cancellation $\Rightarrow$ severe constraints

$d_\perp = 2$: log divergences

can be absorbed into a finite number of parameters:

values of bulk massless fields at the brane position

similar to renormalizable field theory

RGE resum $\Rightarrow$ classical 2d eqs in the transverse ~~space~~

log dependence $\Rightarrow$ higher derivs irrelevant

$\rightarrow$ hierarchy could be determined by minim SM eff. potential

$\rightarrow$ **No susy TeV strings:**

same protection of hierarchy as softly susy at TeV

Do we need susy if $M_{str} \sim$ TeV ?

Type I: non susy string models $\Rightarrow$

$$\Lambda_{bulk} \sim M_I^{4+n} \Rightarrow \Lambda_{brane} \sim M_I^{4+n} r^n \sim M_I^2 M_P^2$$

analog of quadratic div. to Λ in softly broken susy

absence of quadratic sensitivity:

- $\Lambda = 0$ (special models)

- $\Lambda_{brane} \sim M_I^4 \Rightarrow \Lambda_{bulk} \sim M_I^4 / r^n$

satisfied if approximate susy in the bulk

e.g. susy is broken primordially only on the brane

explicit realization: Brane susy breaking

I.A. - Dudas - Sagnotti '99

Aldazabal - Uranga '99

No SUSY in our world (brane)

but it may exist a mm away!

to protect the hierarchy against grav. corrections

Prediction: possible <u>new forces</u> at submm scales

e.g. light scalars:

$$\frac{(\mathrm{TeV})^2}{M_p} \sim 10^{-4}\,\mathrm{eV} = 1\ \mathrm{mm}^{-1}$$

radion - modulus $\equiv \ln r$

coupling to matter relative to gravity:

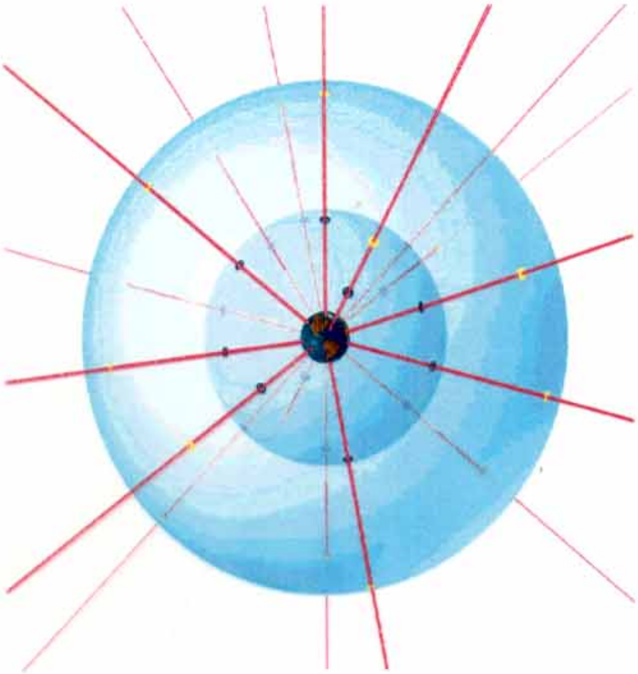
$$\frac{1}{m}\frac{\partial m}{\partial \ln r} = \sqrt{\frac{2n}{n+2}} \sim \mathcal{O}(1)$$

$\Rightarrow$ can be experimentally tested for all $n \geq 2$

I.A. - Benakli - Maillard

Gravity modification at submillimeter distances

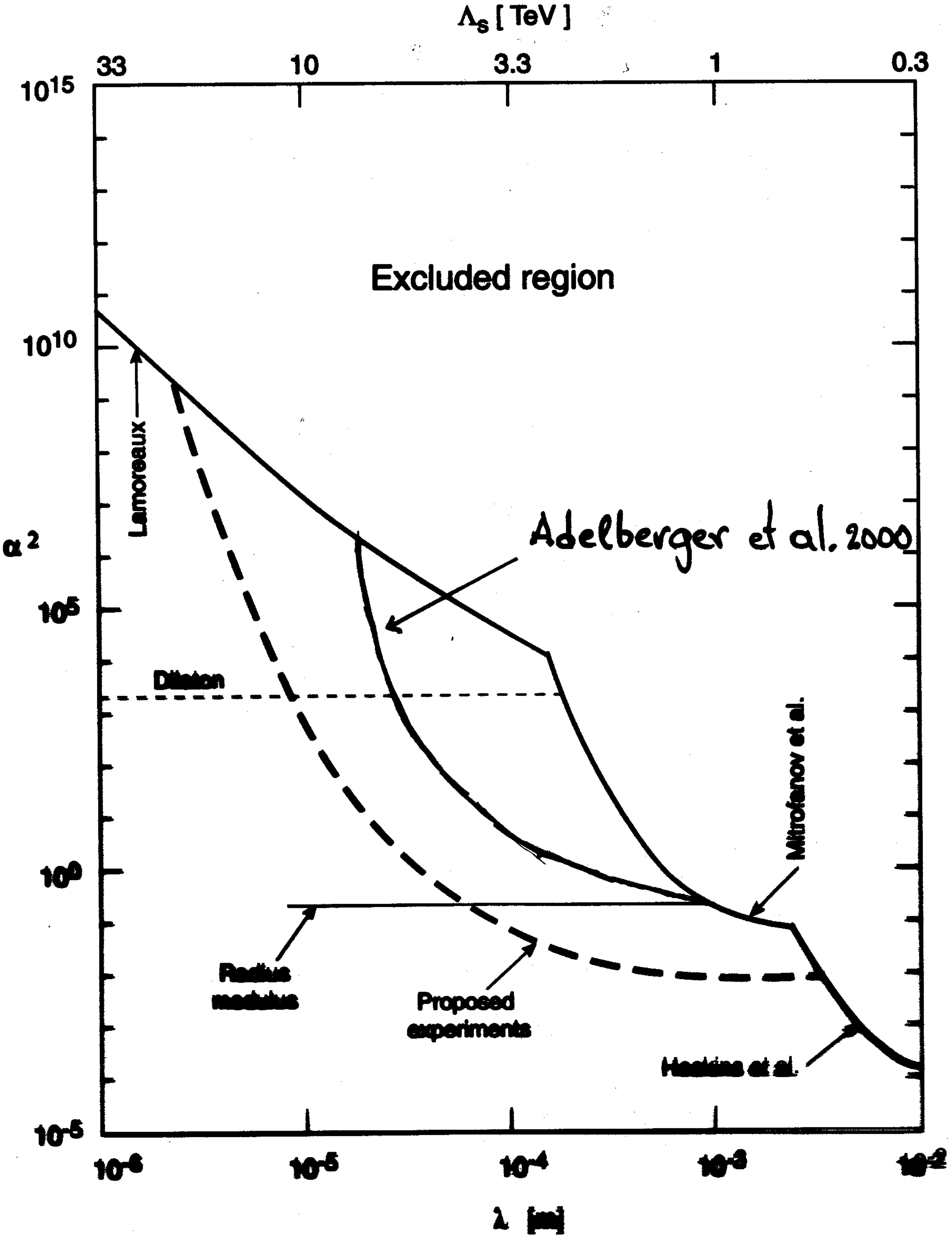
Newton's law: force decreases with area



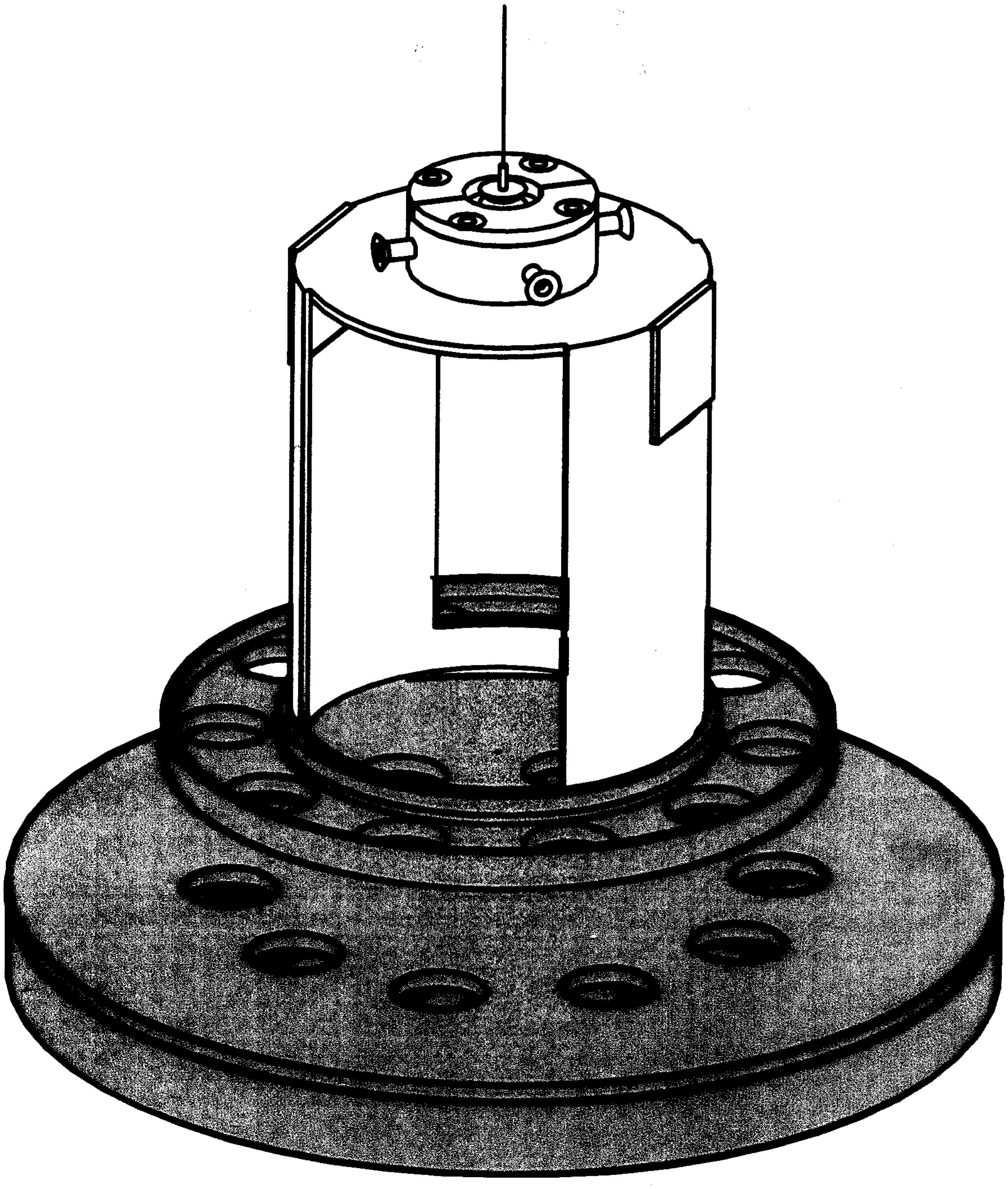
3d: force $\sim 1/r^2$

(3+n)d: force $\sim 1/r^{2+n}$

observable for $n = 2$: $1/r^4$ with $r \lesssim .1$ mm

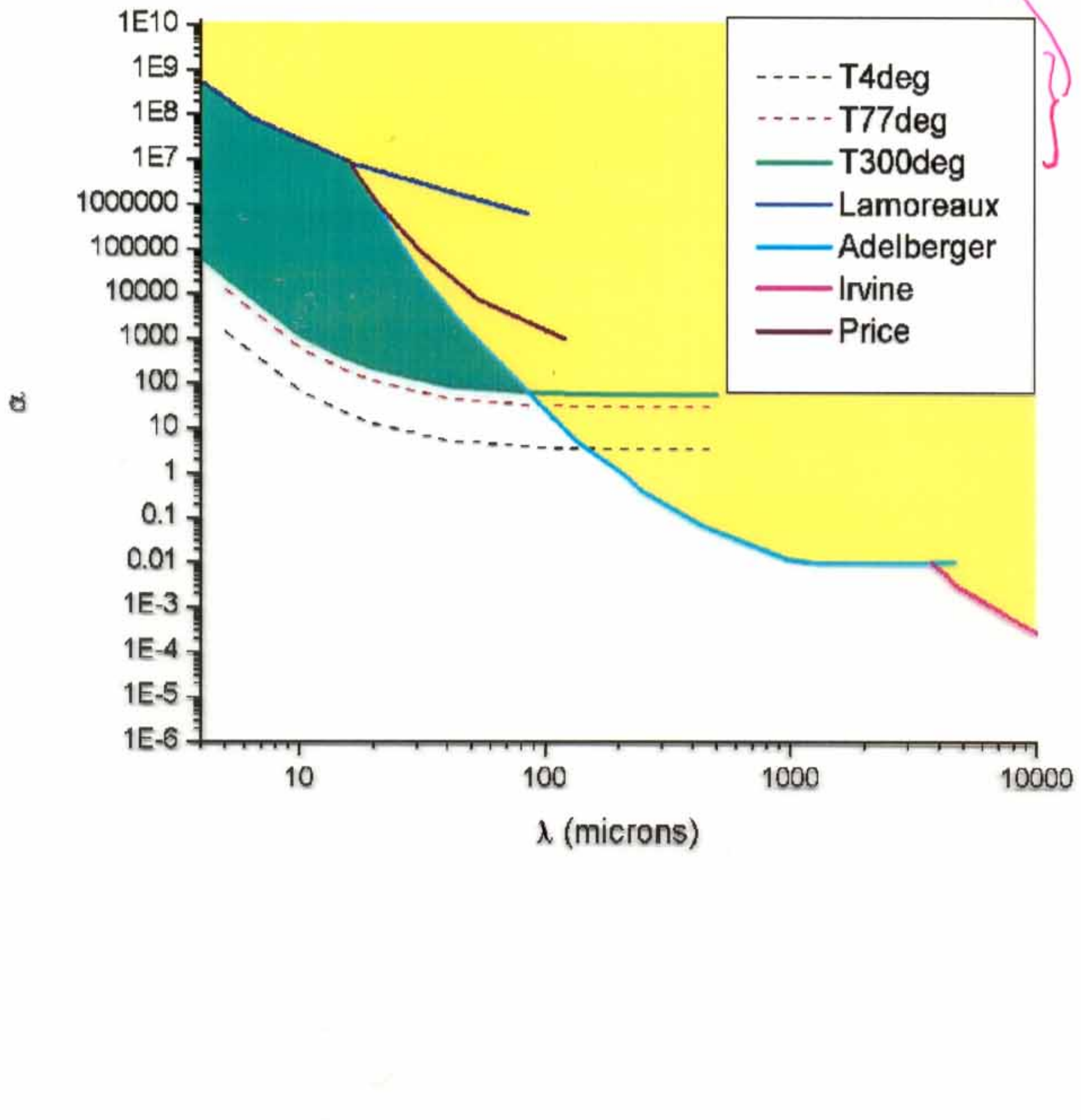


Λ_S [TeV]
33
10
3.3
1
0.3
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
α^2
Excluded region
Lamoreaux
Adelberger et al. 2000
Dilaton
Mitrofanov et al.
Radius modulus
Proposed experiments
Hoskins et al.
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
λ [m]



Limite actuelle: $R_\perp \lesssim 200\ \mu m$ à 95% CL

Kapitulnik et al.



Main experimental predictions

in particle colliders

- Longit. TeV dims $\Rightarrow$ gauge interactions
- Transverse submm dims $\Rightarrow$ strong gravity
- TeV strings $\Rightarrow$ Regge excitations, black holes ?

<u>TeV dims</u>: tower of Kaluza-Klein excitations

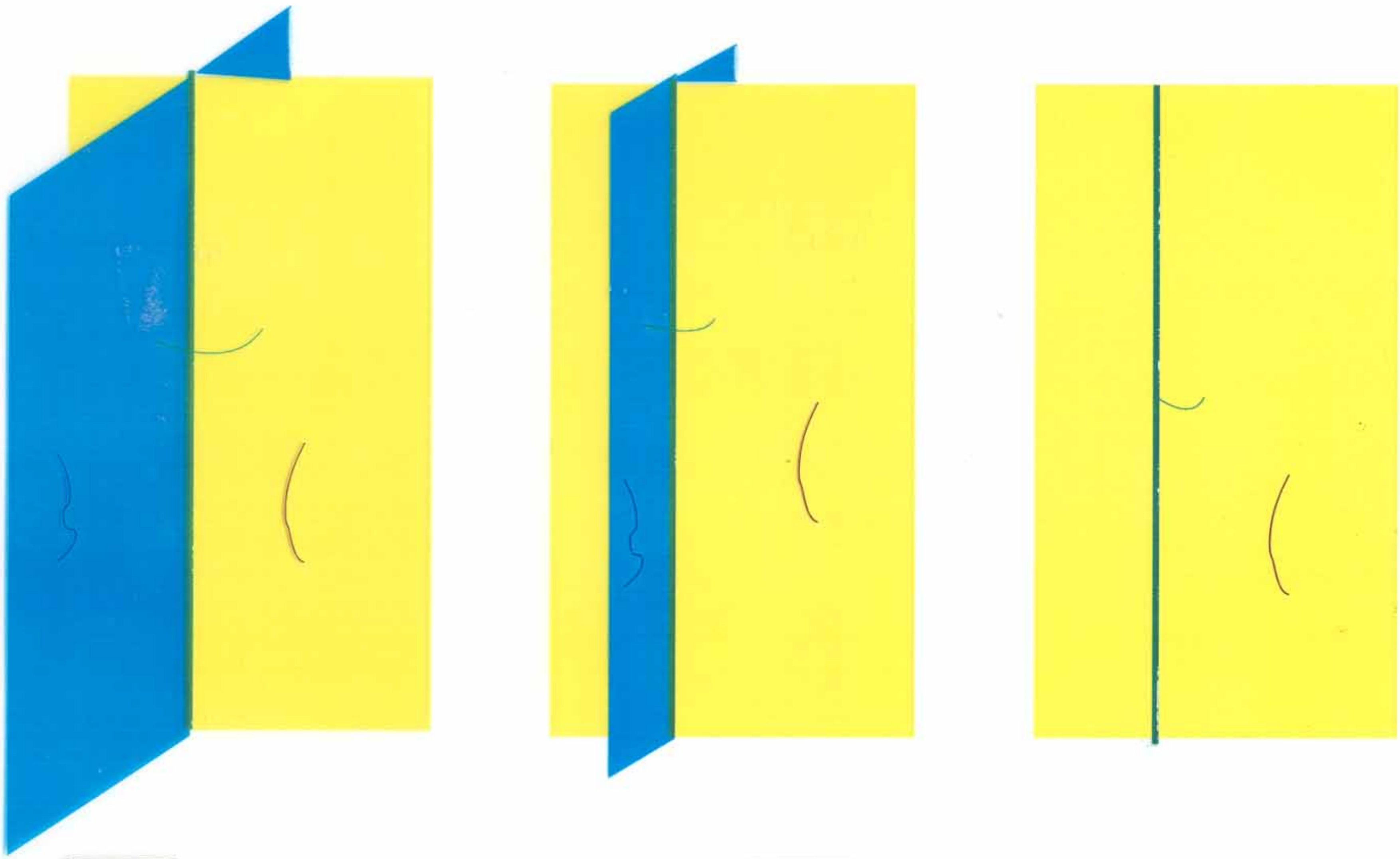
for SM particles

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

$$m_n^2 = m_0^2 + \frac{n^2}{R_{\parallel}^2} \qquad R_{\parallel}^{-1} \lesssim M_s$$

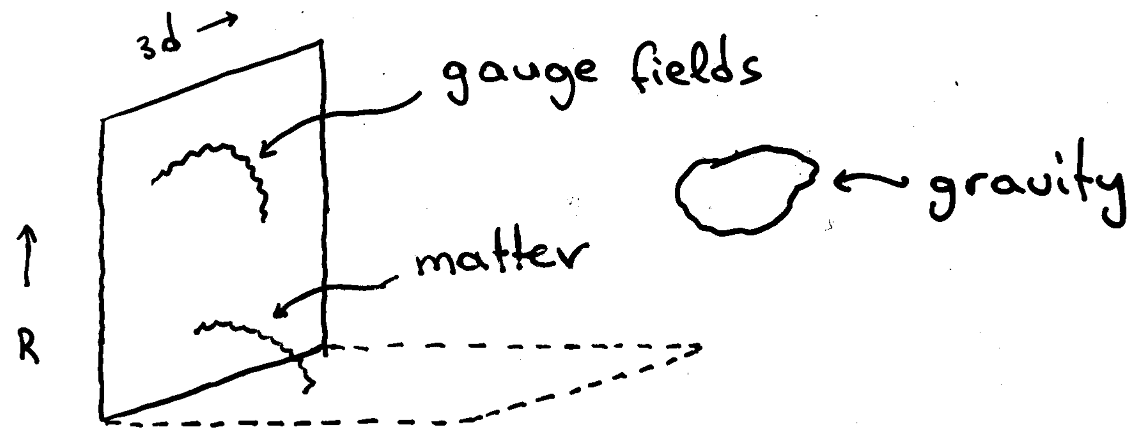
$\Rightarrow \quad \gamma_n \,,\ Z_n \,,\ W_n^{\pm} \,,\ G_n^a$

$R_{\parallel}^{-1}$: 1st scale of new physics



live on // Dbranes
gauge and matter fields.

live on Dbranes intersections
matter fields only.



2 types of open strings :

- both ends move or fixed $\Rightarrow$ gauge fields + matter

  $R_\parallel \Rightarrow$ KK : $1/R_\parallel \lesssim \ell_s^{-1}$ propagation

  $R_\perp \Rightarrow$ windings but no KK : $R_\perp/\ell_s^2 > \ell_s^{-1}$ localization

- one end move , one fixed $\Rightarrow$ only matter

  no KK , no windings

  . automatic chirality

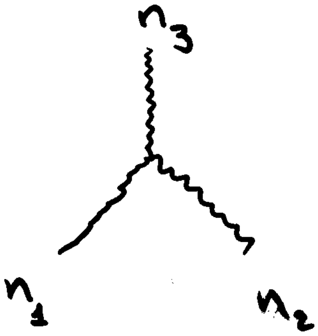
  . KK of gauge bosons unstable

  $\Big\}$ quarks + leptons

similar to Z_2 orbifolds of heterotic I.A. '90

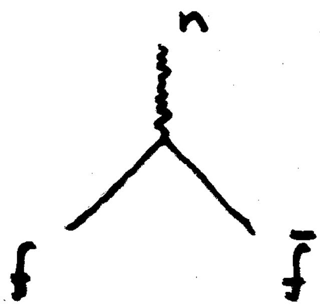
I.A.-Benakli '94

Couplings

(a) 

$$= g\,\delta_{n_1+n_2+n_3}$$ ← momentum conservation

Fourrier Tranform : $\int dy\; F_{\mu\nu}^2(x,y)$

(b) 

$$= g\,\delta^{-n^2\frac{\ell_s^2}{R^2}} \xrightarrow[R\gg\ell_s]{} g$$

$\uparrow$ $\delta > 1$

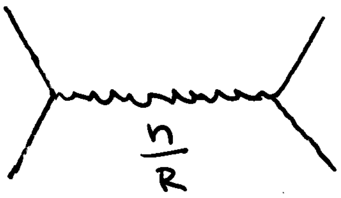
FT : $e^{-\frac{y^2}{2\ell_s^2 \ln\delta}} \xrightarrow[\ell_s\to 0]{} \delta(y)$

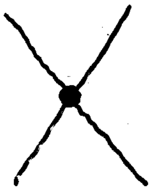
$\Rightarrow$ Gaussian distribution of charge with width

$$\sigma = \sqrt{\ln\delta}\;\ell_s$$ ← "brane thickness"

Experimental constraints

bounds from 4-fermion effective operators (compositeness)

$\sum_{n\neq 0}$ 

$\underset{E \ll R^{-1}}{\simeq}$  $\sim R^2 \sum_{\vec{n}\neq 0} \frac{1}{\vec{n}^2}$

more than 2 dims $\Rightarrow$ regulated sum

$\Rightarrow \sim R^2 (RM_s)^{d-2}$ modulo logs for $d=2$

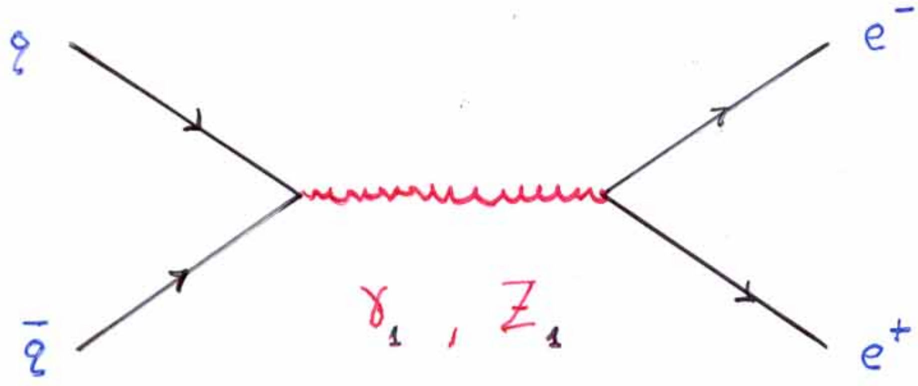
$\Rightarrow R^{-1} \gtrsim$ TeV I.A.- Benakli '94

high precision of Z-width + G_F $\Rightarrow R^{-1} \gtrsim 3$ TeV

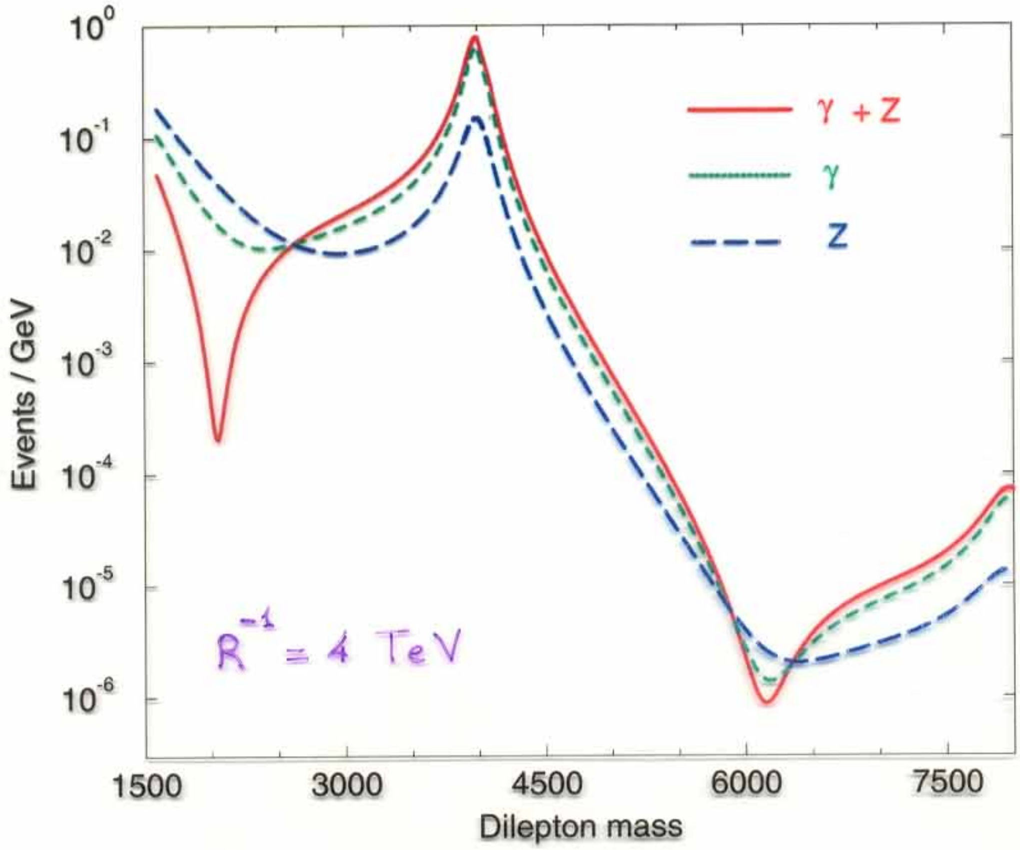
Nath- Yamaguchi
Masip- Pomarol
Marciano , Strumia '99
Delgado- Pomarol -Quiros

$\Rightarrow$ LHC: production at most one KK resonance $R^{-1} \lesssim 6$ TeV

I.A. -Benakli -Quiros '94 ,'99
Nath- Yamada- Yamaguchi
Rizzo - Wells '99
I.A.- Accomando - Benakli


q
$\bar{q}$
e^-
e^+
γ_1 , Z_1

LHC


γ + Z
γ
Z
Events / GeV
Dilepton mass
R^{-1} = 4 TeV
1500
3000
4500
6000
7500
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

I.A. - Accomando - Benakli

$Q\bar{Q} \rightarrow W_n^{\pm} \rightarrow \ell^{\pm} \nu$

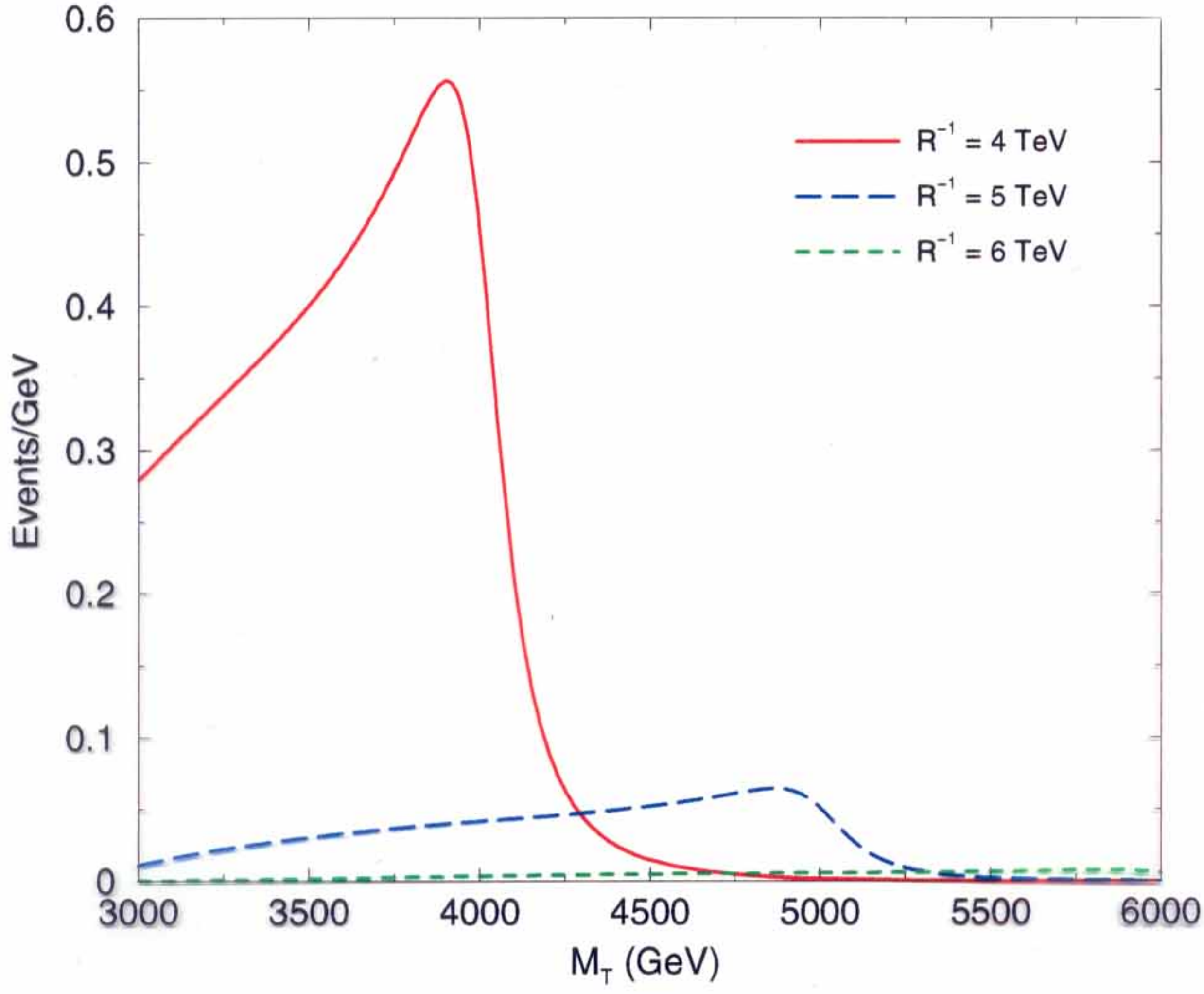
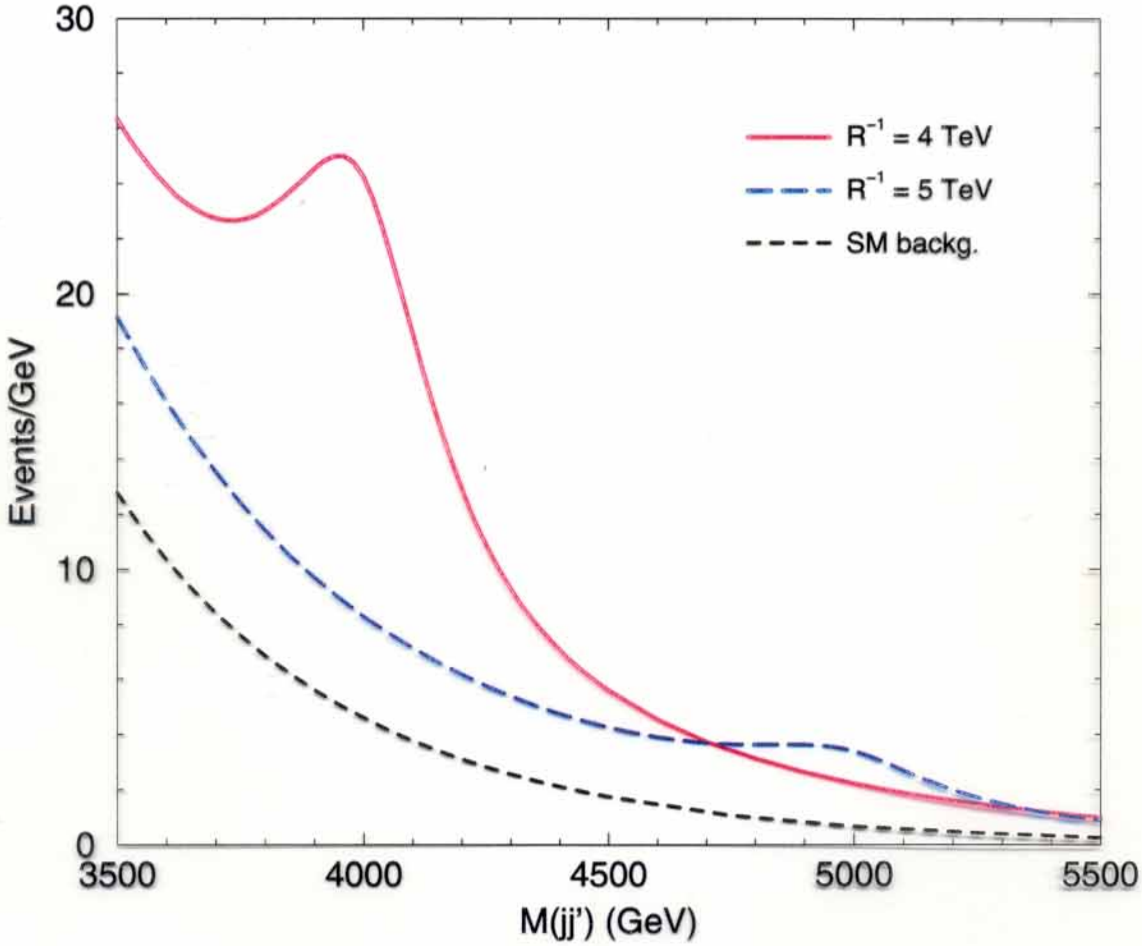


Figure 3: *First resonances in the LHC experiment due to a KK excitation of* $W_{\pm}^{(n)}$ *for one extra-dimension at 4, 5 and 6 TeV. We plot the differential cross section as function of the transverse mass for the W s.*



- no observation $\Rightarrow R^{-1} \gtrsim$ 20 TeV ; 95% CL
- more than one dimension $\Rightarrow$ stronger limits
- universal dimensions $\Rightarrow$ weaker limits

Universal dimensions

- KK momentum conservation $\Rightarrow$

  pair production $\Rightarrow$

  - no resonances
  - weaker limits (300-500 GeV)

- mass splittings from loop effects $\Rightarrow$

  $(-)^{KK}$ possible symmetry $\Rightarrow$

  - similar signals with SUSY
  - lightest KK stable (LKP)

  $\Rightarrow$ dark matter candidate

Hidden submillimeter dimensions

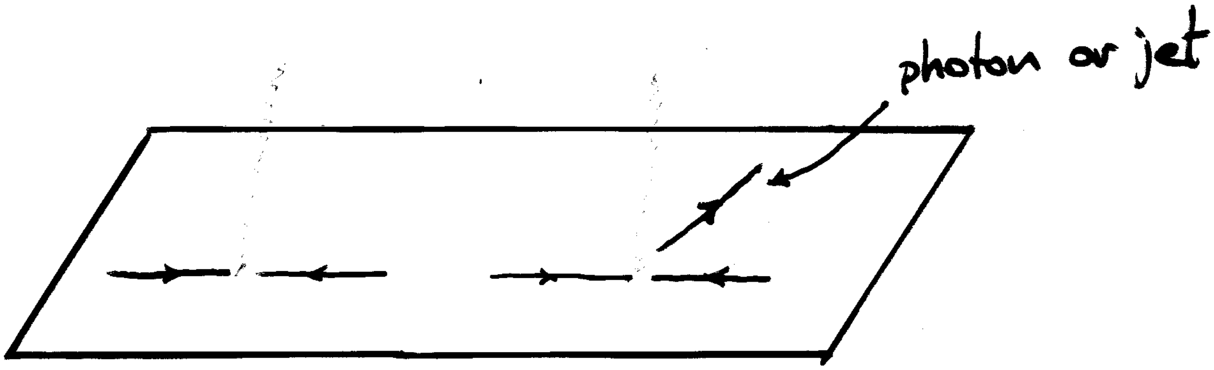
$\Rightarrow$ strong gravity at the TeV

Gravitational radiation in the bulk

3d: Kaluza Klein gravitons very light

$\Rightarrow$ high energy: huge number of particles produced

LHC: 10^{30} massive gravitons of intensity 10^{-30} each



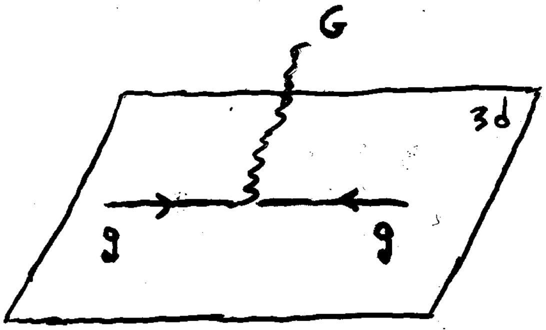
Signal: missing energy

Angular distribution $\Rightarrow$ spin of the graviton

Actual limits from LEP2:

$R_\perp \lesssim .5$ **mm** $(n = 2)$ – 10^{-10} $(n = 6)$

$gg \to G$



$$\sigma(E) \sim \frac{E^p}{M_I^{p+2}} \frac{\Gamma\left(1 - 2E^2/M_I^2\right)^2}{\Gamma\left(1 - E^2/M_I^2\right)^4}$$

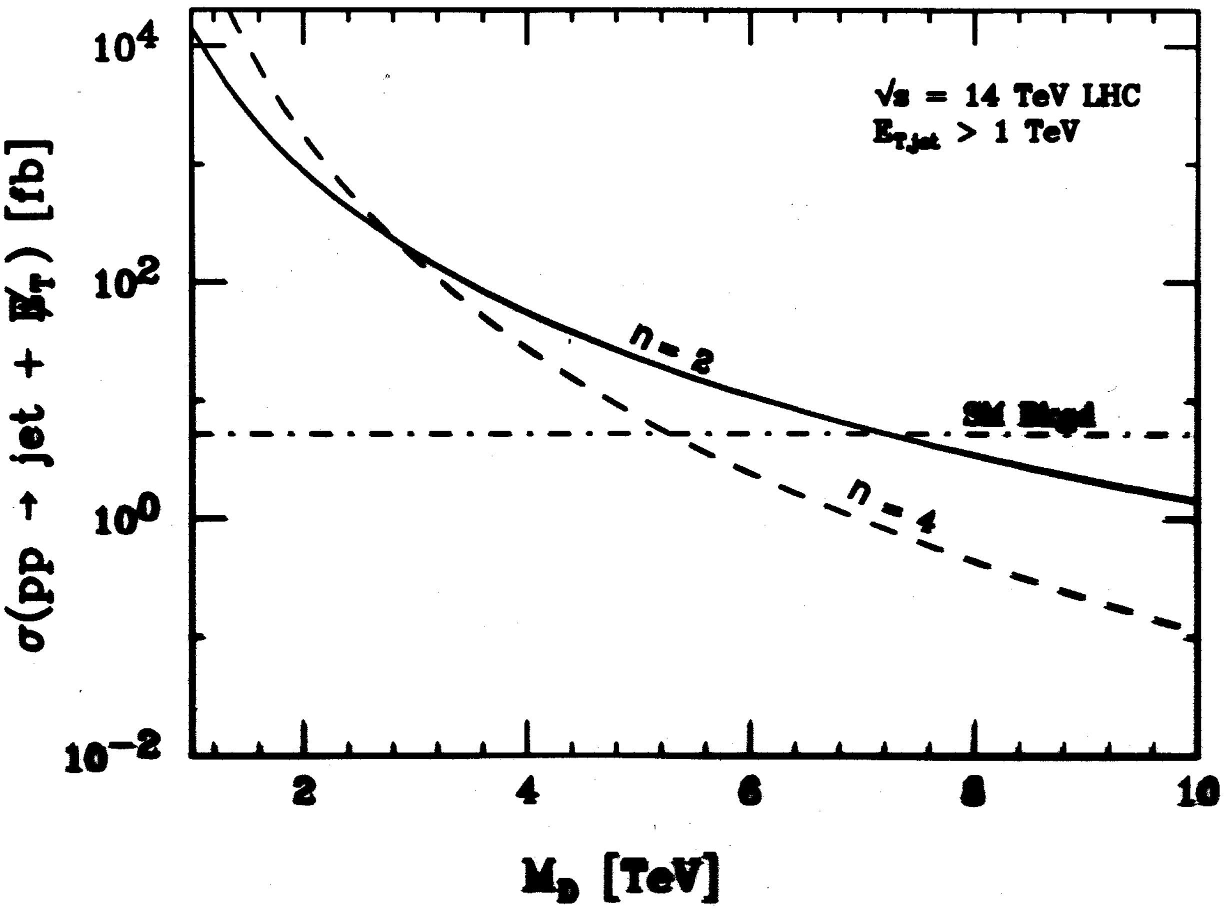
- $E < M_I \Rightarrow \sim E^p / M_I^{p+2}$ gravity in 4+p dims
- $E \sim M_I \Rightarrow$ sequence of poles due to RR resonances
- $E > M_I \Rightarrow$ exp decay due to the UV softness of strings

I.A. – Arkani Hamed – Dimopoulos – Dvali '98

$E < M_I$: reliable computations within eff. field theory

$\Rightarrow$ model independent predictions

Giudice-Rattazzi-Wells '98



no observation ⇒

$R_\perp \lesssim 10^{-2} - 10^{-12}$ mm ($n = 2 - 6$); 95% CL

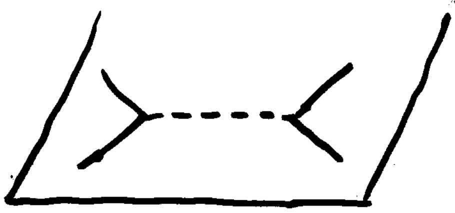
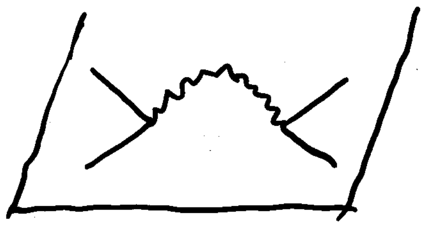
- more dimensions ⇒ weaker limits

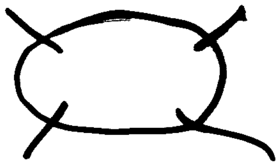
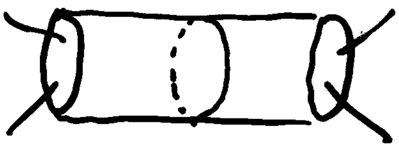
Exchange of massive string modes $\Rightarrow$

4-fermion effective operators

type I string theory : dominant compared to

virtual graviton emission

disk $\Rightarrow$ g_s 1-loop $\Rightarrow$ g_s^2

$\Rightarrow$ loop factor enhancement

$\Rightarrow$ probe string physics

I. A. - Accomando - Benakli '99

Cullen - Perelstein - Peskin '00

Matter fermions : open strings ending

- on the same set of branes

→ dim - 8 effective operators

$$\frac{g^2}{M_I^4} (\bar{\psi} \partial \psi)^2 \rightarrow M_I \gtrsim 500 \text{ GeV}$$

Cullen - Perelstein - Peskin

virtual graviton exchange : $\frac{g^4}{M_I^4} (\bar{\psi} \partial \psi)^2$

- on different sets of branes

→ dim - 6 eff. operators

$$-\frac{g^2}{M_I^2} (\bar{\psi} \gamma \psi)^2 \rightarrow M_I \gtrsim 2-3 \text{ TeV}$$

I.A. - Benakli - Laugier '00

Brane susy breaking in

type I string theory

Stable configurations of antibranes

with branes or orientifolds

↗

non-dynamical branes

with no localized degrees of freedom

and +ve or −ve tension

I.A. – Dudas – Sagnotti

Aldazabal – Uranga '99

→ Interesting model building

Brane susy breaking in type I theory

Stable non-BPS configurations of

branes - antibranes or branes - antiorientifolds

	RR-charge	tension (NS-charge)	
D	+	+	
$\bar{D}$	−	+	
O_-	−	−	
$\bar{O}_-$	+	−	
O_+	+	+	} as D, $\bar{D}$
$\bar{O}_+$	−	+	

$\cancel{\text{susy}}$: $D\bar{D}$, $D\bar{O}_+$, $\bar{D}O_+$

absence of tachyons: $D\bar{D}$ of different type

I.A.-Dudas-Sagnotti '99 e.g. $D9 - \bar{D}5$

or in different positions

Aldazabal - Uranga '99

Simplest model 10D $^{IIB}/_{\Omega}$ Sugimoto

			RR-charge	tension
* $\underline{\Omega = +1}$ $\Rightarrow$	16	O_-9	$-$	$-$
	16	$D9$	$+$	$+$

open sector : antisymmetrization $\Rightarrow$ SO(32) susy

* $\underline{\Omega = -1}$ $\Rightarrow$	16	O_+9	$+$	$+$
	16	$\bar{D}9$	$-$	$+$

open sector: Ω symmetrizes bosons but

antisymmetrizes fermions

$\Rightarrow$ Sp(32) with fermions in the antisym rep

brane susy breaking $\bar{D}O_+$

- tree-level potential $\Rightarrow$ fixing the radii

need branes - antibranes of the same type

ex: $T^4/\mathbb{Z}_2$ $\begin{cases} \text{Untwisted sector}: & \Omega = +1 \\ \text{Twisted sector}: & \Omega = \varepsilon = \pm 1 \end{cases}$

SUSY

brane ~~susy~~

tadpole conditions:

D9 : N_+ $\quad$ $\bar{D}9$: N_- $\quad$ D5 : D_+ $\quad$ $\bar{D}5$: D_-

$N_+ - N_- = 16$ $\qquad$ $D_+ - D_- = 16\,\varepsilon$

$$V_{eff} = e^{-\phi_6} \left\{ (N_+ + N_- - 16)\sqrt{V_4} + \frac{D_+ + D_- - 16\varepsilon}{\sqrt{V_4}} \right\}$$

6D - dilaton

minimization $\Rightarrow$ $V_4 = \dfrac{D_+ + D_- - 16\varepsilon}{N_+ + N_- - 16} \equiv \dfrac{D_-}{N_-}$

- 1-loop potential $\Rightarrow$ fixing the Wilson lines

$\leftrightarrow$ branes separation

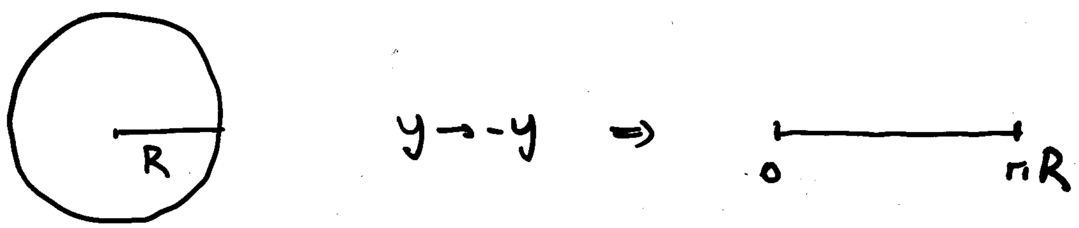
Evading the NS tadpoles:

introduce a small ~~susy~~ in the bulk

by Scherk-Schwarz boundary conditions

I.A.- Benakli - Laugier

- S-S on S^1/Z_2



$y \to -y \Rightarrow$

periodicity under $y \to y + 2\pi R$

bosons: periodic

Z_2 even : $\phi_e(x^\mu, y) = \sum_n \phi_e^{(n)}(x^\mu) \cos\frac{n}{R}y$

Z_2 odd : $\phi_o = \sum_n \phi_o^{(n)}(x^\mu) \sin\frac{n}{R}y$

Explicit realization of susy breaking: Scherk-Schwarz '79

Fayet '85

Rohm '84

Ferrara-Kounnas-Porrati-Zwirner '88

I.A. '90

Fields periodic up to (discrete) R-symmetry transf.

$$\Phi(X+2\pi R) = U\,\Phi(X) \qquad U = e^{2\pi i Q} \quad \Rightarrow$$

KK momentum $\quad p = \dfrac{m+Q}{R}$ mass-shifts for KK modes

$U^N = 1 \Rightarrow Q$ quantized in units of $1/N$

modular invariance $\Rightarrow$ windings $\quad n \to n\,,\quad Q \to Q - n$

R-symmetry $\equiv$ internal rotation

$\Rightarrow$ equivalent to freely acting orbifolds Vafa-Witten '96

$$X \to \mathcal{R}X + \delta \qquad \delta = 2\pi R/N \qquad R' = RN$$

Ex: 2π-rotation $\Rightarrow U = (-)^F \Rightarrow$ mass-shifts only for fermions

fermions : antiperiodic

$\mathbb{Z}_2$-even : $\psi_e = \sum_n \psi_e^{(n)}(x^\mu) \cos \frac{n+\frac{1}{2}}{R} y$

$\mathbb{Z}_2$-odd : $\psi_o = \sum_n \psi_o^{(n)}(x^\mu) \sin \frac{n+\frac{1}{2}}{R} y$

susy parameter : antiperiodic

$$\delta \phi = \psi \eta$$

periodic   anti-periodic

- $y=0$: $\eta_o = 0 \Rightarrow$ half of susy remains : η_e

- $y=\pi R$: $\eta_e = 0 \Rightarrow$ " : η_o

No zero mode of $\eta \Rightarrow$

susy is broken globally

SS $\Rightarrow$ ~~SUSY~~ : Q_e $\qquad$ Q_o

0 ———————— πR

Orientifolds : $O(-,-)$ $\qquad$ $\bar{O}(+,-)$

RR-charge $\qquad$ tension

D-branes : $D(+,+)$ $\qquad$ $\bar{D}(-,+)$

SUSY (linear) $\qquad$ Q_e $\qquad$ Q_o

Non-linear $\qquad$ Q_o $\qquad$ Q_e

Model I : · local charge conservation

· brane SUSY (locally) $\qquad$ Q_e

Model II : $O\,\bar{D}$ $\qquad$ $\bar{O}\,D$

· brane SUSY breaking

but Non-Linear SUSY $\qquad$ Q_e

· only global charge conservation

Example with 8-branes

- bulk : $S^1/\mathbb{Z}_2$ with SS breaking

$$0 \longmapsto\!\!\!\longrightarrow \pi R$$

O_- $\qquad\qquad\qquad$ $\bar{O}_-$

RR charge: -16 $\qquad\qquad$ $+16$

- Model I :

$$\left.\begin{array}{l} 16\ D_8 \text{ on } O_- \\ 16\ \bar{D}_8 \text{ on } \bar{O}_- \end{array}\right\} \Rightarrow SO(16)\times SO(16)$$

"susy"

- Model II :

$$\left.\begin{array}{l} 16\ \bar{D}_8 \text{ on } O_- \\ 16\ D_8 \text{ on } \bar{O}_- \end{array}\right\} \Rightarrow SO(16)\times SO(16)$$

with fermion in symmetric reps : $(136,1)+(1,136)$

$$136 = 135 + \underset{\substack{\uparrow \\ \text{Goldstino}}}{1}$$

Non-linear susy on the brane

$\Rightarrow$ massless Goldstino χ

Sen, Dudas-Mourad, Pradisi-Riccioni

$$\mathcal{L}_{eff} = -\frac{1}{4V^4}\left(\chi \overleftrightarrow{\partial}_\mu \sigma^\nu \chi\right)\left(f \overleftrightarrow{\partial}_\nu \sigma^\mu f\right) + \frac{2C_f}{V^4}\left(f\partial^\mu \chi\right)\left(f\partial_\mu \chi\right)$$

fixed by susy $\nearrow$ $\qquad$ $\nwarrow$ model dependent

Brignole - Feruglio - Zwirner

Matter fermions on the same set of branes $\Rightarrow$

- $\dfrac{V^4}{2} = \underset{\substack{\uparrow \\ \text{number of branes}}}{N} \cdot T \leftarrow$ tension $\qquad T_{3\text{-brane}} = \dfrac{M_s^4}{(2\pi)^3 g_s}$

- $C_f = \begin{cases} 1 & f, \chi \text{ : same internal helicity} \\ 0 & \text{" different "} \end{cases}$

I.A. - Benakli - Laugier

U(1) masses in type I models

I.A. - Kiritsis - Rizos '02

4d U(1) anomalies ⇒ Green-Schwarz mechanism

$$\delta A = d\Lambda \quad \Rightarrow \quad \delta a = -M\Lambda$$

$$-\frac{1}{4g_A^2}F_A^2 - \frac{1}{2}(da + MA)^2 + \frac{a}{M}k_I^A \, \mathrm{tr}\, F_I \wedge F_I$$

$\uparrow$ cancel the anomaly

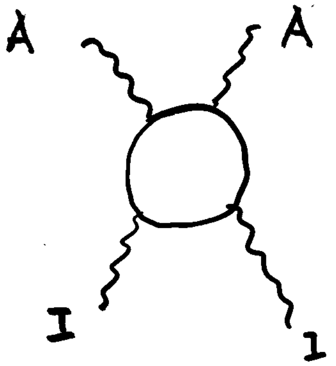
⇒ $U(1)_A$ mass : $M_A = g_A M$

a: Poincaré dual of a 2-form

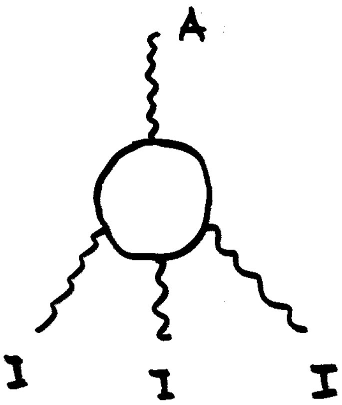
from RR closed string sector

$U(1)_A$ global symmetry remains (in perturbation)

6d $U(1)$ anomalies $\Rightarrow$ a $\begin{cases} \text{2-form } b \\ \text{axion dual to a 4-form} \end{cases}$



$\Rightarrow$ 2-form : $b \wedge \mathrm{tr}\, F_I^2 + (db)^2$



$\Rightarrow$ 0-form : $a\, \mathrm{tr}\, F^3 + (da + MA)^2$

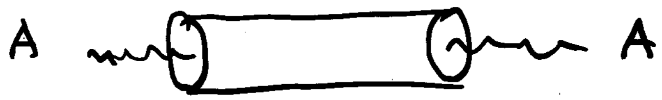
- 2-form $\Rightarrow$ no $U(1)_A$ mass
- 0-form $\Rightarrow$ $U(1)_A$ mass

  Compactification to 4d $\Rightarrow$

  - no anomaly but still $U(1)_A$ mass
  - all k_I must vanish

1-loop string computation in orientifolds

$\Rightarrow$ contact term from the annulus



- $N=4$ sectors $\rightarrow$ 0

- $N=2$ $\Rightarrow$ 6d masses localized in 4 dims

  non vanishing $\longleftrightarrow$ 6d anomalies

- $N=1$ $\rightarrow$ 4d masses localized in 6 dims

$$M_A^2 = \frac{1}{n^3} \sum_{\substack{N=1 \\ \text{sectors } k}} \left(\mathrm{Tr}\, \gamma_k \lambda\right)^2 \mathrm{Str}_k \left[\frac{1}{12} - s^2\right]_{\text{closed channel}}$$

4d helicity

$$\underbrace{\qquad\qquad\qquad}_{-\frac{3}{2} N_v + \frac{1}{2} N_c}$$

$N=2$ sectors : $\mathrm{Str}[\ ]_{\text{closed}} \rightarrow V_2\, \mathrm{Str}[\ ]_{\text{open}}$

$\Rightarrow$ explicit realizations for

(A, a)	sectors	m_A	g_A
(brane, brane)	$N=1$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
(bulk, brane)	$N=1$	$1/\sqrt{V_A}$	$1/\sqrt{V_A}$
(brane, bulk)	$N=2$	$1/\sqrt{V_a}$	$\mathcal{O}(1)$
(bulk, bulk)	$N=2$	$\sqrt{V_a/V_A}$	$1/\sqrt{V_A}$

(brane, bulk) : exp excluded

A light with $g_A \sim \mathcal{O}(1)$

(bulk, brane) : new sub mm forces

$g_A \sim M_s/M_p \sim 10^{-16} \sim 10^6 - 10^8 \times$ gravity $\leftarrow \frac{m_{proton}}{M_p}$

supernova $\Rightarrow$ dim of bulk ≥ 4

(bulk, bulk): large KK mass-shifts $\Rightarrow$ unobservable forces

- all cases : $M_A \lesssim g_s M_s$ up to M_s^2/M_p

$\Rightarrow$ new effects in accelerators

production of $U(1)_A$ + possible KK

- Model building : extra conditions for $U(1)_Y$

to remain massless

anomaly free in all 6d limits

e.g. part of non-abelian groups

- Brane $\cancel{SUSY}$ models :

$D\bar{O}$, $\bar{D}O$: annulus is not affected

$\Rightarrow$ "SUSY" result remains

$D\bar{D}$: extra contributions easy to compute

Other properties

- Electroweak symmetry breaking

$$\mu^2 = - \varepsilon^2 g^2 M_s^2$$

$\uparrow$ calculable loop factor suppression

- B global symmetry

$\Rightarrow$ protect proton decay

- L global symmetry

$\Rightarrow$ no lepton number violation

• R-neutrinos in the bulk

- alternatives of gauge couplings unification