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Theoretical and experimental prospects on extra dimensions

Outline

- Motivations
- String theory: state of the art

  Extra dimensions

  The Universe on a membrane
- TeV strings and mass hierarchy

  large hidden dimensions
- SUSY breaking

  Gravity modification at short distances
- Experimental predictions

  in particle accelerators

Supersymmetry

- elementary scalars : partners of fermions

- stabilizes the gauge hierarchy

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

$\delta M_W^2 =$

$= 0$ susy exact

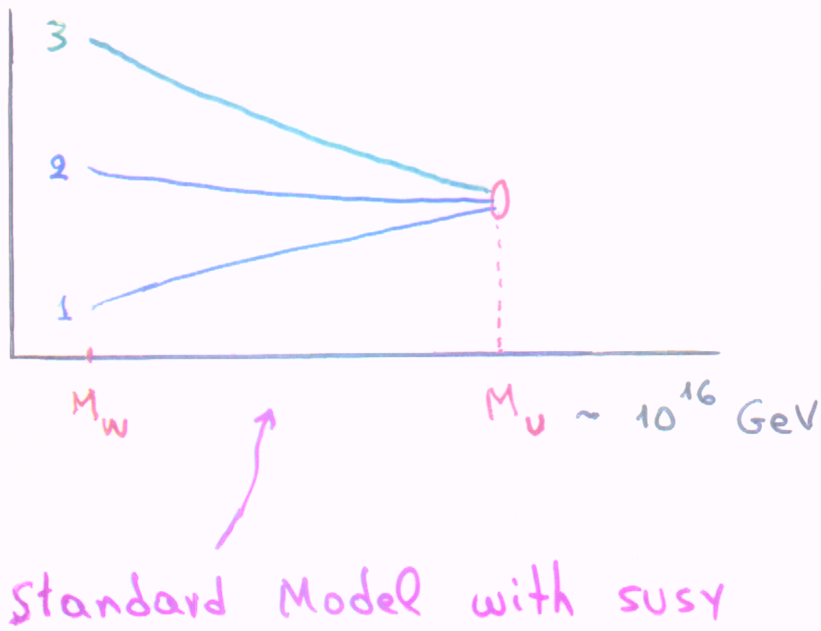
$= \mathcal{O}(m_{SUSY}^2)$ $m_{SUSY}^2 \neq 0$

↑ boson-fermion mass splittin

- rich spectrum of superparticles in the TeV region

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

Unification



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:

$E > R^{-1}$ ← compactification scale

experimental limits on their size

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

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

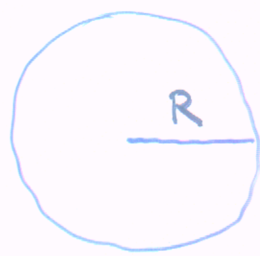
how to detect their existence?

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:

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

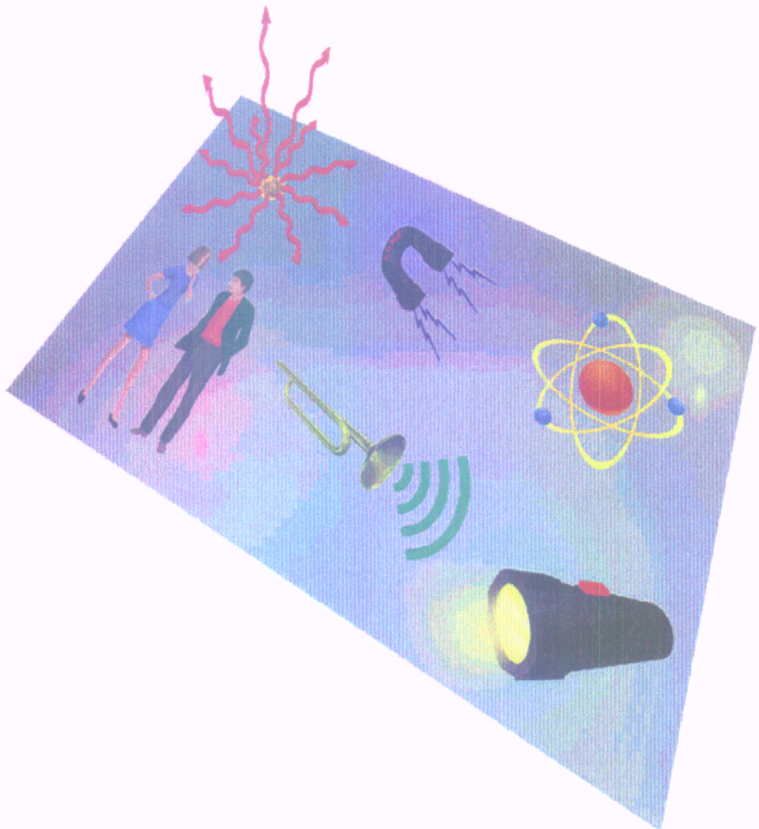
$\Rightarrow$ 3d: tower of Kaluza Klein particles

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:

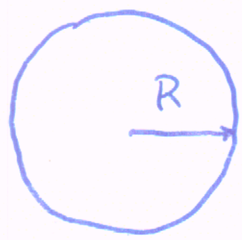
- longitudinal: along the membrane
- transverse: “hidden” dimensions

  only gravitational signal

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

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

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

$$\Rightarrow \quad R \gtrsim \ell_s$$

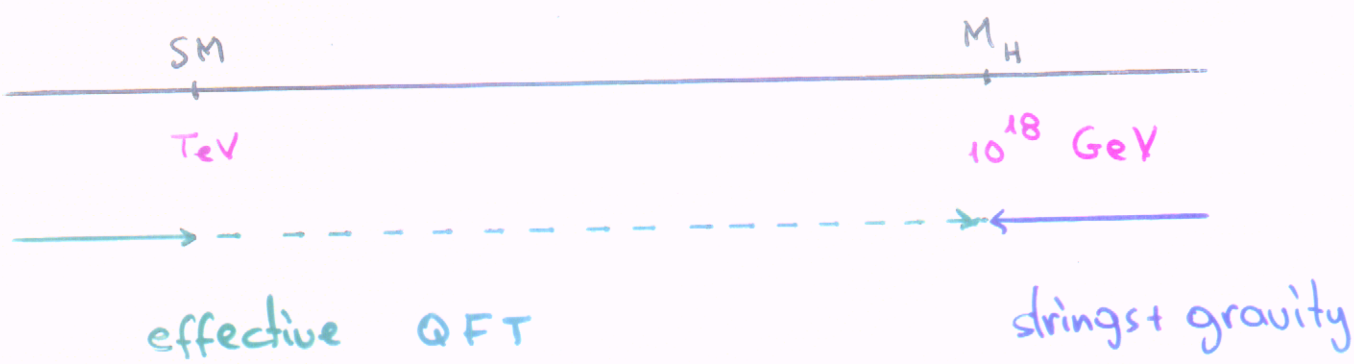
Old view (Heterotic) : near $M_p \sim 10^{19}$ GeV $(10^{-33}$ cm$)$

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

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

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

separate physics in 2 regions :



However physical motivations $\Rightarrow$

large volume may be relevant

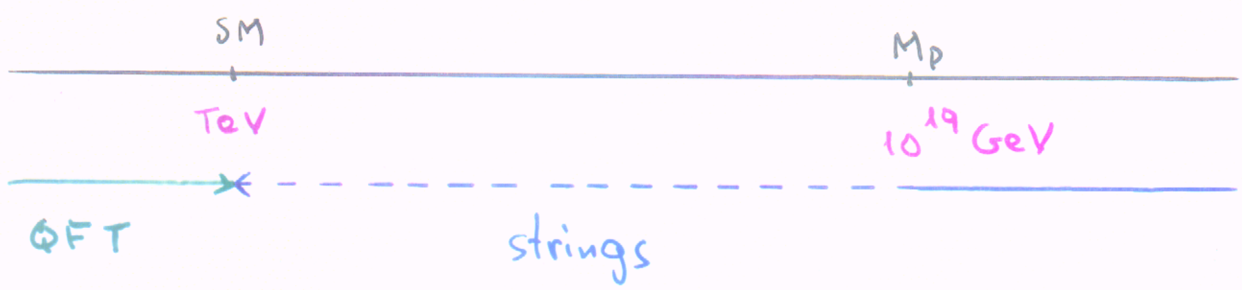
$\not{\text{SUSY}}$ by compactification $\Rightarrow$ $R \sim \text{TeV}^{-1}$ I.A. '90

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



- 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

Realizations of TeV strings

Type I $\Rightarrow$ submm dims

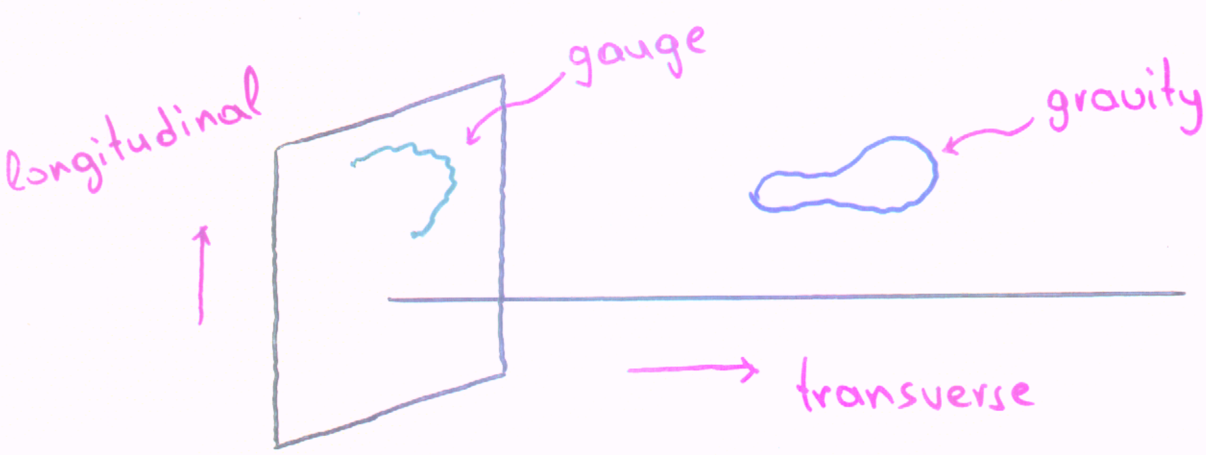
Type II $\Rightarrow$ tiny coupling

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 ⇒ longitud dims ∼ string size

transuerse dims : no constraint

n ⊥ dims of radius r ⇒

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

$M_{P_{(4+n)}}^{2+n}$ Planck mass of 4+n dims

largeness of M_P / M_I ⇒ extra-large r

- string coupling : $\lambda_I \simeq g^2$

- gravity strong at $M_{P_{(4+n)}} \sim M_I \ll M_P$

M_I ↑ TeV, 10^{-16} cm

M_P ↑ 10^{19} GeV, 10^{-33} cm

$M_I \sim 1$ TeV ⇒ $n = 2 - 6$: $r \sim$ mm - fm

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 ?

TeV dims: tower of Kaluza-Klein excitations

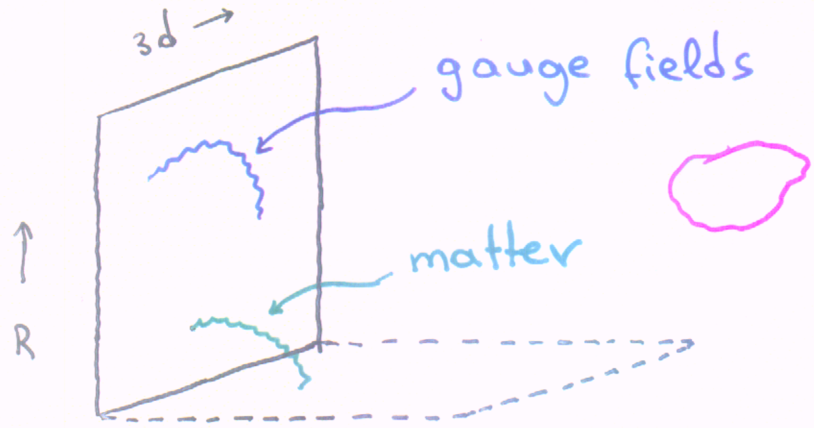
for SM particles

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

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

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

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



2 types of open strings :

- both ends move or fixed $\Rightarrow$ gauge fields + matte[r]

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

$R_{\perp} \Rightarrow$ windings but no KK : $R_{\perp}/\ell_s^2 > \ell_s^{-1}$ localizatio[n]

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

no KK , no windings

. automatic chirality

. KK of gauge bosons unstable

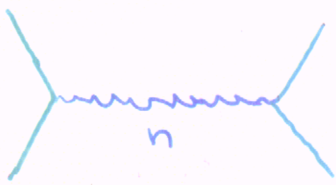
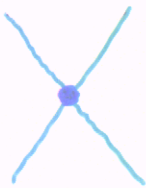
} quarks + lepton[s]

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

I.A.-Benakli '94

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

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

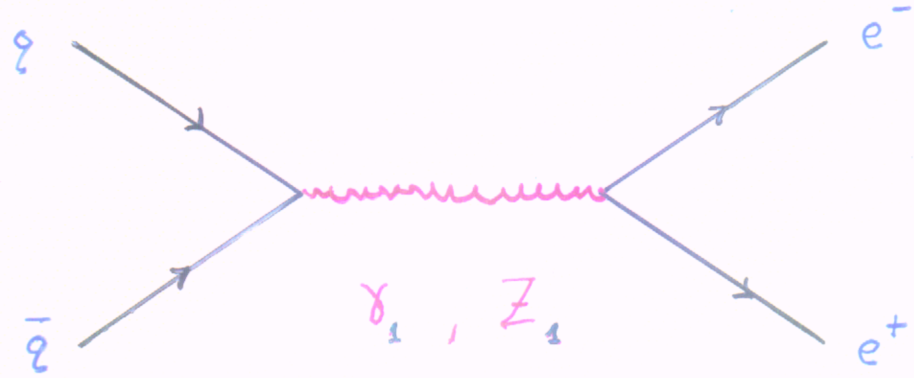
$\Rightarrow R^{-1} \gtrsim$ TeV   I.A.-Benakli '94

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

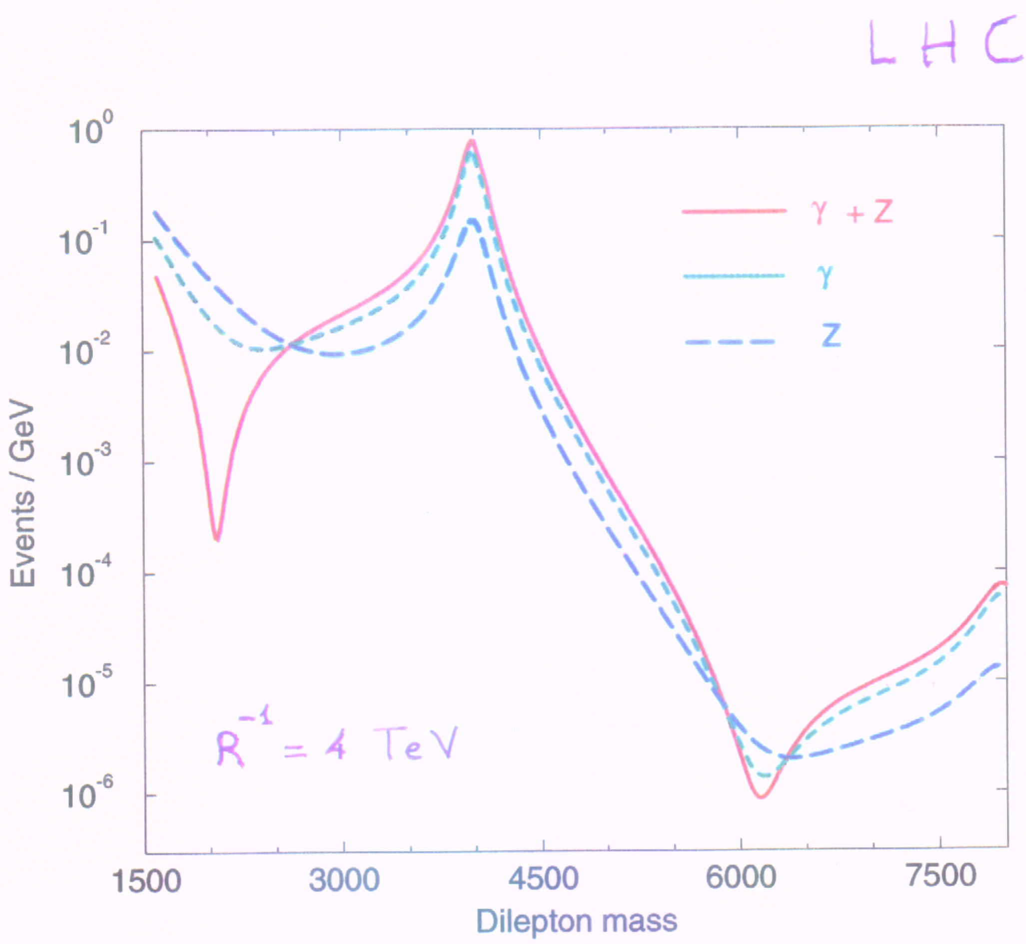
Nath-Yamaguchi
Masip-Pomarol
Marciano, Strumia   '99
Delgado-Pomarol-Quiros

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

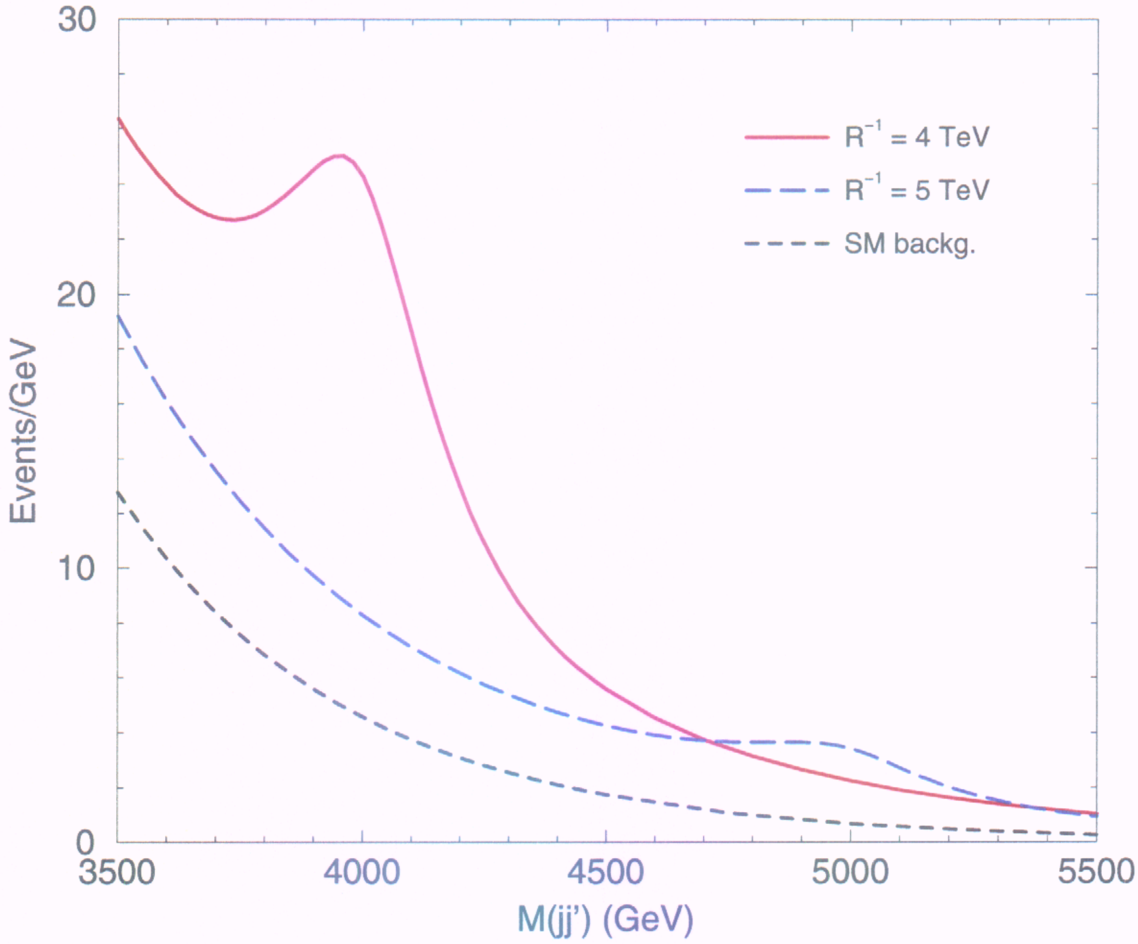
I.A.-Benakli-Quiros '94, '99
Nath-Yamada-Yamaguchi
Rizzo-Wells '99
I.A.-Accomando-Benakli



q
$\bar{q}$
e^-
e^+
γ_1 , Z_1



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



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

Hidden submillimeter dimensions

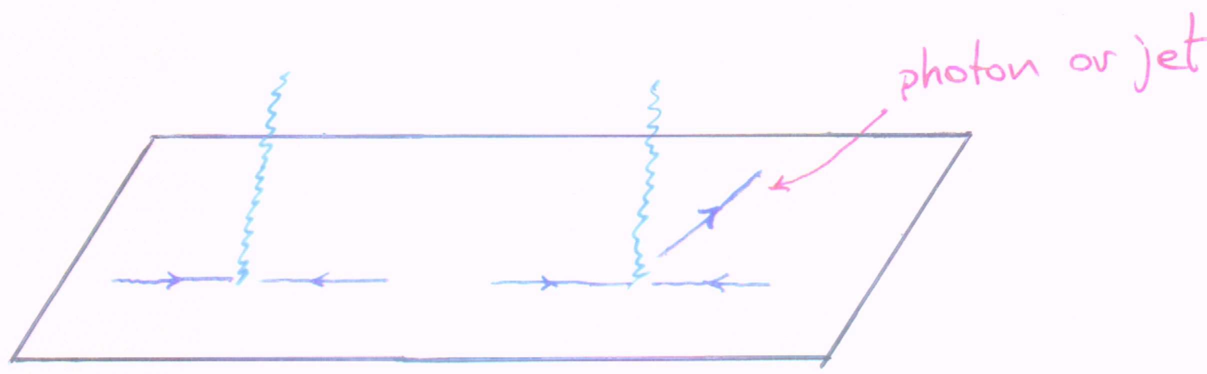
$\Rightarrow$ strong gravity at the TeV

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



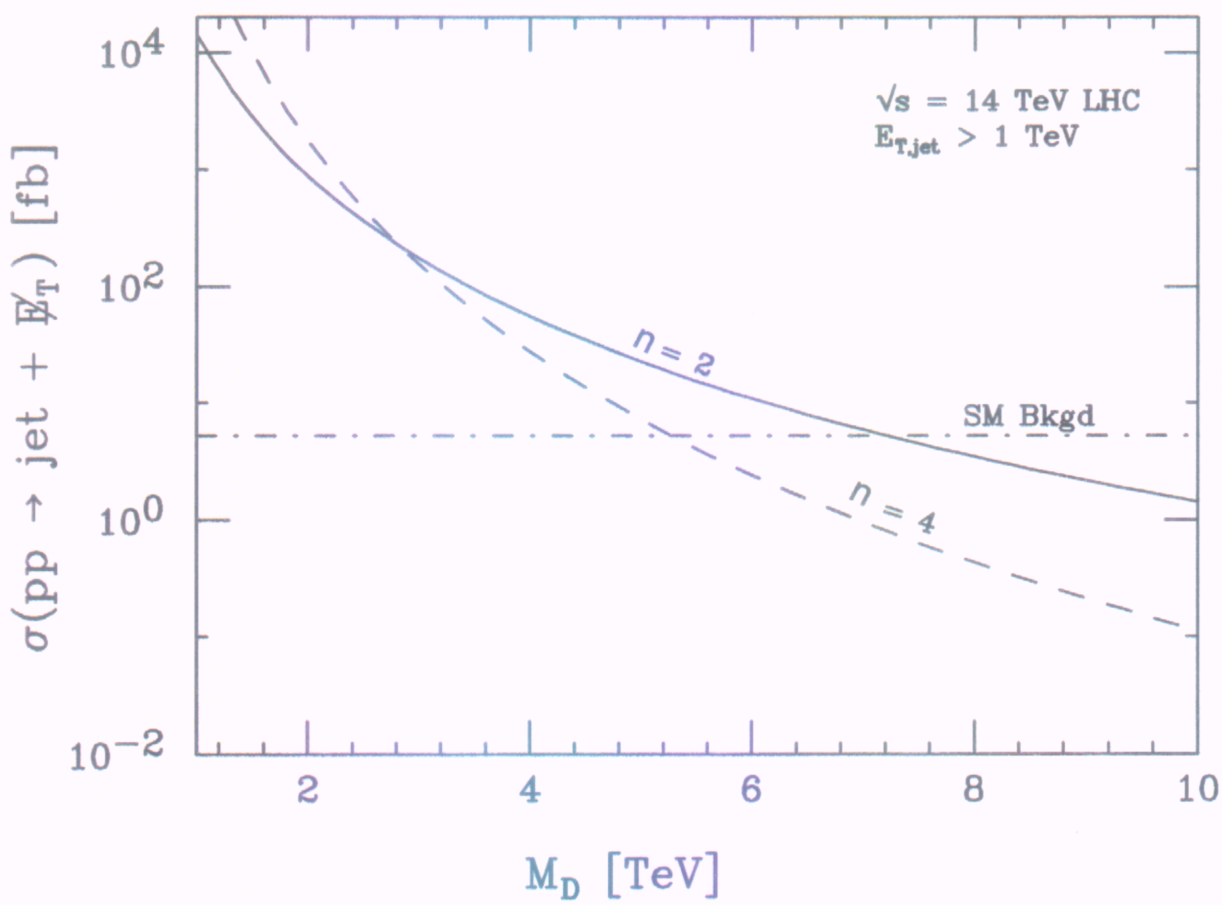
Signal: missing energy

Angular distribution $\Rightarrow$ spin of the graviton

Actual limits from LEP2:

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

Giudice-Rattazzi-Wells '98



no observation ⇒

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

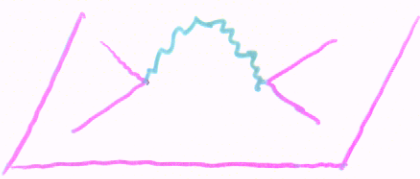
- more dimensions ⇒ weaker limits

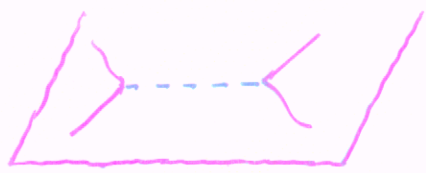
If no longitudinal dims with $R_{\parallel}^{-1} \lesssim M_I$ $\Rightarrow$

main signal :- graviton emission in the bulk

$\Rightarrow$ low scale quantum gravity

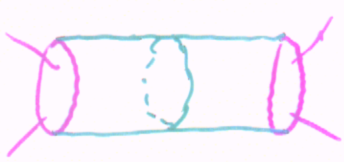
- indirect effects $\Rightarrow$ probe string modes





Type I string theory: graviton emission subdominant

compared to Regge exchanges



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

$\lambda \sim g^2$ $\Rightarrow$ loop factor enhancement ↗

A-A-B '99

Cullen-Perelstein-Peskin '00

Matter fermions : open strings ending

- on the same set of branes

$\Rightarrow$ 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 : $g^4/M_I^4\,(\bar{\psi}\partial\psi)^2$

- on different sets of branes

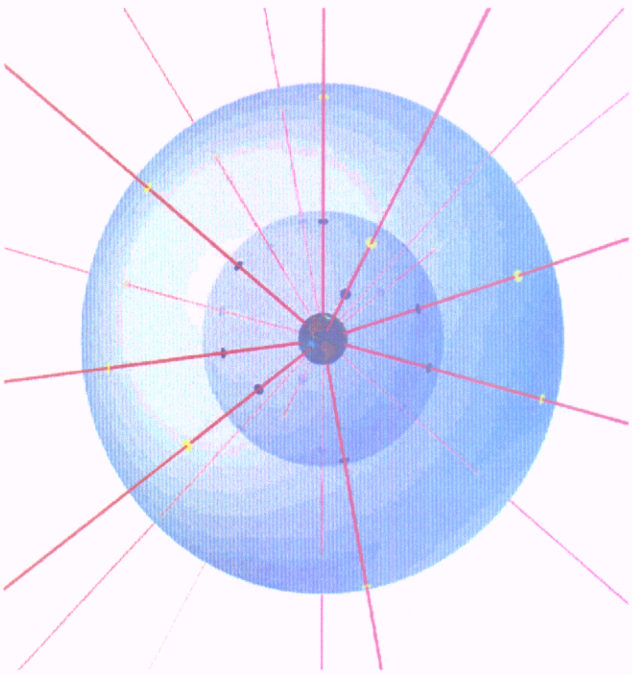
$\Rightarrow$ dim - 6 eff. operators

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

I.A. - Benakli - Laugier '00

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

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 1 mm away!

to protect the gauge hierarchy against gravit. corrections

Prediction: possible new forces at submm scales

e.g. light scalars: $\frac{(\text{TeV})^2}{M_p} \sim 10^{-4}\,\text{eV} = 1\,\text{mm}^{-1}$

modulus $\equiv \ln r$

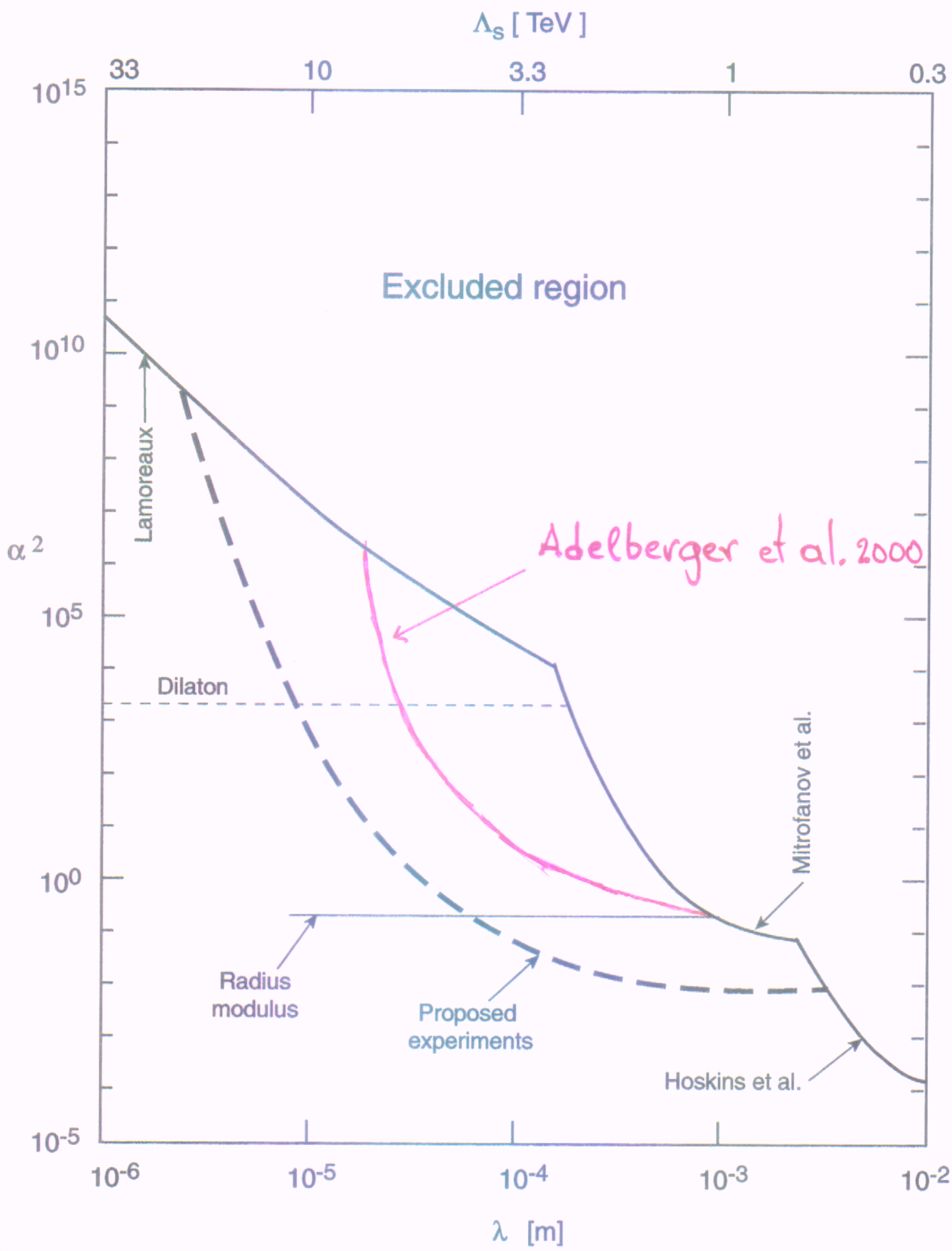
coupling to nucleons relative to gravity:

$$\frac{1}{m_N}\frac{\partial m_N}{\partial \ln r} = \frac{\partial \ln \Lambda_{QCD}}{\partial \ln r} \qquad m_N \sim \Lambda_{QCD} \sim e^{-\frac{1}{b_{QCD}}\frac{2\pi}{\alpha_{QCD}}}$$

$$\sim \frac{\partial}{\partial \ln r}\alpha_{QCD}$$

$\mathcal{O}(1)$ in models with log sensitivity in r e.g. $d_\perp = 2$

$\Rightarrow$ can be experimentally tested

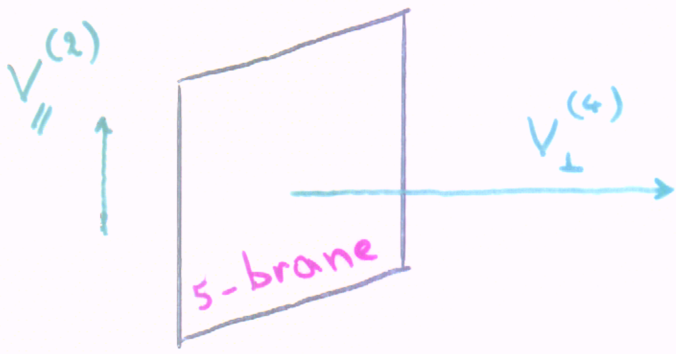

Λ_s [TeV]
33
10
3.3
1
0.3
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
α^2
Excluded region
Adelberger et al. 2000
Lamoreaux
Dilaton
Mitrofanov et al.
Radius modulus
Proposed experiments
Hoskins et al.
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
λ [m]

I.A. - Pioline '99

Type II strings

Non abelian symmetries : non-perturbative on a 5-bra ($\nwarrow$ 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 couplin

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

- No strong gravity at TeV

- signal: 2 longitudinal (TeV) dims $V_{//}^{(2)}$

with gauge interactions

similar in Heterotic with small instantons

Benakli - 03

Theoretical imagination or reality?

Standard Model: imagination 1970
$\longrightarrow$ reality 1984

LHC: explore the physics beyond
the Standard Model

- supersymmetric particles?
  dark matter of the universe?

- new dimensions of space?
  the membrane of our universe?

- unexpected surprise?