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

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

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

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

- In general SM gauge groups on different branes

- Quarks + leptons : on brane intersections

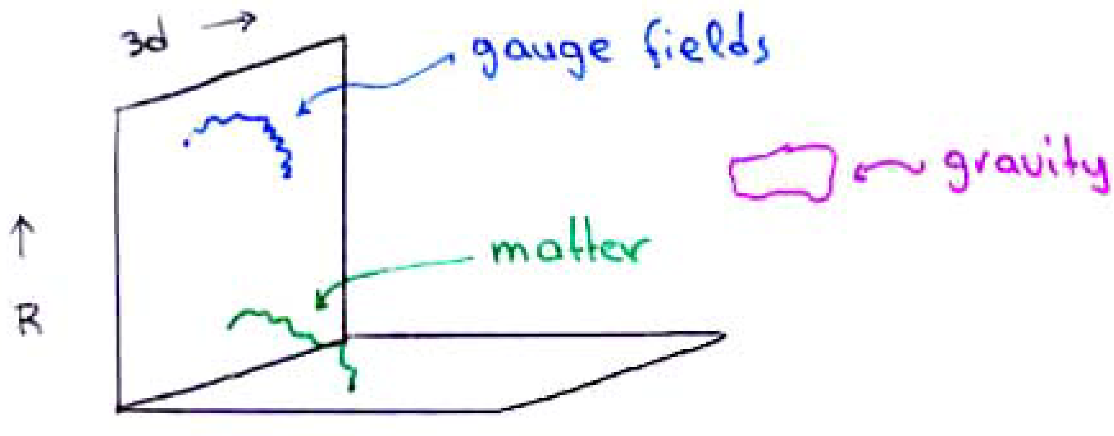
  - localized in 3d ⇒ no KK

  - automatic chirarity

  - KK of gauge bosons unstable

otherwise KK momentum conservation

⇒ stable charged excitations

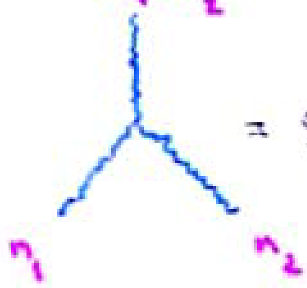


similar to Z_2-orbifolds of heterotic string I.A. '90

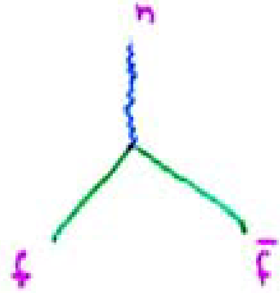
I.A. - Benakli '94

Exp. constraints

* equal couplings



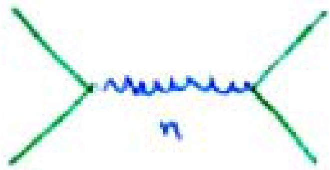
$= g$



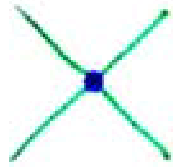
$$= g\,\delta^{-\frac{n^2}{R^2 M_s^2}} \underset{RM\to\infty}{\sim} g \qquad \delta \geq 1$$

* bounds from 4-fermion eff ops (compositeness)

$\sum_{n\neq 0}$



$\underset{E \ll R^{-1}}{\simeq}$



$$\sim R^2 \sum_{\vec{n}\neq 0} \frac{1}{\vec{n}^2}$$

for more than $d=2$ dims $\Rightarrow$ regulated sum

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

$\Rightarrow$ $\boxed{R^{-1} \gtrsim \text{TeV}}$ up to 2 dims if $RM_s \gg 1$

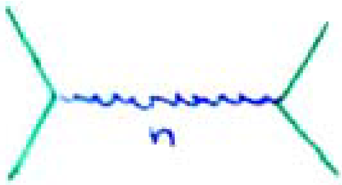
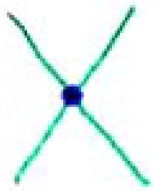
I.A. - Benakli '94

high precision of Z-width + G_F $\Rightarrow$ $R^{-1} \gtrsim 2.5$ TeV $d=1$

Nath - Yamaguchi
Masip - Pomarol '99
Marciano

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

I.A.-Benakli-Quiros '94, '99

$q\bar{q} \to \gamma_n, Z_n \to \ell^+\ell^-$ I.A.-Accomando-Benakli '99

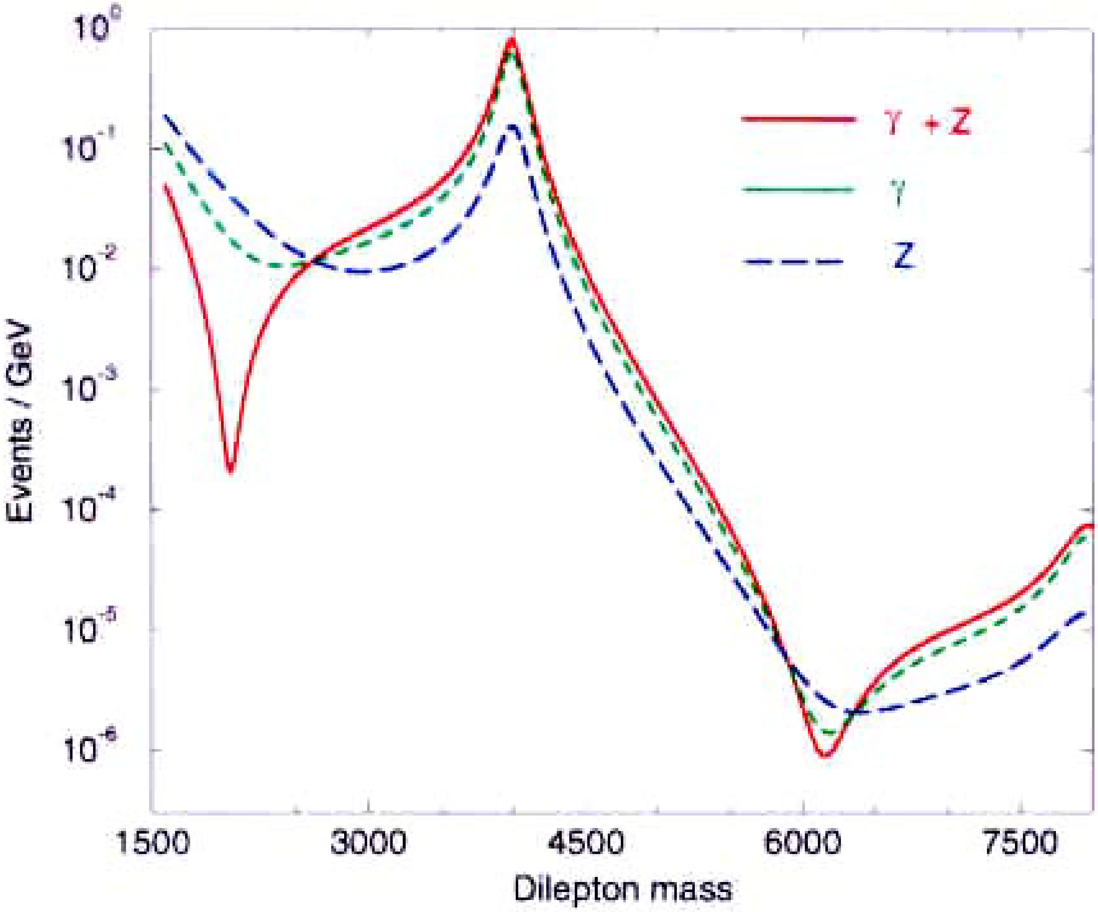


Figure 5: *First resonances in the LHC experiment due to a KK excitation of photon and Z for one extra-dimension at 4 TeV. From highest to lowest: excitation of photon+Z, photon and Z boson.*

I.A. - Accomando - Benakli

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

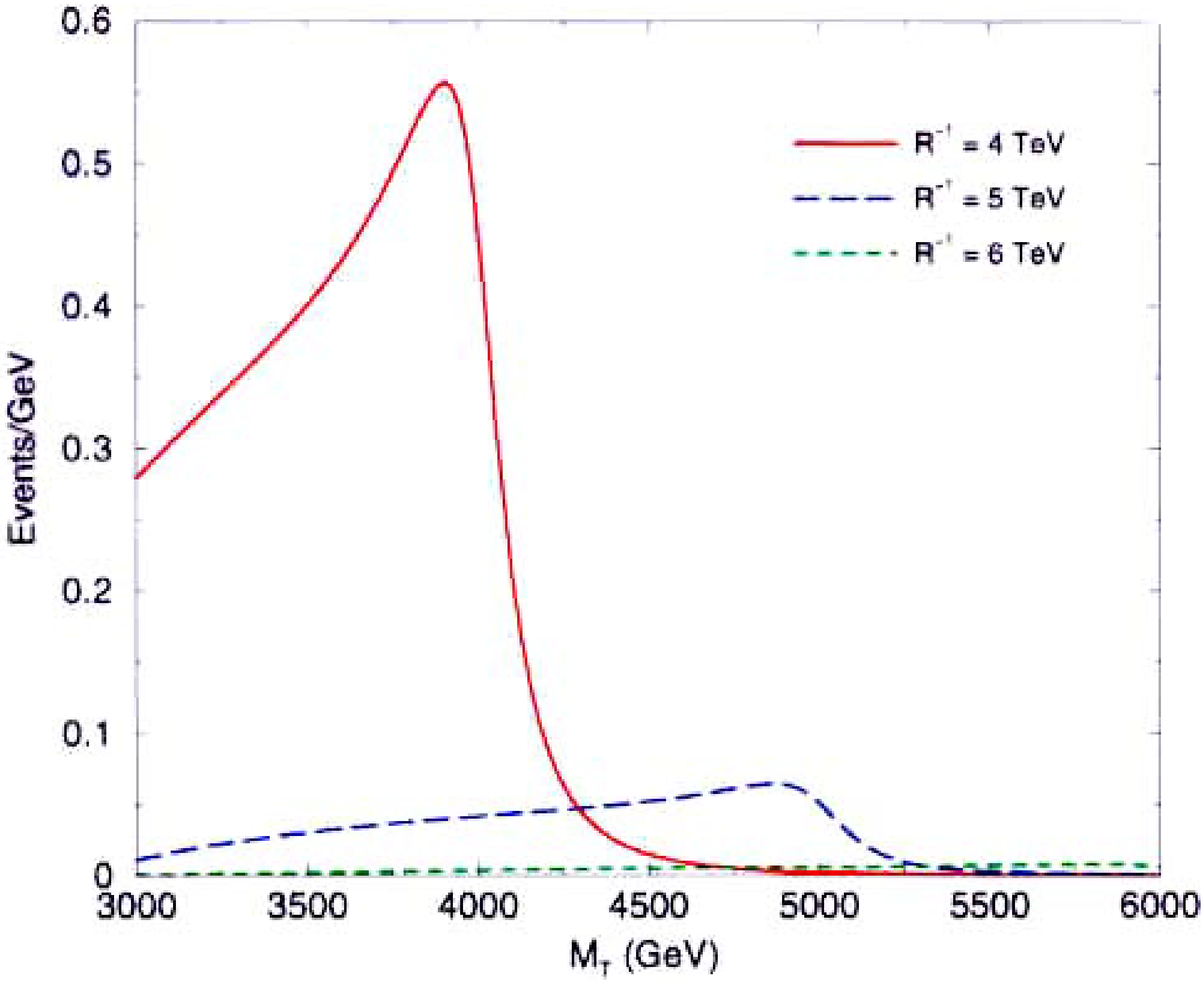


Figure 3: *First resonances in the LHC experiment due to a KK excitation of $W_{\pm}^{(n)}$ for one extra-dimension at 4, 5 and 6 TeV. We plot the differential cross section as function of the transverse mass for the W's.*

I.A.- Accomando-Benakli

$q\bar{q} \to G_\mu \to 2$ jets

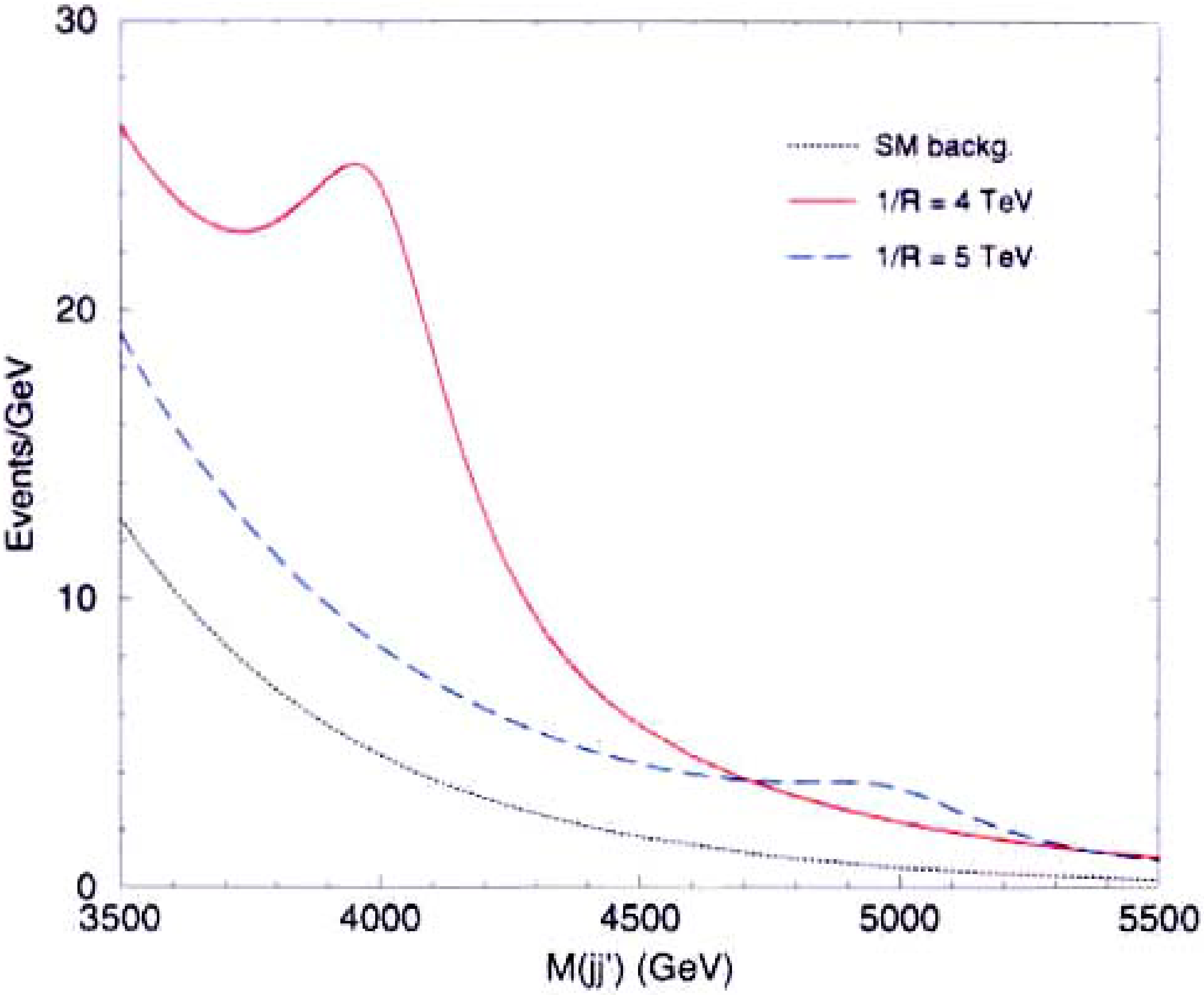


Figure 1: *First resonances in the LHC experiment due to a KK excitation of gluon for one extra-dimension at 4 and 5 TeV.*

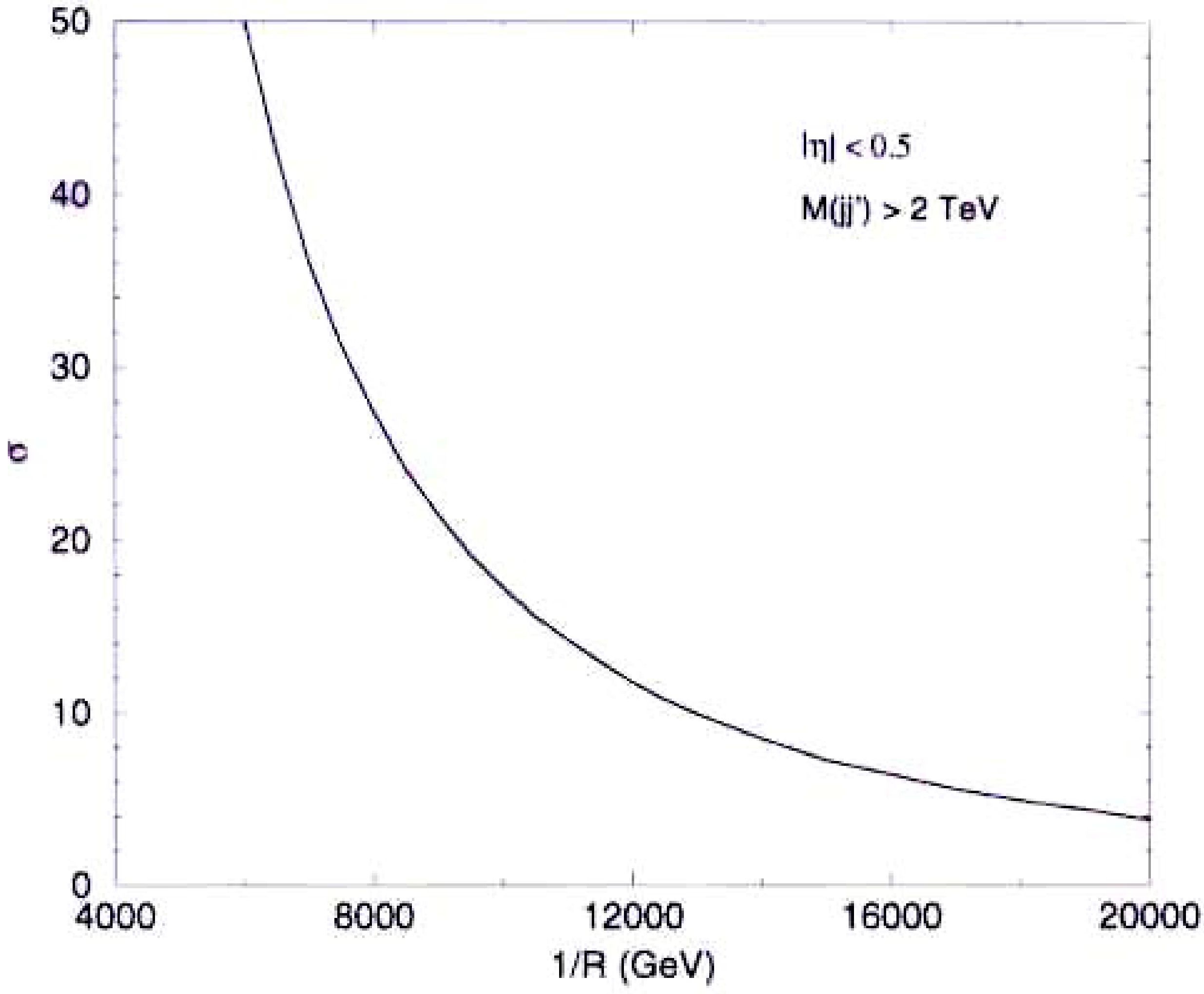


Figure 2: *Number of standard deviation in number of observerd dijets from the expected standard model value, due to the presence of a TeV-scale extra-dimension of compactification radius R.*

$R^{-1} \gtrsim 20$ TeV 95% CL

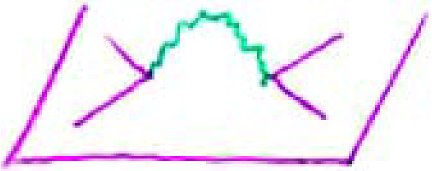
TEVATRON : 4 TeV

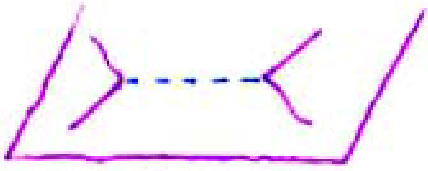
If no longitudinal dims with $R_{\parallel}^{-1} \lesssim M_I$ $\Rightarrow$

main signal : - graviton emission in the bulk

$\Rightarrow$ low scale quantum gravity

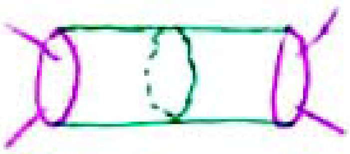
- indirect effects $\Rightarrow$ probe string modes

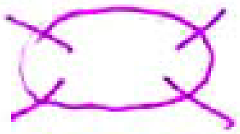




Type I string theory: graviton emission subdominant

compared to Regge exchanges





1-loop $\Rightarrow \lambda^2$

disk $\Rightarrow \lambda$

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

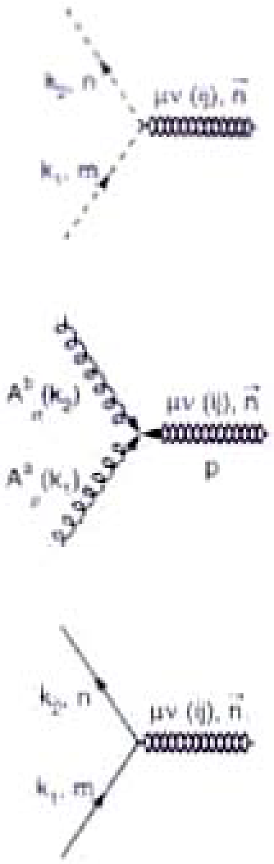
A-A-B '97

Cullen-Perelstein-Peskin '00

Han- Lykken - Zhang . hep-ph/9811350

for each KK level.

A.2 Vertex Feynman Rules



$\tilde{h}^{\vec{n}}_{\mu\nu}\Phi\Phi$: $\quad -i\kappa/2\ \delta_{mn}\left(m^2_\Phi \eta_{\mu\nu} + C_{\mu\nu,\rho\sigma} k_1^\rho k_2^\sigma \right)$

$\tilde{\phi}^{\vec{n}}_{ij}\Phi\Phi$: $\quad i\,\omega\,\kappa\ \delta_{ij}\,\delta_{mn}\left(k_1 \cdot k_2 - 2 m^2_\Phi \right)$

$\tilde{h}^{\vec{n}}_{\mu\nu}AA$: $\quad -i\kappa/2\ \delta^{ab}\left((m^2_A + k_1 \cdot k_2)\, C_{\mu\nu,\rho\sigma} + D_{\mu\nu,\rho\sigma}(k_1, k_2) + \xi^{-1} E_{\mu\nu,\rho\sigma}(k_1, k_2) \right)$

$\tilde{\phi}^{\vec{n}}_{ij}AA$: $\quad i\,\omega\,\kappa\ \delta_{ij}\,\delta^{ab}\left(\eta_{\rho\sigma} m^2_A + \xi^{-1}(k_{1\rho} p_\sigma + k_{2\sigma} p_\rho) \right)$

$\tilde{h}^{\vec{n}}_{\mu\nu}\bar{\psi}\psi$: $\quad -i\kappa/8\ \delta_{mn}\left(\gamma_\mu (k_{1\nu} + k_{2\nu}) + \gamma_\nu (k_{1\mu} + k_{2\mu}) - 2\eta_{\mu\nu}(\not{k}_1 + \not{k}_2 - 2 m_\psi) \right)$

$\tilde{\phi}^{\vec{n}}_{ij}\bar{\psi}\psi$: $\quad i\,\omega\,\kappa\ \delta_{ij}\,\delta_{mn}\left(3/4\ \not{k}_1 + 3/4\ \not{k}_2 - 2 m_\psi \right)$

Figure 4: Three-point vertex Feynman rules. The KK states are plot in double-sinusoidal curves. The symbols $C_{\mu\nu,\rho\sigma}$, $D_{\mu\nu,\rho\sigma}(k_1, k_2)$ and $E_{\mu\nu,\rho\sigma}(k_1, k_2)$ are defined in Eqs. (A.10), (A.11) and (A.12) respectively. m_Φ, m_A and m_ψ are masses of the scalar, vector and fermion. $\omega = \sqrt{\frac{2}{3(n+2)}}$, $\kappa = \sqrt{16\pi G_N}$ and ξ is the gauge-fixing parameter.

In the following we list the complete leading order Feynman rules in three figures, Figs. 4, 5 and 6. Some of the symbols used are defined as follows:

$$C_{\mu\nu,\rho\sigma} = \eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho} - \eta_{\mu\nu}\eta_{\rho\sigma}\ , \tag{A.10}$$

$$D_{\mu\nu,\rho\sigma}(k_1, k_2) = \eta_{\mu\nu} k_{1\sigma} k_{2\rho} - \left[\eta_{\mu\sigma} k_{1\nu} k_{2\rho} + \eta_{\mu\rho} k_{1\sigma} k_{2\nu} - \eta_{\rho\sigma} k_{1\mu} k_{2\nu} + (\mu \leftrightarrow \nu) \right] , \tag{A.11}$$

Giudice - Rattazzi - Wells hep-ph/9811291

$pp \to$ jet + G

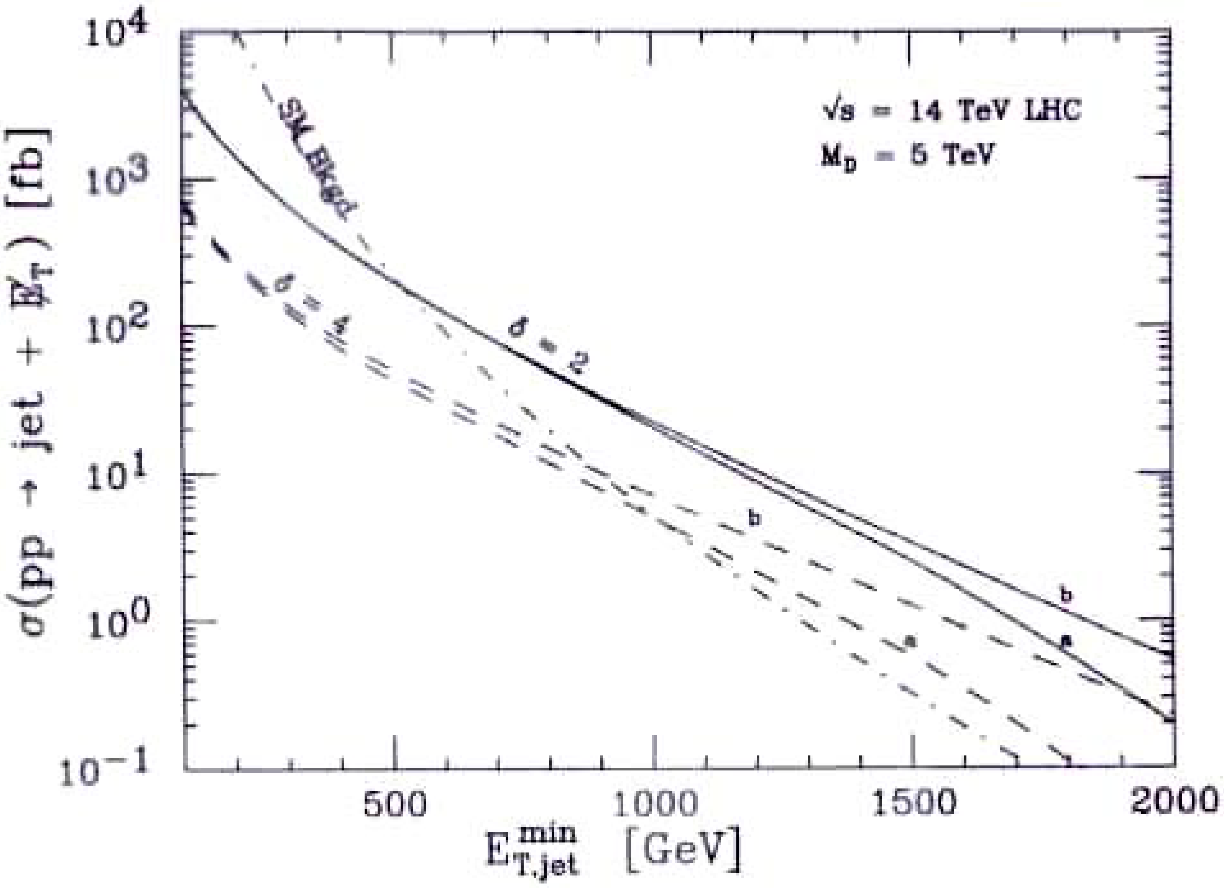
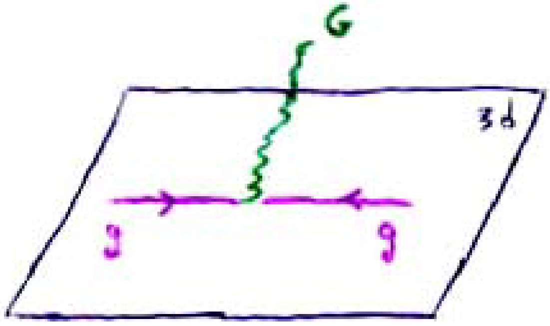


Figure 3: The total jet + nothing cross-section at the LHC integrated for all $E_{T,jet} > E_{T,jet}^{min}$ with the requirement that $|\eta_{jet}| < 3.0$. The Standard Model background is the dash-dotted line, and the signal is plotted as solid and dashed lines for fixed $M_D = 5$ TeV with $\delta = 2$ and 4 extra dimensions. The **a** (**b**) lines are constructed by integrating the cross-section over $\hat{s} < M_D^2$ (all $\hat{s}$).

$gg \longrightarrow G$



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

- $E < M_I \Rightarrow \sim E^p / M_I^{p+2}$ 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

Mirabelli - Perelstein - Peskin hep-ph/9811337

$p\bar{p} \to$ jet + G

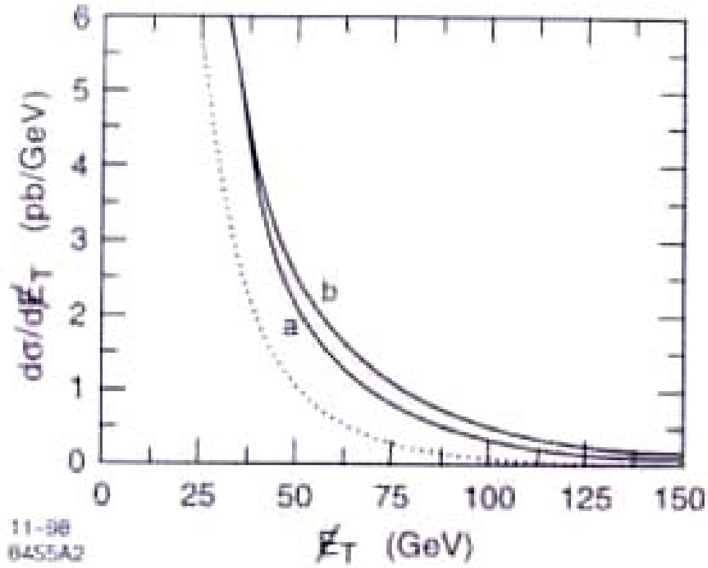


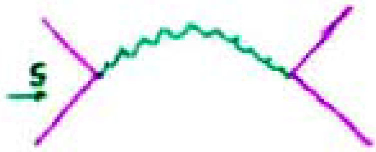
Figure 2: Spectrum of missing energy in events with one jet, computed for $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, with a rapidity cut $|y| < 2.4$. The dotted curve is the Standard Model expectation. The solid curves show the additional cross section expected in the model of ref. [4] with (a) $n = 2$, $M = 750$ GeV, (b) $n = 6$, $M = 610$ GeV.

Current and future limits on $M_{P(n+4)}$

Collider		R / M ($n = 2$)	R / M ($n = 4$)	R / M ($n = 6$)
Present:	LEP 2	4.8×10^{-2} / 1200	1.9×10^{-9} / 730	6.9×10^{-12} / 520
	Tevatron	11.0×10^{-2} / 750	2.4×10^{-9} / 610	5.8×10^{-12} / 610
Future:	Tevatron	3.9×10^{-2} / 1300	1.4×10^{-9} / 900	4.0×10^{-12} / 810
	LC	1.2×10^{-3} / 7700	1.2×10^{-10} / 4500	6.5×10^{-13} / 3100
	LHC	3.4×10^{-3} / 4500	1.9×10^{-10} / 3400	6.1×10^{-13} / 3300

Table 1: Current and future sensitivities to large extra dimensions, expressed as 95% confidence limits on the size of extra dimensions R (in cm) and the effective Planck scale M (in GeV). The assumptions of each analysis are explained in the text.

- virtual graviton exchange



$$\lim_{r\to\infty} \frac{1}{M_p^2} \sum_{\vec{n}} \frac{1}{s - \frac{\vec{n}^2}{r^2}} \qquad M_p^2 = \frac{1}{g^4} M_I^{2+p} r^p$$

more than 2 dims $\Rightarrow$ regulated sum

$$\simeq \frac{g^4}{M_I^{2+p} r^{p-2}} \underbrace{\sum_{\vec{n}} \frac{\delta^{-\vec{n}^2/r^2 M_I^2}}{\vec{n}^2 - s r^2}}_{\frac{2}{p-2}(r M_I)^{p-2}}$$

$\Rightarrow$ dimension 8 effective operator $(\bar{\psi}\partial\psi)^2$:

$$\frac{g^4}{M_I^4} \cdot \begin{cases} \frac{2}{p-2} & p>2 \\ \ln M_I^2/s & p=2 \end{cases}$$

- open string Regge exchanges : g^2/M_I^4 for every p

$\Rightarrow$ stronger limits for $p>2$: $M_I \gtrsim 1$ TeV

Cullen - Perelstein - Peskin

Gravity modification at submm scales

1) Change of Newton's law

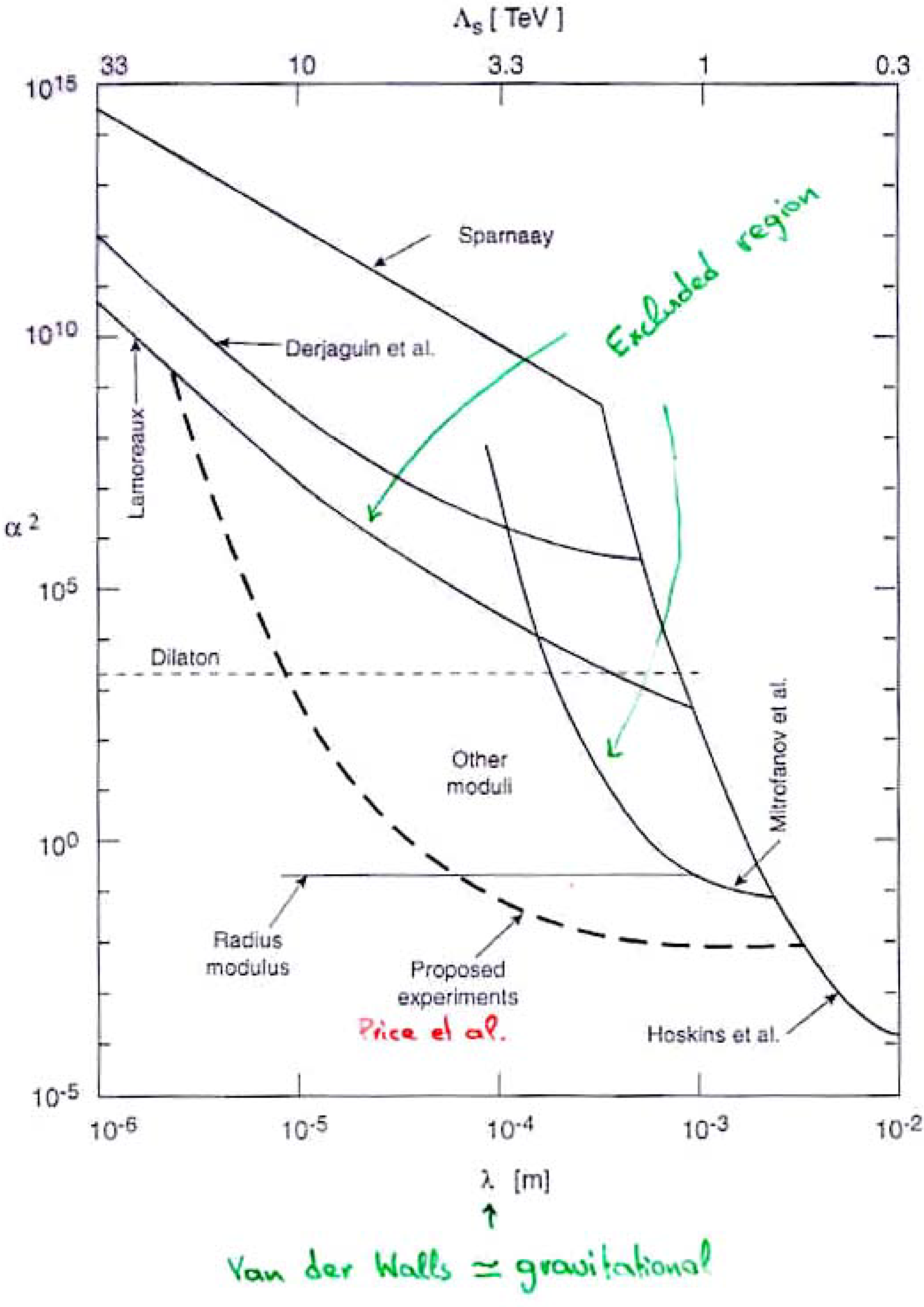
$$\frac{1}{r^2} \longrightarrow \frac{1}{r^{2+p}} \qquad \begin{array}{l} p=2 \Rightarrow \frac{1}{r^4} \text{ in (sub)mm} \leftarrow \text{testable} \\ \vdots \\ p=6 \Rightarrow \frac{1}{r^8} \text{ in (sub)fm} \end{array}$$

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

(i) primordially on the brane $\Rightarrow$ suppressed in the bulk

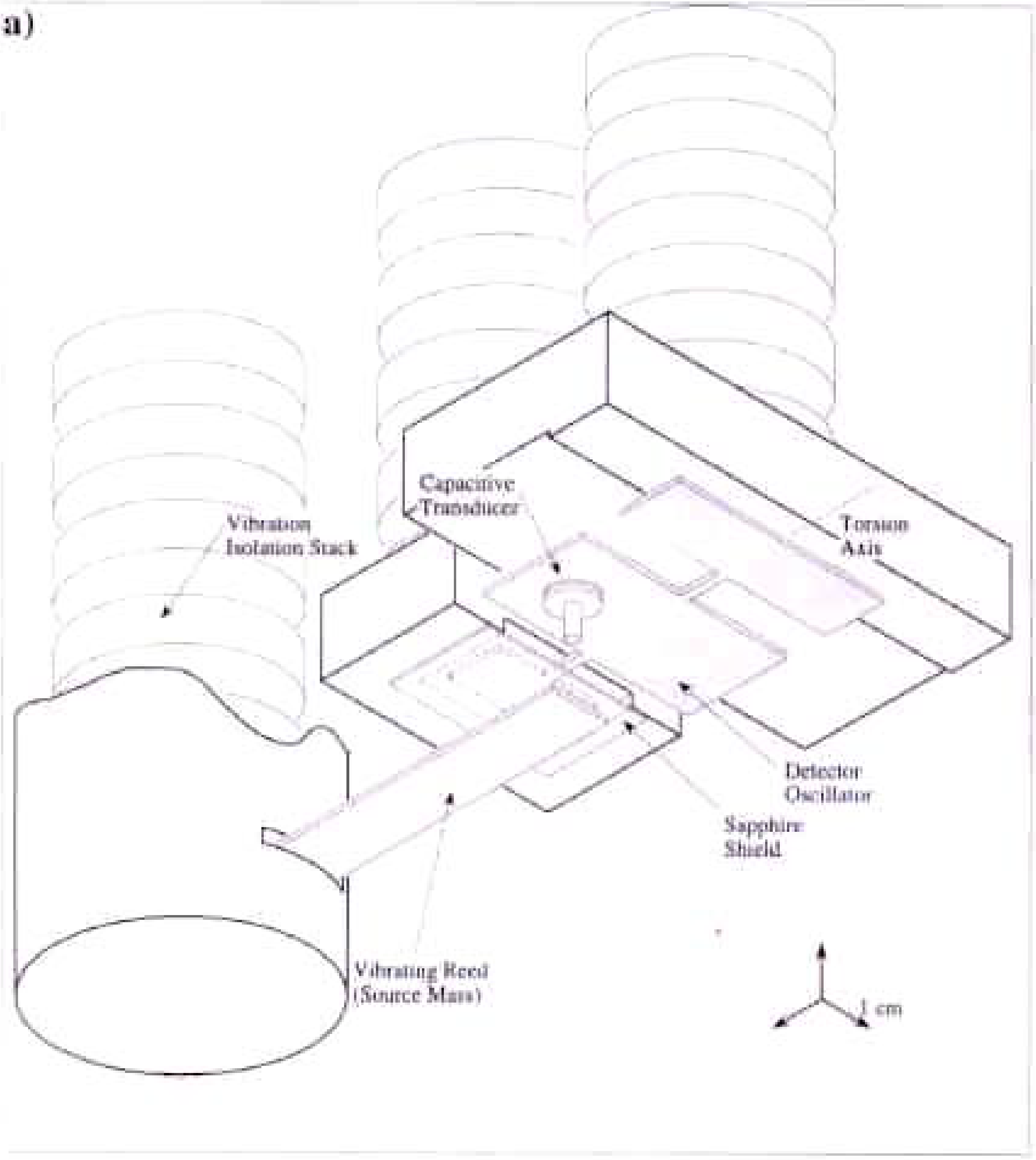
$$\rho_{brane} \sim M^4 \quad \Rightarrow \quad \rho_{bulk} \sim M^4 / r^p$$

$$\Rightarrow m^2_{modulus} \sim \frac{M^4}{M_p^2} \qquad \text{modulus} \equiv \ln r$$



Λ_s [TeV]
33
10
3.3
1
0.3
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
α^2
Sparnaay
Derjaguin et al.
Lamoreaux
Excluded region
Dilaton
Other moduli
Mitrofanov et al.
Radius modulus
Proposed experiments
Price et al.
Hoskins et al.
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
λ [m]
Van der Walls $\simeq$ gravitational

a)


Capacitive
Transducer
Vibration
Isolation Stack
Torsion
Axis
Detector
Oscillator
Sapphire
Shield
Vibrating Reed
(Source Mass)
1 cm

b)


Detector (Oscillator)
Torsion Axis
R
Shield
Source Mass Positions

Gauge hierarchy

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

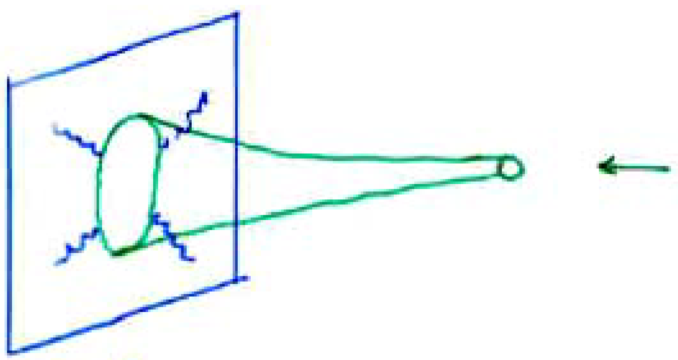
$$r\, M_I \simeq \left(g^2\, {M_P}/{M_I} \right)^{2/n} \sim \begin{cases} 10^{15} & n=2 \\ 10^{5} & n=6 \end{cases} \qquad \text{or } \lambda_{II} \simeq 10^{-14}$$

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

no large corrections to SM couplings as $rM_I \to \infty$

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 $\Rightarrow$ quatratic UV $\quad r \sim M_P^2$

Condition: 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 1 mm away !

to protect the gauge hierarchy against gravit. corrections

Prediction : possible new forces at submm scales

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

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

Origin of EW symmetry breaking ?

mild hierarchy : $\frac{m_W}{M_s} \lesssim O(10^{-1})$

string tree-level : $- \; m_W = 0$

$- \; m_W \sim n \, M_s$ $\quad n \gtrsim O(1)$

$- \; m_W \sim a \leftarrow$ flat direction

$\Rightarrow$ only possibility : radiative breaking

$$V = \lambda (h^+ h)^2 + \mu^2 (h^+ h)$$

(a) $\mu = 0$ at tree

$\mu^2 < 0$ at one loop non susy vacuum

(b) $\langle h \rangle$ flat at tree

lifted radiatively (2 higgses)

I.A. - Benakli - Quiros hep-ph/0004091

Simplest case: one SM higgs on our brane-world

open string with both ends on the brane $\Rightarrow$

(1) tree-level potential $\equiv$ same as susy

$$\lambda = \frac{1}{8}\left(g^2 + g'^2\right) \qquad \text{D-terms}$$

(2) $\mu^2 = -\frac{1}{N}\, g^2\, \varepsilon^2\, M_s^2$

N : order of the orbifold group

ε : estimated by an explicit computation in a toy model

$\langle h \rangle = (0, v/\sqrt{2})$: $v^2 = -\mu^2/\lambda$ $\Rightarrow$

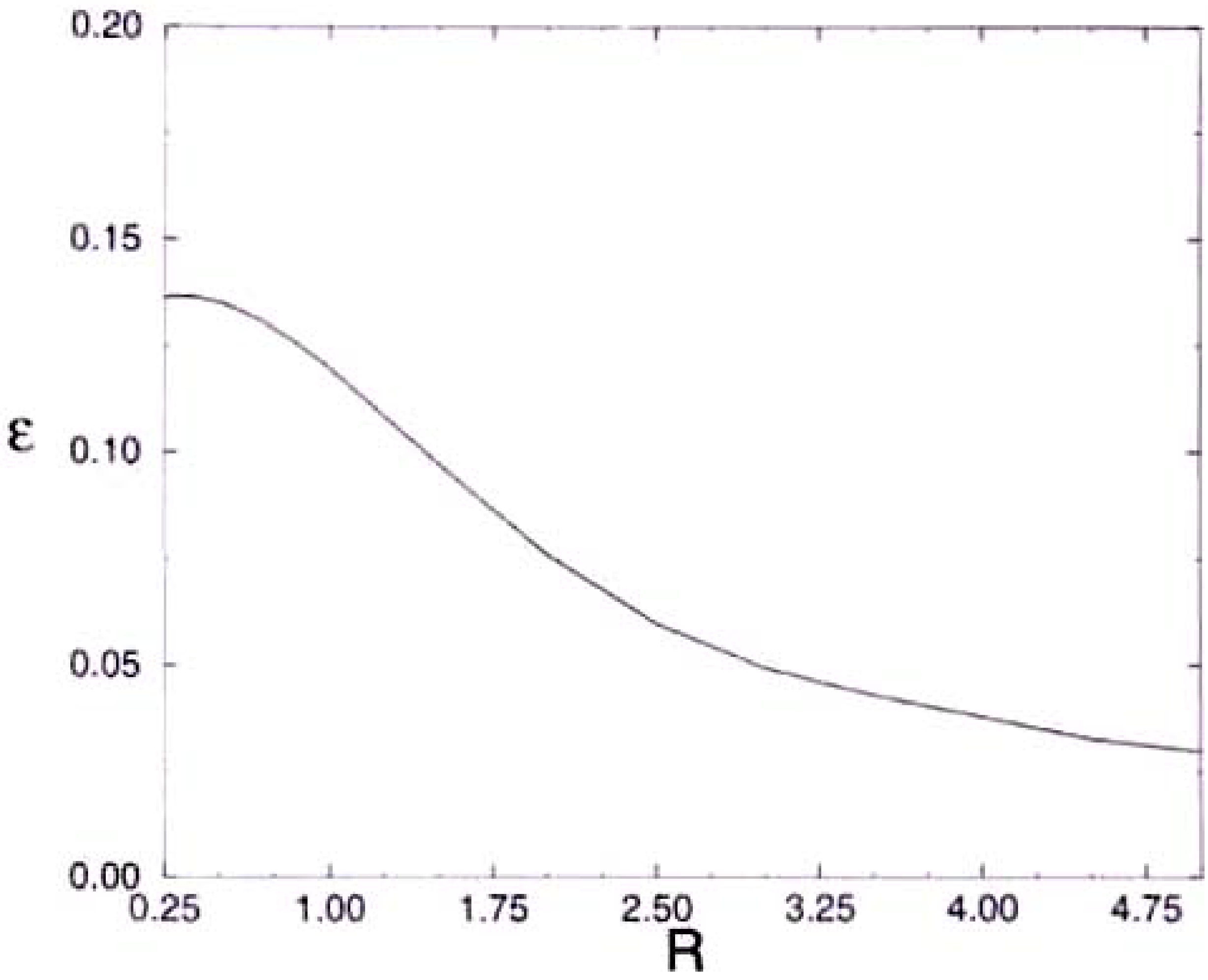
Expansion around the origin

gauge invariance : $a^2 \longrightarrow \mathrm{Tr}\, \Phi^2$

$$V_{eff} = V_0 + \frac{1}{2}\mu^2 \,\mathrm{Tr}\, \Phi^2 + \mathcal{O}(\Phi^4)$$

$$\mu^2 = -\,\varepsilon^2(R)\, g^2\, M_s^2$$

$$\varepsilon^2(R) = \frac{R^3}{2\pi^2}\int_0^\infty \frac{dl}{(2l)^{5/2}}\, \frac{\theta_2^4}{4\eta^{12}}\left(il+\frac{1}{2}\right) \sum_n n^2 e^{-2\pi n^2 R l}$$



(1) $M_h = M_Z$

same as MSSM for $\tan\beta,\ m_A \to \infty$

(2) $M_s = \dfrac{M_h \sqrt{N}}{\sqrt{2}\, g\, \varepsilon}$

- Low-energy SM radiative corrections top-quark sector

$\Rightarrow$ $M_h \sim 120$ GeV

$M_s \sim$ a few TeV $\quad \mathcal{O}(1-10)$

- string threshold corrections

  - model dependent
  - can be very important

  e.g. for two large dims in the bulk

  $\ln R_\perp M_s \sim \ln M_P/M_s$

$\rightarrow$ both M_s and M_h can be increased sufficiently low M allows power-law running

in the region $R^{-1} \to M$

number of KK

$$\frac{1}{g_i^2(\mu)} = \frac{1}{g_i^2(R^{-1})} - \frac{b_i^{SM}}{8\pi^2}\ln(\mu R) - \frac{b_i^{KK}}{8\pi^2}\left(2\mu R - \ln\mu R\right)$$

$N=1$ SUSY $\Rightarrow$ KK at least $N=2$

minimal choice: NO KK for chiral states

- $SU(3)\times SU(2)\times U(1)$ 1 vector + 2 W-fermions + 2 scalars
- 1 Higgs hypermultiplet 2 fermions + 4 scalars

$\Rightarrow$ approximate unification at weak coupling

Dienes - Dudas - Gherghetta '98

e.g. $R^{-1} = 1$ TeV $\Rightarrow$ $M \simeq 45$ TeV within 2%

however power UV sensitivity $\Rightarrow$

(string) thresholds are important

Alternative possibility: Bachas '98

M_I is at TeV but gauge couplings unify at a higher scale due to log sensitivity for $d_\perp = 2$

$$\ln r M_I = \ln \frac{r M_I^2}{M_I}$$

winding scale: $r_D^{-1} \equiv r M_I^2 \sim 10^{16}$ GeV for $\begin{cases} d_\perp = 2 \\ M_I = 10 \text{ TeV} \end{cases}$

T-dual to $r^{-1} \sim mm^{-1}$

effective "running" in the transverse space (bulk)

however in $N=1$ orientifolds logs are also controled by $N=2$ β-functions $\Rightarrow$ model dependent

I.A. - Bachas - Dudas '99

$$\frac{1}{g_a^2} = \underbrace{\frac{1}{g^2} + s_a m}_{\text{tree}} + \underbrace{\sum_{i=1}^{3} \hat{b}_a^i \left(\ln T_i + f(U_i) \right)}_{\text{1-loop}}$$

- $\frac{1}{g^2}$: same collection of branes
- m : twisted (blow-up) moduli

in all examples: anomalous $U(1)$'s $\Rightarrow$ $m = 0$

- $T = R_1 R_2 \qquad U = \frac{R_1}{R_2}$ for every torus $i = 1, 2, 3$

$R_1 \sim R_2 \to \infty \quad \Rightarrow \quad b_a \ln R_1 R_2 \qquad d_\perp = 2$

$R_1 >> R_2 \quad \Rightarrow \quad b_a \, R_1/R_2 \qquad d_\perp = 1$

$f(U) \sim R_1/R_2$

A D-brane embedding of the Standard Model

I.A. - Kiritsis - Tomaras hep-ph/0004214

N coincident branes $\Rightarrow U(N)$

$U(1)$: coupling $= g_N/\sqrt{2N}$

with charge of $\underset{\sim}{N} = 1$

$\Rightarrow$ gauged "baryon" number

$\Rightarrow$ minimal choice : $U(3) \times U(2) \times U(1)$

color branes (g_3) weak branes (g_2) g_1

U(1) brane with $\begin{cases} U(3) \Rightarrow g_1 = g_3 \\ U(2) \Rightarrow g_1 = g_2 \end{cases}$

fermion generation $\quad U(3) \times U(2) \times U(1)$

$Q \quad (\mathbf{3}, \mathbf{2}; 1, w, 0)_{1/6} \qquad w = \pm 1$

$u^c \quad (\bar{\mathbf{3}}, \mathbf{1}; -1, 0, x)_{-2/3} \qquad x = \pm 1 \text{ or } 0$

$d^c \quad (\bar{\mathbf{3}}, \mathbf{1}; -1, 0, y)_{1/3} \qquad y = \pm 1 \text{ or } 0$

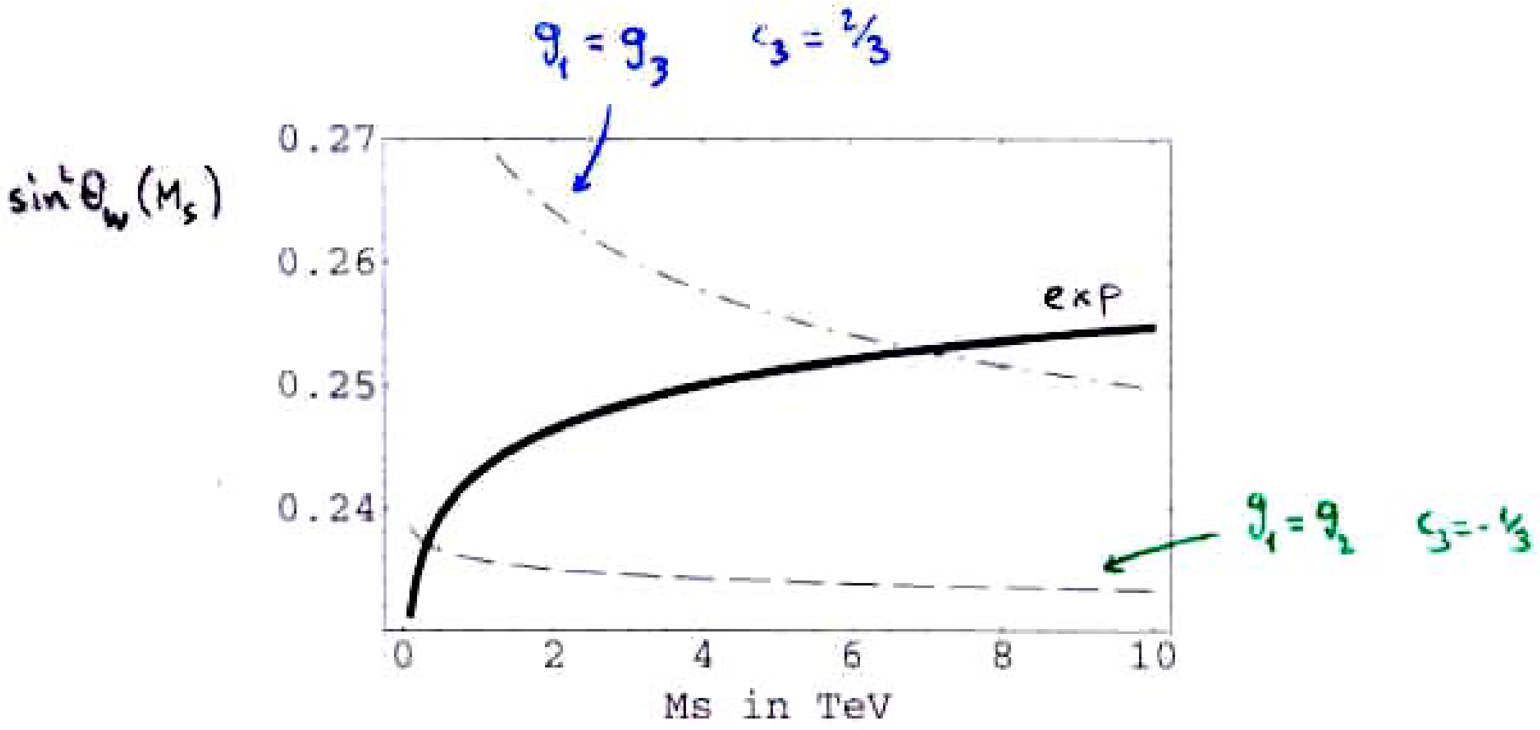
$L \quad (\mathbf{1}, \mathbf{2}; 0, 1, z)_{-1/2} \qquad z = \pm 1 \text{ or } 0$

$\ell^c \quad (\mathbf{1}, \mathbf{1}; 0, 0, 1)_{1}$

hypercharge $\quad Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow 4$ possibilities

$c_3 = -1/3 \quad c_2 = \pm 1/2 \quad x = -1 \quad y = 0 \quad w = \pm 1 \quad z = -1/0$

$c_3 = 2/3 \quad c_2 = \pm 1/2 \quad x = 0 \quad y = 1 \quad w = \mp 1 \quad z = -1/0$



correct prediction for $\sin^2\theta_W$ for $M_s \sim$ few TeV

U(1) with color branes

- masses to all quarks + leptons $\Rightarrow$ 2 Higgs doublets

- the remaining two U(1)'s : anomalous

  Green - Schwarz anomaly cancellation :

  shifting of 2 axions $\Rightarrow$ U(1)'s become massive

  $\Rightarrow$ global (perturbative) symmetries :

  • baryon number $\Rightarrow$ proton stability

  • PQ - type symmetry $\Rightarrow$ electroweak axion

  can be explicitly broken by moving slightly away from the orbifold point

- R - neutrinos : open strings in the bulk

  Arkani Hamed - Dimopoulos - Dvali - March Russell

  Dienes - Dudas - Gherghetta '98

Higgs : $c_2 = -1/2$ $\quad H\ (1, 2; 0, 1, 1)_{1/2} \quad H'\ (1, 2; 0, -1, 0)_{1/2}$

$$H' Q u^c \qquad H^+ L e^c \qquad H^+ Q d^c$$

$c_2 = 1/2$ $\quad \tilde{H}\ (1, 2; 0, -1, 1)_{1/2} \quad \tilde{H}'\ (1, 2; 0, 1, 0)_{1/2}$

$$\tilde{H}' Q u^c \qquad \tilde{H}' L e^c \qquad \tilde{H}^+ Q d^c$$

$H' L \nu_R$

$\tilde{H} L \nu_R$

R-neutrinos in the bulk

$$\int d^{4+p}x \;\; \bar{\nu} \not{\partial} \nu \qquad\qquad \nu = (\nu_R \, , \, \bar{\nu}^c_R) \qquad \Rightarrow$$

$$\int d^4x \, (r M_s)^p \sum_n \left\{ \bar{\nu}_{Rn} \not{\partial} \nu_{Rn} + \bar{\nu}^c_{Rn} \not{\partial} \nu^c_{Rn} + \frac{n}{r} \nu_{Rn} \nu^c_{Rn} + \text{c.c.} \right\}$$

$$S_{int} = \lambda \int d^4x \;\; H(x) \, L(x) \, \nu_R(x, \vec{y}=0)$$

$$\langle H \rangle = v \quad \Rightarrow \quad \frac{\lambda v}{\sqrt{(r M_s)^p}} \sum_n \nu_L \nu_{Rn}$$

$$\frac{\lambda v}{(r M_s)^{p/2}} \ll \frac{1}{r} \quad \Leftrightarrow \quad \lambda \frac{v}{M_s} \ll (r M_s)^{\frac{p}{2}-1} \quad \Rightarrow$$

- $n \neq 0$: masses of KK ν_n unaffected

- $n = 0$: Dirac mass for neutrino $\quad m_\nu = \dfrac{\lambda v}{(r M_s)^{p/2}}$

$$M_p = \frac{1}{g^2} M_s^{1+p/2} \, r^{p/2} \quad \Rightarrow$$

$$m_\nu = \frac{\lambda}{g^2} v \frac{M_s}{M_p} \sim 10^{-2}\,\text{eV} \quad \text{for } M_s \simeq 10 \text{ TeV}$$