Phenomenology of extra dimensions

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Outline

The outline of this talk is

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- Introduction: Extra Dimensions and Branes
- Transverse Extra Dimensions
  - Gravitational experiments
  - Collider experiments
  - Astrophysical bounds
- Longitudinal Extra Dimensions
  - Indirect detection
  - Direct detection
  - Gauge-Higgs unification
- Conclusion

Extra Dimensions and Branes

- Unification of strong, electroweak and gravitational interactions lead to string theories
- Cancellation of conformal anomaly in string theories

$$\Updownarrow$$

D=10

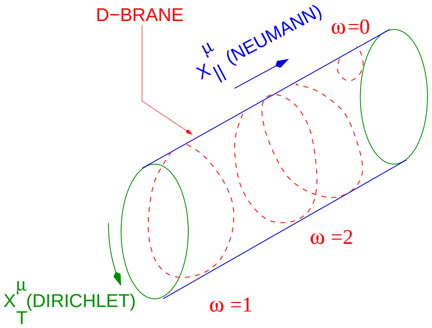
$$\Updownarrow$$

EXTRA DIMENSIONS

- Extra dimensions must be compactified
- D-branes are subsurfaces where open strings can end
- Extra dimensions can be
  - LONGITUDINAL to the brane with KK-modes n/R
  - TRANSVERSE to the brane with winding modes nRM_s^2

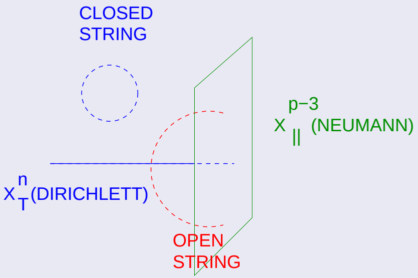
In string theories

A Dp-brane is defined by imposing N-conditions (KK-modes) along its LONGITUDINAL directions, $X_{||}^{\mu}, \mu = 0, 1, \ldots, p$, and D-conditions (winding modes) along its TRANSVERSE directions, $X_T^I, I = p + 1, \ldots, D$



Typically, in type I strings

- Closed strings describe gravity
- Open strings with ends bounded to propagate on Dp-branes describe gauge interactions
- 6 internal compact dimensions= [p-3] (longitudinal)+[n=(9-p)] (transverse)



COMPACT DIMENSIONS

Fundamental relation

$$M_P^2 = \frac{1}{g^4(R_{||}M_s)^{p-3}} M_s^{2+n} R_T^n; \qquad \lambda_s = g^2(R_{||}M_s)^{p-3}$$

- $g, \lambda_s \sim 1 \Rightarrow (R_{||}M_s)^{p-3} \sim 1 \Rightarrow R_{||} \sim \ell_s$, $\ell_s = M_s^{-1}$
- Defining the (4+n) Newton constant $G_N^{(4+n)}$ and Planck scale M_* as $G_N^{(4+n)} = \frac{1}{M_*^{(2+n)}} = g^4(R_{||}M_s)^{p-3}\ell_s^{2+n}$

ADD relation: ADD, hep-ph/9803315

$$M_P^2 = M_*^{2+n} R_T^n$$

- "Explains" the weakness of gravitational interactions by the size of extra-large transverse dimensions
- Opens up the possibility for $R_{||} \sim \ell_I \sim 1/TeV$ and their experimental detection

Transverse Extra Dimensions

Let R_T be the (common) radius of transverse dimensions where gravity propagates

From ADD relation for $M_* = 1$ TeV

n	1	2	6
R_T	10^8 Km	0.7 mm	0.3 fm
		10^{-2} eV	30 MeV
	excluded	inconsistent	consistent

From ADD relation for $M_* = 2$ TeV

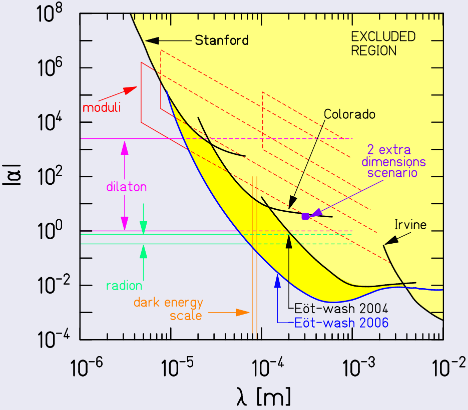
n	1	2	6
R_T	10^7 Km	0.2 mm	0.1 fm
	excluded	barely consistent	consistent

Gravitational experiments

Deviation from Newton's law: table-top experiments

$$V(r) = \begin{cases} -\frac{G_N}{r}\left(1+\alpha e^{-r/R_T}+\cdots\right), & r \geq R_T \\ -\frac{G_N^{(4+n)}}{r^{1+n}}, & r \ll R_T \end{cases}$$

[D.J. Kapner et al. PRL98 (2007) 021101]



Collider experiments

Based on missing energy in reactions corresponding to the production of KK-gravitons in the bulk. For instance

$$e^+e^- \longrightarrow \gamma \sum_n G^{(n)}$$

Every single graviton couples $\sim 1/M_P^2$ but the large amount of gravitons cancels (using ADD relation) the M_P^2 dependence $\Downarrow$

$$\sigma \sim s^{n/2}/M_*^{n+2}$$

The 95% confidence limits on [1], R_T [cm] and M_* [GeV]. R_T and M_* related by ADD relation

Bounds from collider experiments

Collider	R_T / M_* $(n = 2)$	R_T / M_* $(n = 6)$
LEP 2	4.8×10^{-2} / 1200	6.9×10^{-12} / 520
Tevatron	3.9×10^{-2} / 1300	4.0×10^{-12} / 810
LC (1 TeV)	1.2×10^{-3} / 7700	6.5×10^{-13} / 3100
LHC	3.4×10^{-3} / 4500	6.1×10^{-13} / 3300

[1] E. Mirabelli, M. Perelstein and M. Peskin, hep-ph/9811337

Astrophysical bounds

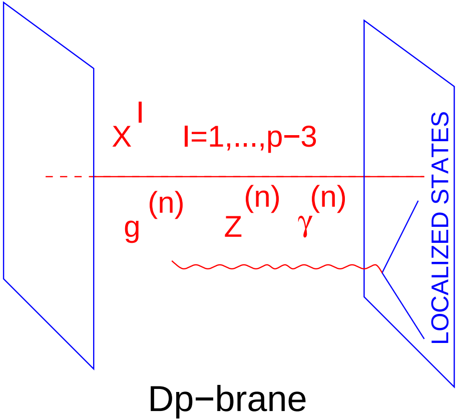
Bounds for two extra dimensions

- The strongest bounds come from astrophysics and cosmology and concern mainly $n = 2$.
- Graviton emission during supernovae cooling and the observed neutrino flux from the supernova SN 1987A put an upper bound on the rate of energy loss through graviton emission
- For the case of $n = 2$ it puts the bound

$$M_* > 50 \; TeV, \;\; M_l > 7 \; TeV$$

Longitudinal Extra Dimensions

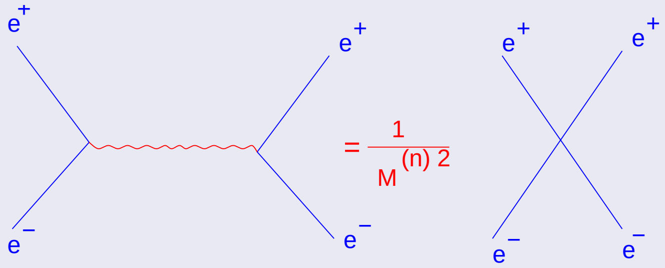
The SM propagate in a Dp-brane, with p-3 longitudinal dimensions wrapped on compact space (orbifold) with 4D boundaries at the fixed points



Indirect detection

Indirect detection

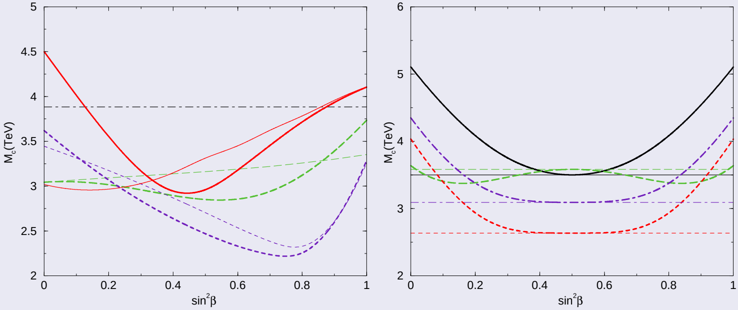
Through the modification of EW observables $(M_W, \Gamma_{\ell\ell}, \Gamma_{had}, A^{\ell}_{FB}, Q_W, \dots)$ by the exchange of KK-modes $Z^{(n)}, \gamma^{(n)}$ [a]



[a] A. Delgado, A. Pomarol and M. Q., JHEP 01 (2000) 030

Bounds From indirect production

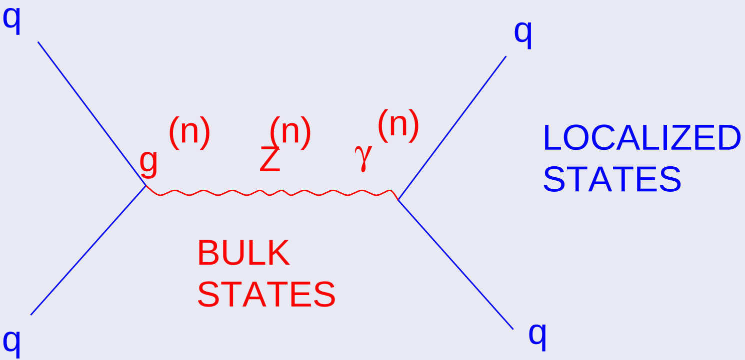
The numerical results are [$\tan\beta = v_2/v_1$, $M_c \equiv 1/R_{||}$, thick (MSSM), thin (SM)]



Direct detection

Direct production

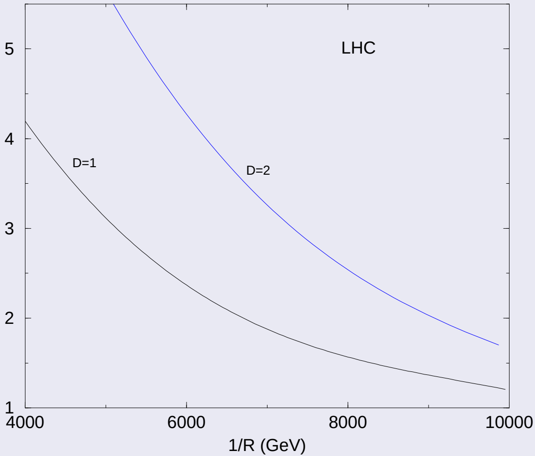
In hadron colliders through Drell-Yan processes [a]



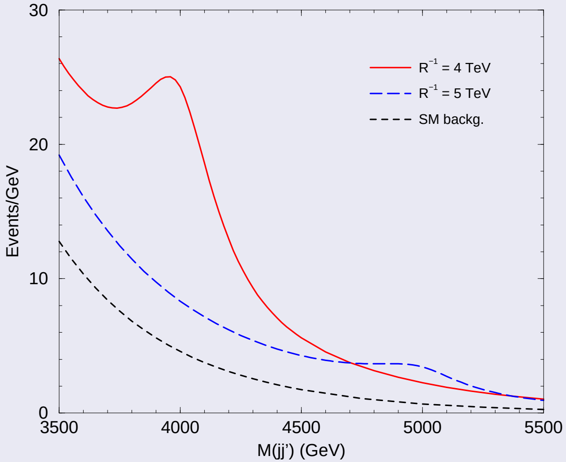
[a] I. Antoniadis, K. Benakli and M. Q., hep-ph/9905311

KK production at LHC

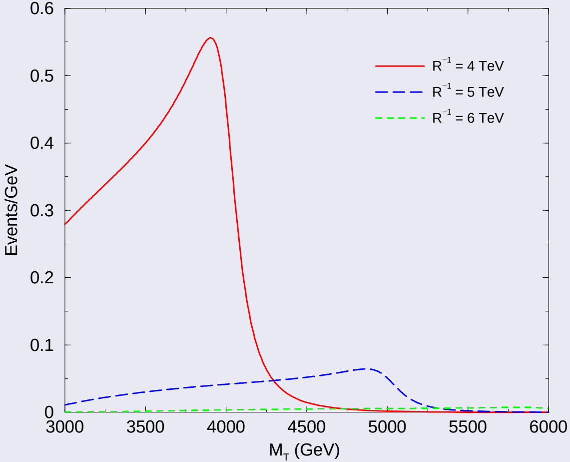
For LHC $(5\ fb^{-1})$, D=1,2 extra dimensions, $(N - N^{SM})/\sqrt{N^{SM}}$ as a function of $1/R_L$ for Drell-Yan processes where $\gamma^{(n)} + Z^{(n)} \to \ell\ell$



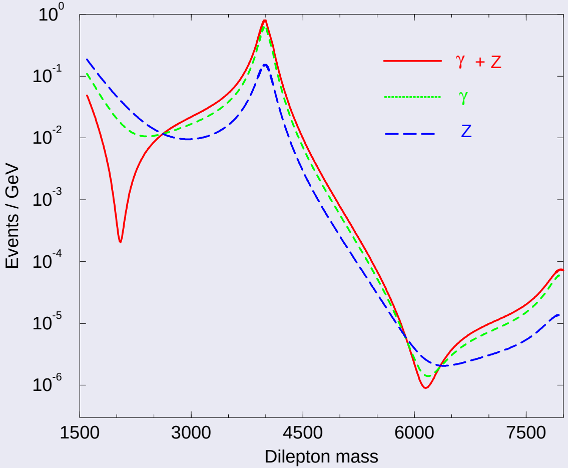
Production at LHC of gluon Kaluza-Klein excitations



Production at LHC of $W^{\pm}$ Kaluza-Klein excitations



Production at LHC of γ, Z Kaluza-Klein excitations



Gauge Higgs Unification

- In higher dimensional theories there is a symmetry which can protect the Higgs mass from quadratic divergences: a higher dimensional gauge symmetry
- The gauge bosons of a higher dimensional gauge symmetry decompose as

Lorentz Decomposition

$$A_M^A = A_\mu^A, \; A_i^A \; [\mu = 0, \dots, 3, i = 1, \dots, d]$$

- A_μ^A are gauge bosons in four dimensions
- A_i^A are scalar in the adjoint representation

Orbifold constructions

We need to compactify extra dimensions in an orbifold: e.g. for $d = 1$ (A_μ, A_5)

$$S^1/\mathbb{Z}_2$$

- The orbifold group has to act non trivially on the group generators such that:

Orbifold Decomposition

$$A_\mu^A = A_\mu^a(even),\ \ A_\mu^{\hat a}(odd)$$
$$A_5^A = A_5^a(odd),\ \ A_5^{\hat a}(even)$$

- Only even fields have zero modes $\phi_{even}^{(n)}, n = 0, 1, 2, \ldots$ while odd field have only non zero modes $\phi_{odd}^{(n)}, n = 1, 2, \ldots$
- The Higgs mechanism acts for all modes as

Higgs mechanism

$$(A_\mu^{\hat a}\ massless + A_5^{\hat a})^{(n\neq 0)} = A_\mu^{\hat a\,(n\neq 0)} massive$$
$$(A_\mu^{a}\ massless + A_5^{a})^{(n\neq 0)} = A_\mu^{a\,(n\neq 0)} massive$$

- The massless states are the zero modes

Massless states

$$A_\mu^{a\,(n=0)},\ \ A_5^{\hat a\,(n=0)}$$

- To get a doublet out of an adjoint one has to make a careful orbifold breaking
- One has to enlarge the gauge group since the

SM Higgs is NOT in the adjoint representation of $SU(2) \times U(1)$

- For instance

$SU(3) \to SU(2) \times U(1)$

Achieved by the orbifold action
$A_\mu(-y) = U A_\mu(y) U^\dagger,\ A_5(-y) = -U A_5(y) U^\dagger$ with

$$diag(-1, -1, +1)$$

which breaks $SU(3)$ into $SU(2) \times U(1)$

- The Higgs mass is protected from quadratic divergences in the bulk of the extra dimension by the five-dimensional gauge symmetry

- The orbifold has two fixed points at $y = 0, \pi R$ which are singular and four-dimensional
- The Higgs mass is protected from quadratic divergences at the fixed points by the shift symmetry (inherited from the five-dimensional gauge invariance) $\delta A_5 = \partial_y A_5$

How to get the gauge bosons

$$\begin{pmatrix} A^3_\mu + A^8_\mu/\sqrt{3} & A^2_\mu - iA^2_\mu & A^4_\mu - iA^5_\mu \\ A^1_\mu + iA^2_\mu & -A^3_\mu + A^8_\mu/\sqrt{3} & A^6_\mu - iA^6_\mu \\ A^4_\mu + iA^5_\mu & A^6_\mu + iA^7_\mu & -2A^8_\mu/\sqrt{3} \end{pmatrix}$$

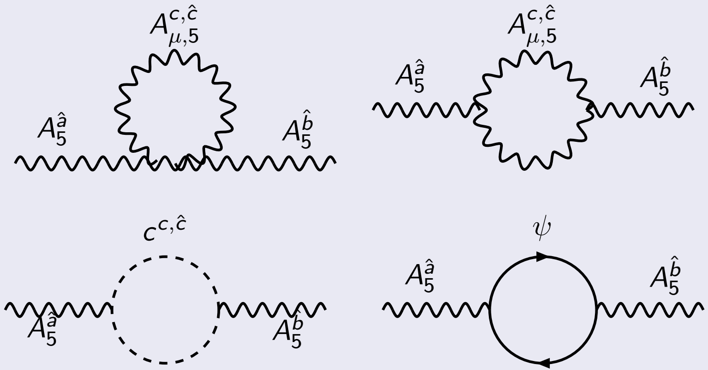
How to get the Higgs bosons

$$\begin{pmatrix} A^3_5 + A^8_5/\sqrt{3} & A^2_5 - iA^2_5 & A^4_5 - iA^5_5 \\ A^1_5 + iA^2_5 & -A^3_5 + A^8_5/\sqrt{3} & A^6_5 - iA^6_5 \\ A^4_5 + iA^5_5 & A^6_5 + iA^7_5 & -2A^8_5/\sqrt{3} \end{pmatrix}$$

- Since the space is compactified there can be finite contributions to the $A_5^{\hat{a}}$ mass proportional to $1/R$

Hosotani breaking

The diagrams contributing to the mass of $A_5^{\hat{a}}$ are



$$m_{\hat{a}}^2 = \frac{3g^2}{32\pi^4 R^2}\zeta(3)\left[3C_2(\mathcal{G}) - 4T(R)N_f\right]$$

There is a number of difficulties with this (otherwise very nice) scenario

Drawbacks

- In more than five dimensions a (quadratically divergent) tadpole localized at the fixed points F_{ij} is generated by radiative corrections while the quartic Higgs coupling is sizeable and generated by the term F_{ij}^2 in the bulk
- In five dimensions there is no localized tadpole but there is neither a tree-level quartic coupling which means difficulties with *too small a Higgs mass*
- It is difficult to have a theory with the correct prediction for the weak angle [extra $U(1)'s$ are usually required]
- Fermion masses are difficult to accomodate since they come from gauge couplings: in particular the top quark use to be too light
- The compactification scale is usually too small in conflict with EWPT
- The theory has a very low cutoff after which it becomes non-perturbative

Some of these difficulties can be alleviated by embedding GHU in a warped (Randall-Sundrum) five-dimensional space time

Wayouts

- Warped models are valid up to scales of order M_{GUT} or M_{Planck} and they can unify
- The Higgs is holographic, i.e. it is localized towards the IR brane [at higher scales it is composite]
- Fermion masses can be implemented by means of their localization, i.e. five-dimensional masses
- The top quark (to get a big mass) is localized as the Higgs. So it is also holographic
- EWPT as well as corrections to the $Zb\bar{b}$ vertex lead to KK-masses in the $2.5 - 4$ TeV, which imply $\sim 1\%$ fine-tuning for the Higgs mass (similar to the MSSM)
- These models are the modern version of technicolor theories: they make use of the AdS/CFT correspondence for calculability

Conclusions

Concluding

- Strings and Large Extra Dimensions well motivated theoretically
- Large Extra Dimensions have unambiguous experimental signatures
- Large Extra Dimensions + Low Scale quantum Gravity effects at reach at present (Tevatron) and future (LHC) colliders
- Large Extra Dimensions can also help to solve theoretical Particle Physics problems (hierarchy, EWSB, flavor,...)

If found it would possibly be the most important revolution in the history of Particle Physics