Phenomenology of superstrings and extra dimensions

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1. Motivations, the problem of mass hierarchy, main BSM proposals
2. Strings, branes and extra dimensions
3. Phenomenology of low string scale
4. Magnetized branes and moduli stabilization
5. Non compact extra dimensions and localized gravity

Standard Model

- very accurate description of nature at present energies
- EW breaking sector (Higgs) not yet discovered

  $\rightarrow$ many questions:

  - are there elementary scalars in nature?

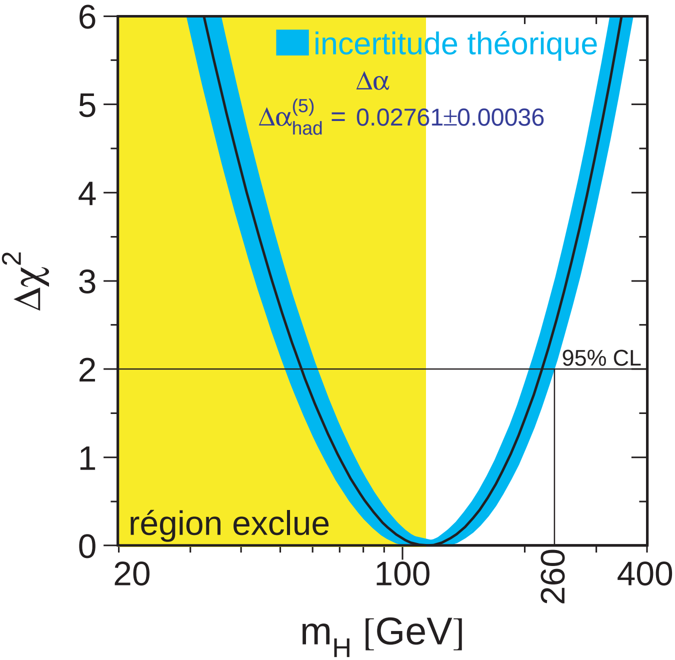
  - minimal (1 scalar) or more complex sector?

- global χ^2 fit of precision tests : Higgs is light $\Rrightarrow$

  - confidence for discovery at LHC/Tevatrron

  - perturbative physics at higher energies

  Higgs mass $\leftrightarrow$ quartic coupling: $m_H^2 = 2\lambda v^2 \ \Rrightarrow\ \lambda < 1$


incertitude théorique
Δα
$\Delta\alpha^{(5)}_{had} = 0.02761\pm0.00036$
95% CL
région exclue
$\Delta\chi^2$
0
1
2
3
4
5
6
20
100
260
400
m_H [GeV]

Why Beyond the Standard Model?

Theory reasons:

- Include gravity
- Charge quantization
- Mass hierarchies: $m_{\text{electron}}/m_{\text{top}} \simeq 10^{-5} \quad M_W/M_{\text{Planck}} \simeq 10^{-16}$

Experimental reasons:

- Neutrino masses
  - Dirac type $\Rightarrow$ new states
  - Majorana type $\Rightarrow$ Lepton number violation, new states
- Unification of gauge couplings
- Dark matter

Newton's law

$m \bullet \longleftarrow r \longrightarrow \bullet\, m \qquad F_{\rm grav} = G_N \frac{m^2}{r^2} \qquad G_N^{-1/2} = M_{\rm Planck} = 10^{19}$ GeV

Compare with electric force: $F_{\rm el} = \frac{e^2}{r^2} \;\Rightarrow$

effective dimensionless coupling $G_N m^2$ or in general $G_N E^2$ at energies E

$E = m_{\rm proton} \;\Rightarrow\; \frac{F_{\rm grav}}{F_{\rm el}} = \frac{G_N m_{\rm proton}^2}{e^2} \simeq 10^{-40} \Rightarrow$ Gravity is very weak !

At what energy gravitation becomes comparable to the other interactions?

$M_{\rm Planck} \simeq 10^{19}$ GeV $\rightarrow$ Planck length: 10^{-33} cm

$10^{15} \times$ the LHC energy!

(Hyper)charge quantization

All color singlet states have integer charges Why?

$SU(3) \times SU(2) \times U(1)_Y \qquad Q = T_3 + Y$

$$\begin{aligned} q &= (3,2)_{1/6} \\ u^c &= (\bar{3},1)_{-2/3} \\ d^c &= (\bar{3},1)_{1/3} \\ \ell &= (1,2)_{-1/2} \\ e^c &= (1,1)_{1} \end{aligned}$$

$$q = \begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix} \qquad \ell = \begin{pmatrix} \nu_0 \\ e_{-1} \end{pmatrix}$$

In a non-abelian theory charges are quantized

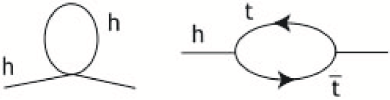
e.g. $SU(2)$: T_3 eigenvalues are 1/2-integers

Mass hierarchy problem

Higgs mass: very sensitive to high energy physics

1-loop radiative corrections:

dominant contributions:



$$\mu^2_{\rm eff} = \mu^2_{\rm bare} + \left(\frac{\lambda}{8\pi^2} - \frac{3\lambda_t^2}{8\pi^2}\right)\Lambda^2 + \cdots$$

UV cutoff: $\int^\Lambda \frac{d^4k}{k^2}$ scale of new physics

High-energy validity of the Standard Model : $\Lambda >> \mathcal{O}(100)$ GeV $\Rightarrow$

"unatural" fine-tuning between $\mu^2_{\rm bare}$ and radiative corrections

order by order

Mass hierarchy problem

example: $\Lambda \sim \mathcal{O}(M_{\rm Planck}) \sim 10^{19}$ GeV, loop factor $\sim 10^{-2}$

$$\Rightarrow \mu^2_{1-\rm loop} \sim 10^{-2} \times 10^{38} = \pm 10^{36}\ (\text{GeV})^2$$

$$\text{need } \mu^2_{\rm bare} \sim \mp 10^{36}\ (\text{GeV})^2 - 10^4\ (\text{GeV})^2$$

- adjustment at the level of 1 part per 10^{32} $\mu^2_{\rm bare}/\mu^2_{1\ \rm loop} = -1 \mp 10^{-32}$
- new adjustment at the next order, etc

  highest order N: $\left(10^{-2}\right)^N \times 10^{38} \lesssim 10^4 \Rightarrow N \gtrsim 18$ loops !
- no fine tuning : $10^{-2}\Lambda^2 \lesssim 10^4\ (\text{GeV})^2 \Rightarrow \Lambda \lesssim 1$ TeV

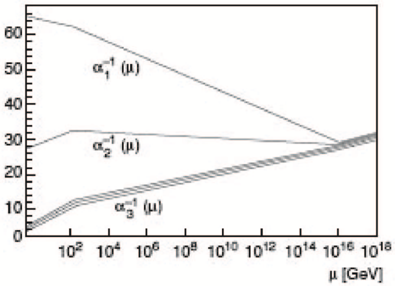
  $\rightarrow$ new physics within LHC range !

Gauge coupling unification

Energy evolution of gauge couplings $\alpha_i = \frac{g_i^2}{4\pi}$:

$$\frac{d\alpha_i}{d\ln Q} = -\frac{b_i}{2\pi}\alpha_i^2 \quad \Rightarrow \quad \alpha_i^{-1}(Q) = \alpha_i^{-1}(Q_0) - \frac{b_i}{2\pi}\ln\frac{Q}{Q_0}$$

low energy data $\rightarrow$ extrapolation at high energies:

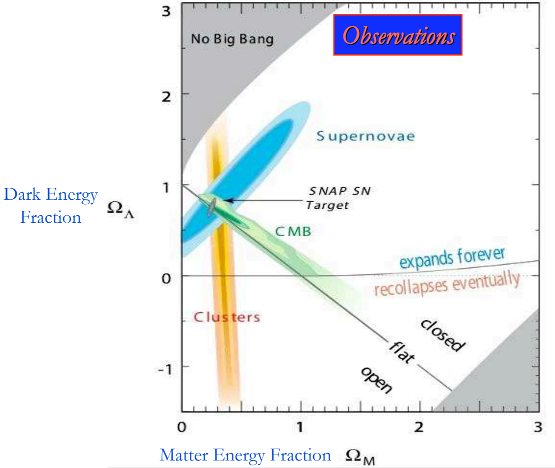


$\Rightarrow$ unification at $M_{GUT} \simeq 10^{15} - 10^{16}$ GeV

Observable Universe

- Ordinary baryonic matter: only a tiny fraction
- Non-luminous (dark) matter: 25-30%

  Natural explanation: new stable Weakly Interacting Massive Particle (WIMP)



Directions Beyond the Standard Model

guidance the mass hierarchy

1. Compositeness
2. Symmetry: - supersymmetry
   - little Higgs
   - conformal
   - higher dim gauge field
3. Low UV cutoff: - low scale gravity $\Rightarrow$ · large extra dimensions
   · warped extra dimensions
   · DGP localized gravity
   - low string scale $\Rightarrow$ · low scale gravity
   · ultra weak string coupling
   - large N degrees of freedom
   - higgsless
4. Live with the hierarchy: landscape of vacua, environmental selection
   $\rightarrow$ split supersymmetry

Compositeness

strong dynamics at $\sim$ TeV $\Rightarrow$ Higgs bound state of fermion bilinears

as the pions in QCD and chiral symmetry breaking

$\longrightarrow$ concrete proposal: technicolor

generic models $\Rightarrow$ · FCNC

· conflict with EW precision data

$\Rightarrow$ highly disfavored

Symmetry

Examples of naturally small masses

• Fermions: chiral symmetry

$$\mathcal{L}_F = i\bar{\psi}_L \not{D} \psi_L + i\bar{\psi}_R \not{D} \psi_R + m\left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$$

$m = 0$ respects: $\psi_L \to \psi_L \quad ; \quad \psi_R \to e^{i\theta}\psi_R$

$\Rightarrow$ radiative corrections: $\delta m \propto g^2 m$ $\qquad g$: gauge coupling

e.g. QED: $\psi \equiv$ electron, $g \equiv e$

no $g^2\Lambda$ term: linear divergence cancels between electron and positron

in a relativistic quantum field theory

• Vector bosons: gauge symmetry

$$\mathcal{L}_V = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2}m^2 A_\mu^2$$

$m = 0$ respects: $A_\mu \to A_\mu + \partial_\mu \omega$ $\quad$ e.g. QED: photon mass vanishes

Symmetry

- Scalars: ?

- Shift symmetry : Goldstone boson

$$\phi \to \phi + c \quad \Rightarrow \quad \mathcal{L}_{\rm GB}(\partial_\mu \phi) = \frac{1}{2}(\partial_\mu \phi)^2 + \frac{1}{\Lambda^4}\left[(\partial_\mu \phi)^2\right]^2 + \cdots$$

$\Rightarrow$ Higgs quartic coupling should vanish to lowest order

Higgs : pseudo-Goldstone boson? $\quad \to$ Little Higgs models

symmetry broken by new gauge interactions

- scale invariance: $x^\mu \to a x^\mu \quad \varphi_d \to a^{-d}\varphi(ax)$

conformal dimension

scalar field: $d = 1$

$$\mathcal{L}_{\rm S} = \frac{1}{2}(\partial_\mu \phi)^2 + \lambda \phi^4 \quad \text{invariant}$$

however broken hardly by radiative corrections renormalization scale

$\to$ embed SM in a conformal invariant theory ?

A different strategy:

1) connect scalars to fermions or gauge fields postulating new symmetries

2) use chiral or gauge symmetry to protect their mass

- $\delta\phi = \xi\psi \quad \Rightarrow$ supersymmetry
- $\delta\phi = \epsilon A \quad \Rightarrow$ extra dimensions

  component of a higher-dimensional gauge field

Advantages of SUSY

- natural elementary scalars
- gauge coupling unification: theory perturbative up to the GUT scale
- LSP: natural dark matter candidate
- extension of space-time symmetry: new Grassmann dimensions
- prediction of light Higgs
- rich spectrum of new particles within LHC reach

Problems of SUSY

- too many parameters: soft breaking terms

  SUSY breaking mechanism $\Rightarrow$ dynamical aspect of the hierarchy

  $+$ theory of soft terms

- SM global symmetries are not automatic

  B, L from R-parity, conditions on soft terms for FCNC suppression

- SUSY GUTs: no satisfactory model

  doublet/splitting, large Higgs reps, strong coupling above $M_{\rm GUT}$

- μ problem: SUSY mass parameter but of the order of the soft terms

- SUSY not yet discovered $\Rightarrow$ already a few % fine-tuning

  'little' hierarchy problem

Strings and extra dimensions

Standard Model of electroweak + strong Interactions

- Quantum Field Theory: Quantum Mechanics + Special Relativity
- Principle: gauge invariance $U(1) \times SU(2) \times SU(3)$

String theory

- Quantum Mechanics + General Relativity

Consistent theory : 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 ?

p-plane: extended in p spatial dimensions

$p = 0$: particle, $\quad p = 1$: string,...

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

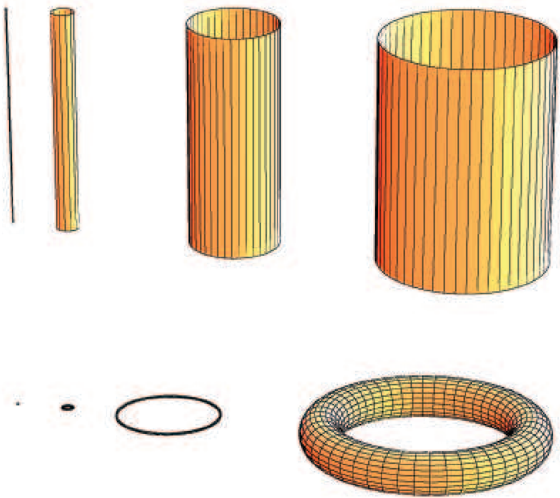
light signal : $E \gtrsim 1$ TeV

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

how to detect their existence?

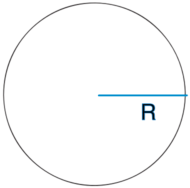
motion in the internal space $\Rightarrow$ mass spectrum in 3d

Dimensions D=??



example: - one internal circular dimension

- light signal



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

$\Rightarrow$ quantization of internal momenta: $p = \frac{n}{R}$; $n = 0, 1, 2, \dots$

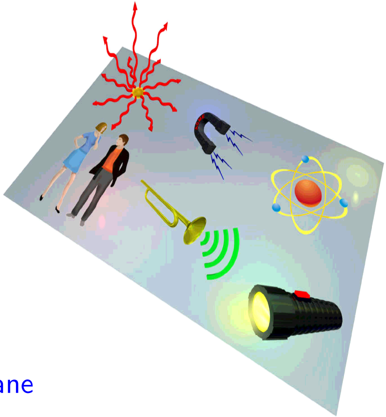
$\Rightarrow$ 3d: tower of Kaluza Klein particles with masses $M_n = n/R$

$$p_0^2 - \vec{p}^2 - p_5^2 = 0 \;\Rightarrow\; p^2 = p_5^2 = \frac{n^2}{R^2}$$

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

$\Leftrightarrow$ propagation in the internal space

Our universe on a membrane

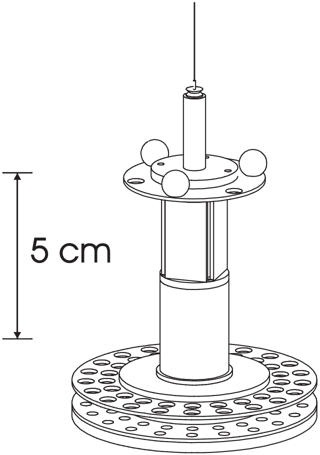


Two types of new dimensions:

- longitudinal: along the membrane
- transverse: "hidden" dimensions

  only gravitational signal $\Rightarrow R_\perp \lesssim 1$ mm !

Adelberger et al. '06



$R_\perp \lesssim 45\ \mu$m at 95% CL

- dark-energy length scale $\approx 85\mu$m

Low scale gravity

Extra large $\perp$ dimensions can explain the apparent weakness of gravity

total force = observed force $\times$ volume $\perp$

total force $\simeq \mathcal{O}(1)$ at 1 TeV

n dimensions of size $R_\perp$

$n = 1 : \; R_\perp \simeq 10^8$ km — excluded

$n = 2 : \; R_\perp \simeq 0.1$ mm $\quad (10^{-12}$ GeV$)$

possible

$n = 6 : \; R_\perp \simeq 10^{-13}$ mm $\quad (10^{-2}$ GeV$)$

- distances $> R_\perp$: gravity 3d

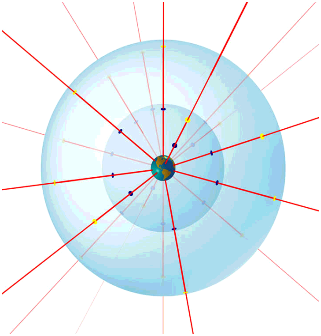
  however for $< R_\perp$: gravity (3+n)d

- strong gravity at 10^{-16} cm $\leftrightarrow 10^3$ GeV

10^{30} times stronger than thought previously!

Gravity modification at submillimeter distances

Newton's law: force decreases with area



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

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

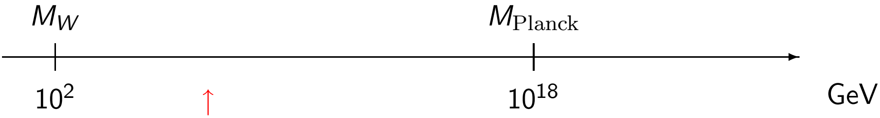
observable for $n = 2$: $1/r^4$ with $r \lesssim .1$ mm

At what energies strings may be observed?

- What is their size/tension $l_s \leftrightarrow M_s$?

- What is the size of the extra dimensions?

Before 1994: $M_{\rm string} \simeq M_{\rm Planck} \sim 10^{18}$ GeV $\qquad l_{\rm string} \simeq 10^{-32}$ cm



After 1994: $M_{\rm string}$ is an arbitrary parameter

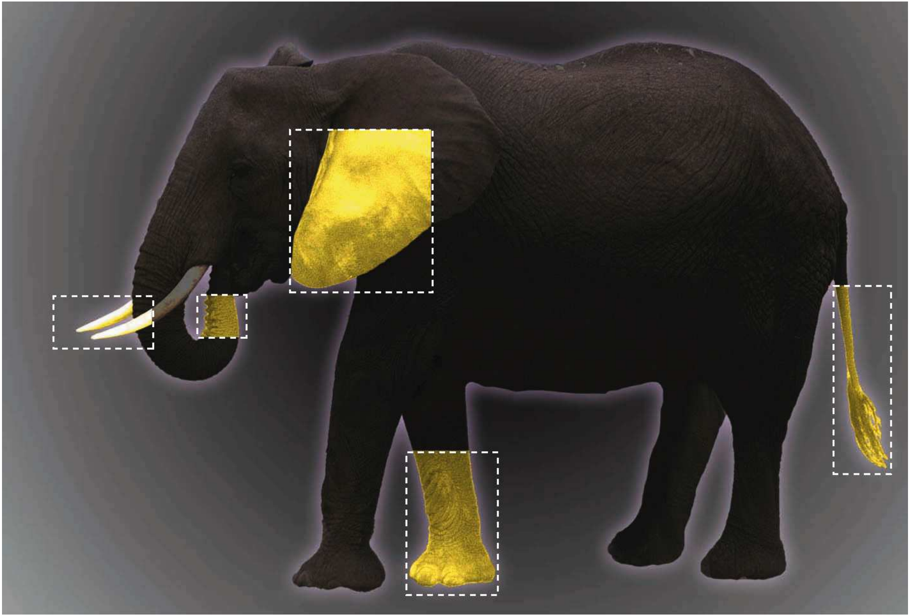
Interesting possibility: $M_{\rm string} \sim M_W \Rightarrow$

realize the idea of hidden dimensions

explain the hierarchy $M_W/M_{\rm Planck}$

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

What is String Theory?



- Heterotic string: Natural framework for SUSY and unification

  However mismatch between string and GUT scales

  $M_s = g M_{\mathrm{Planck}} \simeq 50 M_{\mathrm{GUT}}$

- Framework of type I string theory : D-brane world

Natural separation of

global SUSY from gravity

$\swarrow \qquad\qquad \searrow$

D-branes/open strings closed strings

Type I string theory $\Rightarrow$ D-brane world

- gravity: closed strings
- gauge interactions: open strings

with their ends attached on membranes   Dirichlet branes or D-branes

Dimensions of finite size: n transverse $6-n$ parallel

calculability $\Rightarrow R_{\parallel} \simeq l_{\rm string}$; $R_{\perp}$ arbitrary

$M_P^2 \simeq \frac{1}{\alpha^2} M_s^{2+n} R_{\perp}^n$ $\alpha = g_s$

Planck mass in $4+n$ dims: M_*^{2+n}

small M_s/M_P : extra-large $R_{\perp}$

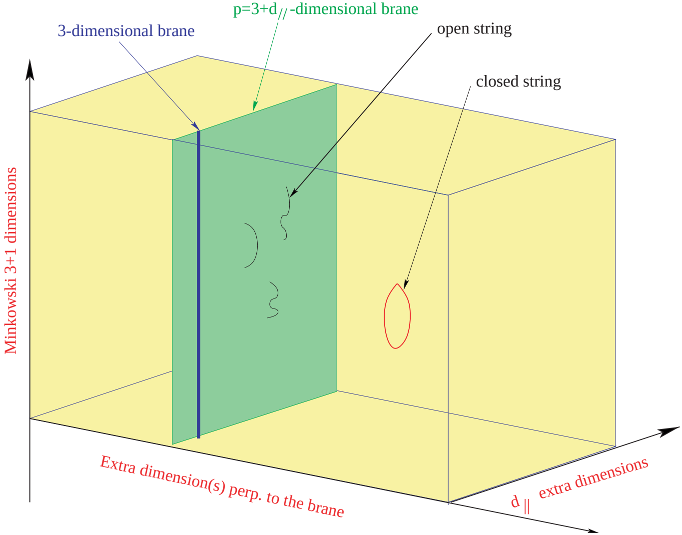
$M_s \sim 1$ TeV $\Rightarrow R_{\perp} \sim .1 - 10^{-13}$ mm $(n = 2-6)$

weak string coupling: $g_s = \alpha$

Braneworld

2 types of compact extra dimensions:

- parallel ($d_{\parallel}$): $\lesssim 10^{-16}$ cm (TeV)
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



Experimental predictions

- particle accelerators

  - Large TeV dimensions   seen by gauge interactions

  - Extra large hidden dimensions   transverse $\Rightarrow$ strong gravity

  - massive string vibrations

- microgravity experiments

  - gravity modifications at short distances

    new submillimeter forces

Large TeV dimensions

longitudinal dimensions: $R^{-1} \lesssim M_s \Rightarrow R^{-1}$ first scale of new physics

increasing the energy I.A. '90

- could happen for some of the internal dims
- explain coupling constant ratios g_2/g_3
- susy breaking
- fermion masses displace light generations

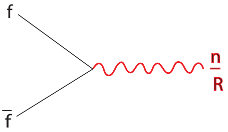
Massive tower of Kaluza Klein modes for Standard Model particles

$$M_n^2 = M_0^2 + \frac{n^2}{R^2} \quad ; \quad n = \pm 1, \pm 2, \ldots$$

$\Rightarrow$ excited states of photon, $W^{\pm}$, Z, gluons

Localized fermions (on 3-brane intersections)

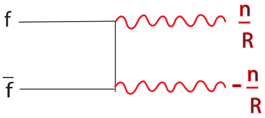
$\Rightarrow$ single production of KK modes I.A.-Benakli '94



- strong bounds indirect effects: $R^{-1} \gtrsim 3\,\mathrm{TeV}$
- new resonances but at most $n = 1$

Otherwise KK momentum conservation

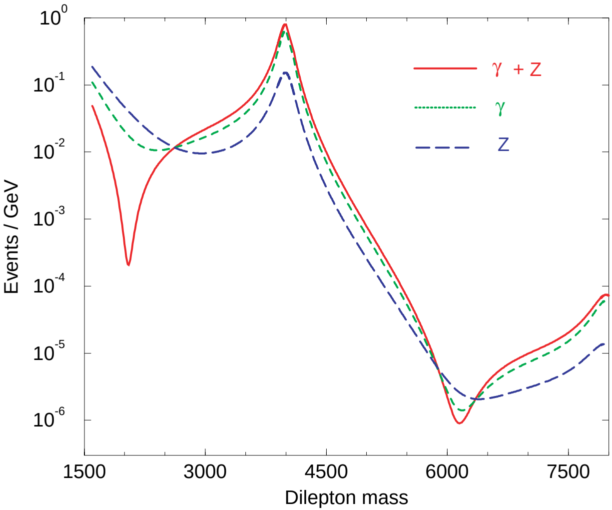
$\Rightarrow$ pair production of KK modes (universal dims)



- weak bounds $R^{-1} \gtrsim$ 300-500 GeV
- no resonances
- lightest KK stable : dark matter candidate

Servant-Tait '02

$R^{-1} = 4$ TeV



- no observation in dijets $\Rightarrow R^{-1} \gtrsim 20$ TeV ; 95% CL

- more than one dimension : stronger limits

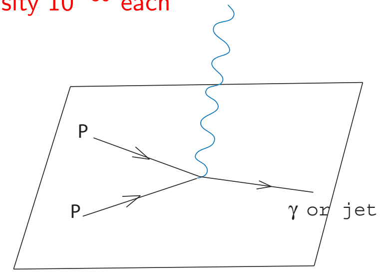
Hidden submillimeter dimensions

$\Rightarrow$ strong gravity at the TeV: gravitational radiation in the bulk

3d: Kaluza Klein gravitons very light

: high energy: huge number of particles produced

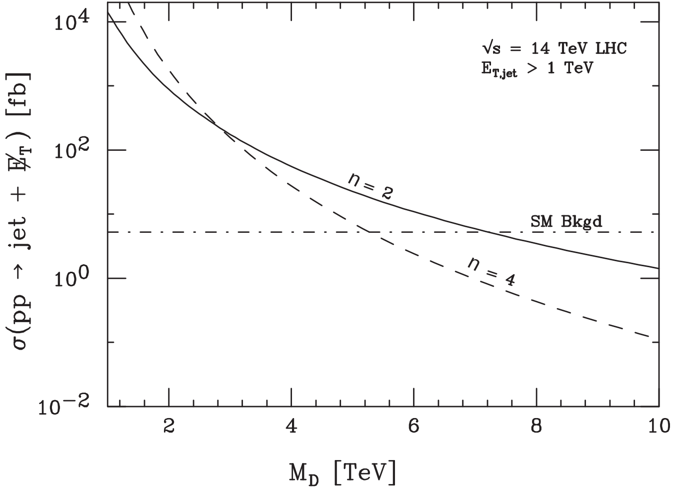
LHC: 10^{30} massive gravitons of intensity 10^{-30} each



Signal: missing energy

Angular distribution $\Rightarrow$ spin of the graviton

Giudice-Rattazzi-Wells '98



- no observation $\Rightarrow$ $R_\perp \lesssim 10^{-2} - 10^{-12}$ mm ($n = 2 - 6$); 95% CL

- more dimensions $\Rightarrow$ weaker limits

Limits on $R_\perp$ in mm

Experiment	$R_\perp(n=2)$	$R_\perp(n=4)$	$R_\perp(n=6)$
Collider bounds			
LEP 2	4.8×10^{-1}	1.9×10^{-8}	6.8×10^{-11}
Tevatron	5.5×10^{-1}	1.4×10^{-8}	4.1×10^{-11}
LHC	4.5×10^{-3}	5.6×10^{-10}	2.7×10^{-12}
NLC	1.2×10^{-2}	1.2×10^{-9}	6.5×10^{-12}
Astrophysics/cosmology bounds			
SN1987A	3×10^{-4}	1×10^{-8}	6×10^{-10}
COMPTEL	5×10^{-5}	-	-

Supernova constraints

cooling due to graviton production e.g. $NN \to NN+$ graviton

number of gravitons: $\sim (TR_\perp)^n$ $T >> R_\perp^{-1}$

~ 10 MeV

$\Rightarrow$ production rate: $P_{\rm gr} \sim \frac{1}{M_p^2}(TR_\perp)^n \sim \frac{T^n}{M_*^{(2+n)}}$

$P_{\rm gr} < P_\nu$: $M_*\big|_{n=2} \gtrsim 50\ {\rm TeV}$ $\Rightarrow$ $M_s \gtrsim 10\ {\rm TeV}$

Massive string vibrations

indirect effects: virtual exchanges $\Rightarrow$ effective interactions

e.g. four-fermion operators

Actual limits: Matter fermions on

- same set of branes $\Rightarrow M_s \gtrsim 500$ GeV dim-8: $\frac{g^2}{M_s^4}(\bar{\psi}\partial\psi)^2$

- brane intersections :$M_s \gtrsim 2-3$ TeV dim-6: $\frac{g^2}{M_s^2}(\bar{\psi}\psi)^2$

High energies $\Rightarrow$

- direct production: string physics

- strong gravity: production of micro-black holes?

Relevance to low–energy physics

Question:

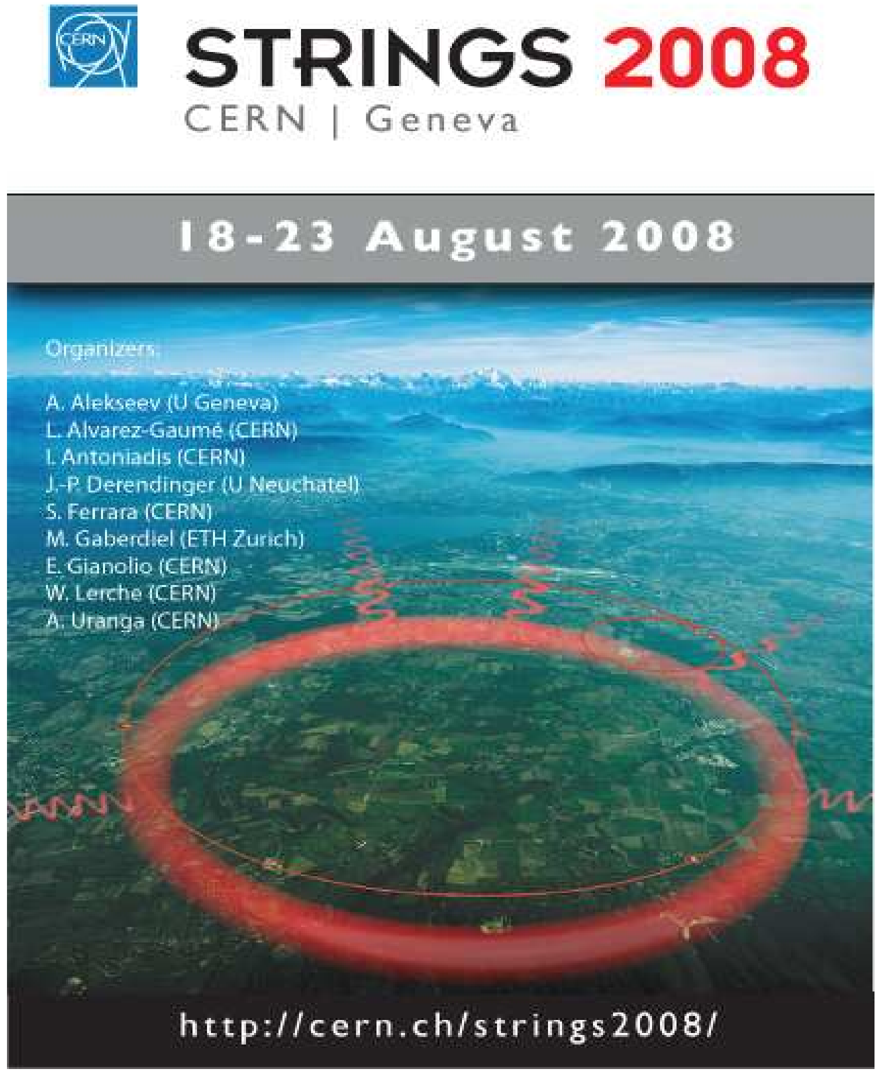
Can we make **model–independent**

low–energy **string predictions**

from parton amplitudes

in superstring theory ?

String signatures at LHC ?



Model–independent tree parton amplitudes

N–point parton superstring amplitudes in $D = 4$:

N–gluon

2–fermion + $(N-2)$–gluon

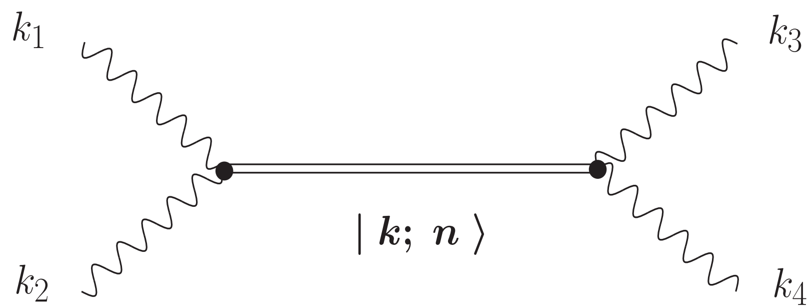
- completely model independent
- for any string compactification
- any number of supersymmetries
- even with broken supersymmetry

No intermediate exchange of KKs, windings or emmission of graviton !

Universal sum over infinite exchange of string Regge (SR) excitations:

masses: $M_n^2 = M_{\text{string}}^2\, n$

maximal spin: $n+1$



Physics of large extra dimensions and low string scale

What about strong gravity effects ?

Black hole production at energies $\sim \frac{M_{\text{string}}}{g^2_{\text{string}}}$

Horowitz-Polchinski '96
Meade-Randall '07

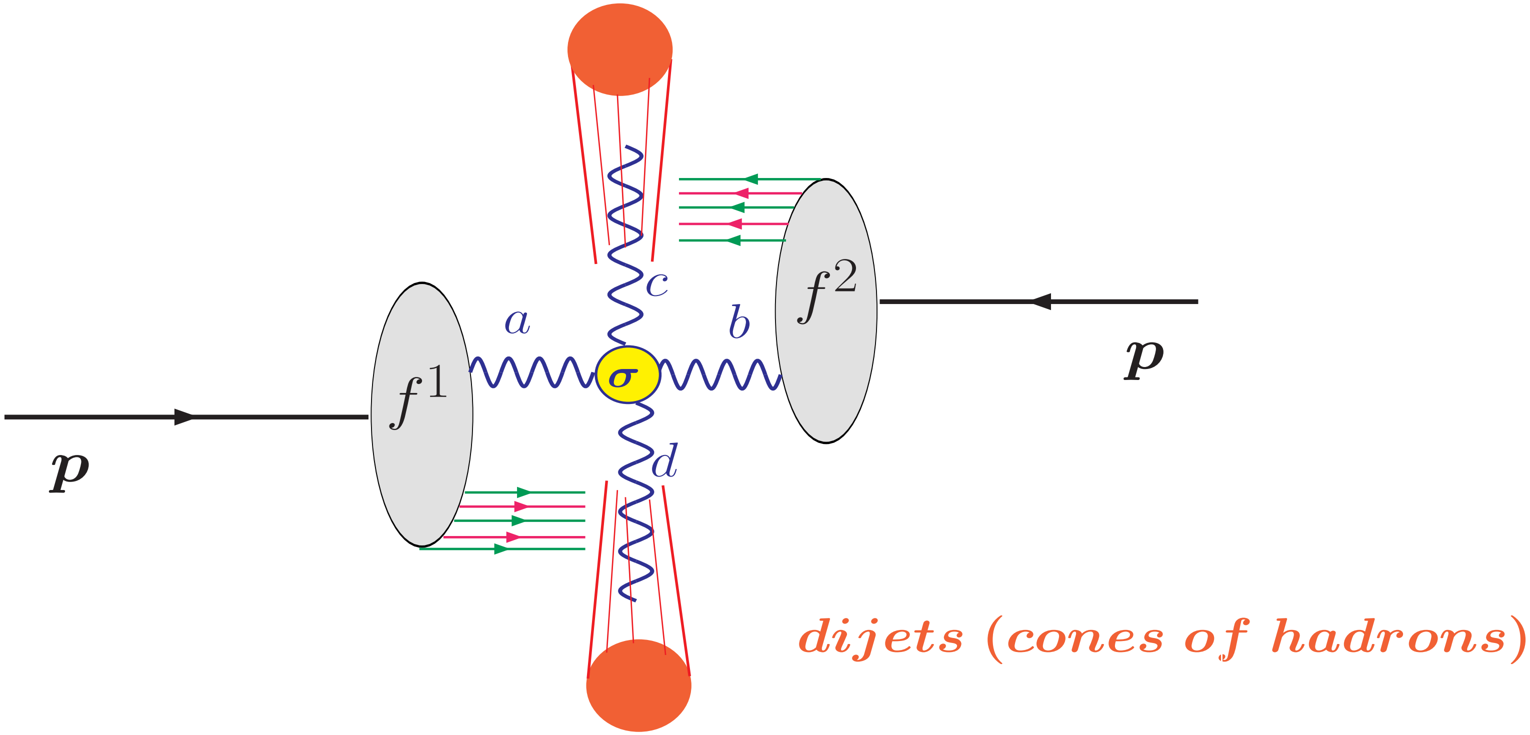
$$\boxed{n \sim g_{\text{string}}^{-2} > 1} \qquad g_{\text{string}} \simeq \alpha \sim 0.1$$

$\Longrightarrow$ For $g_{\text{string}} < 1$ strong gravity effects occur above M_{string}

$\Longrightarrow$ We may first see SR's from 1-st, $\ldots$, n-th level

Dijet signals for low M_{string} at LHC

Two jets:



$$\boxed{\sigma(pp \to 2\ \text{jets}) = \sum_{a,b,c,d} \int dx_1\ dx_2\ f_a^1(x_1; Q^2)\ f_b^2(x_2; Q^2)\ \sigma_{ab\to cd}(\underbrace{x_1 x_2 s}_{\hat{s}}, \underbrace{Q^2}_{\hat{t}}; \alpha')}$$

Look for **resonances of string Regge excitations** propagating in s–channel

Cross sections

$$\boxed{\begin{array}{ccc} |\mathcal{M}(gg\to gg)|^2 & , & |\mathcal{M}(gg\to q\bar{q})|^2 \\ |\mathcal{M}(q\bar{q}\to gg)|^2 & , & |\mathcal{M}(qg\to qg)|^2 \end{array}} \Bigg\}$$

completely model–independent:
for any CY orientifold !

Lüst-Stieberger-Taylor '08

$$\boxed{\begin{aligned} |\mathcal{M}(gg\to gg)|^2 \ = \ & g_{YM}^4 \ \left(\frac{1}{s^2}+\frac{1}{t^2}+\frac{1}{u^2}\right) \\ & \times \ \left[\ \frac{9}{4}\ \left(s^2V_s^2+t^2V_t^2+u^2V_u^2\right)-\frac{1}{3}\ (\,sV_s+tV_t+uV_u\,)^2\ \right] \end{aligned}}$$

$$\boxed{|\mathcal{M}(gg\to q\bar{q})|^2 = g_{YM}^4\ \frac{t^2+u^2}{s^2}\ \left[\ \frac{1}{6}\ \frac{1}{tu}\ (tV_t+uV_u)^2-\frac{3}{8}\ V_t\ V_u\ \right]}$$

$$V_s = -\tfrac{tu}{s}\ B(t,u) = 1-\tfrac{2}{3}\pi^2\,tu+\ldots \qquad V_t : s\leftrightarrow t \qquad V_u : s\leftrightarrow u$$

YM–limits agree with e.g. book "*Collider Physics*" by Barger, Phillips

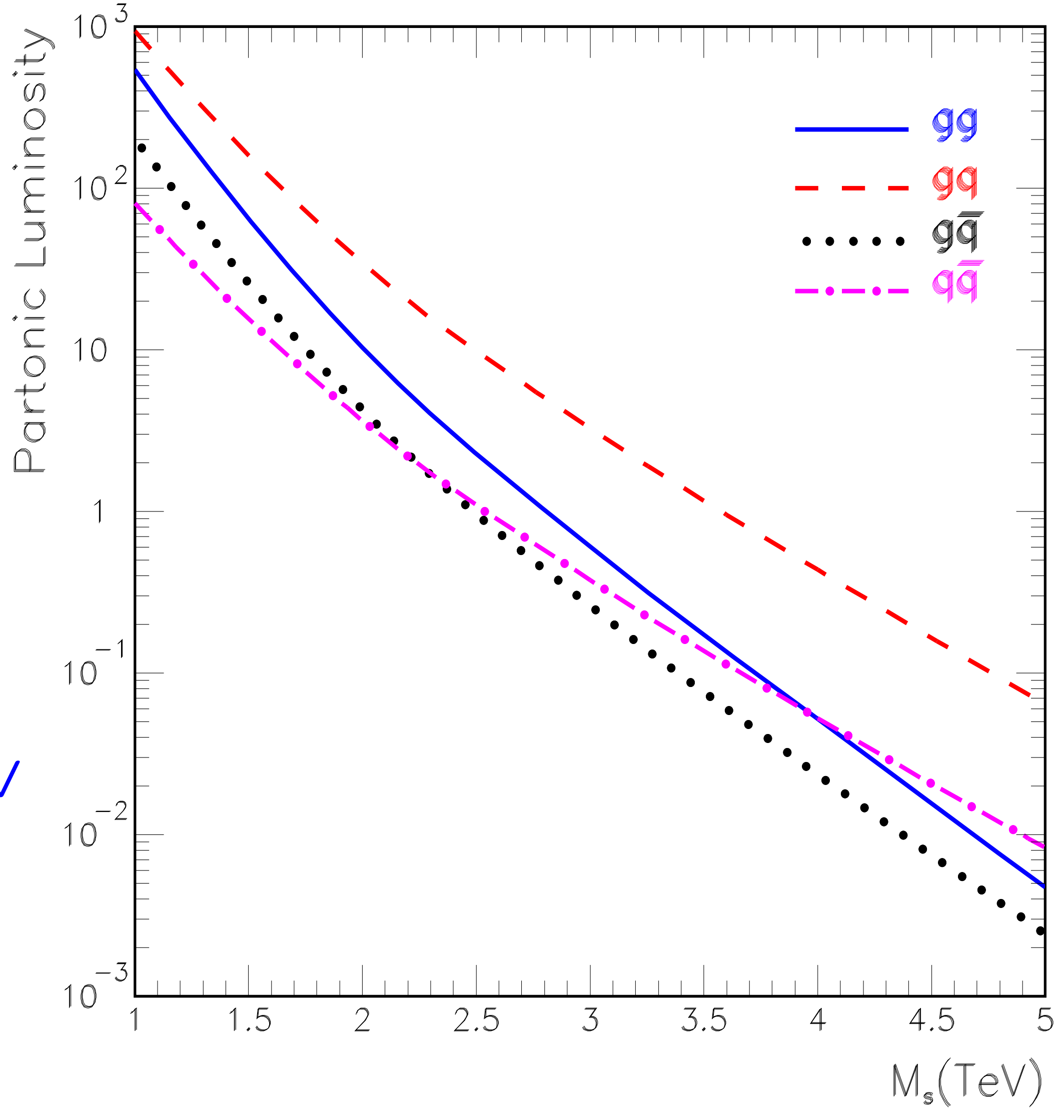
In addition we need:

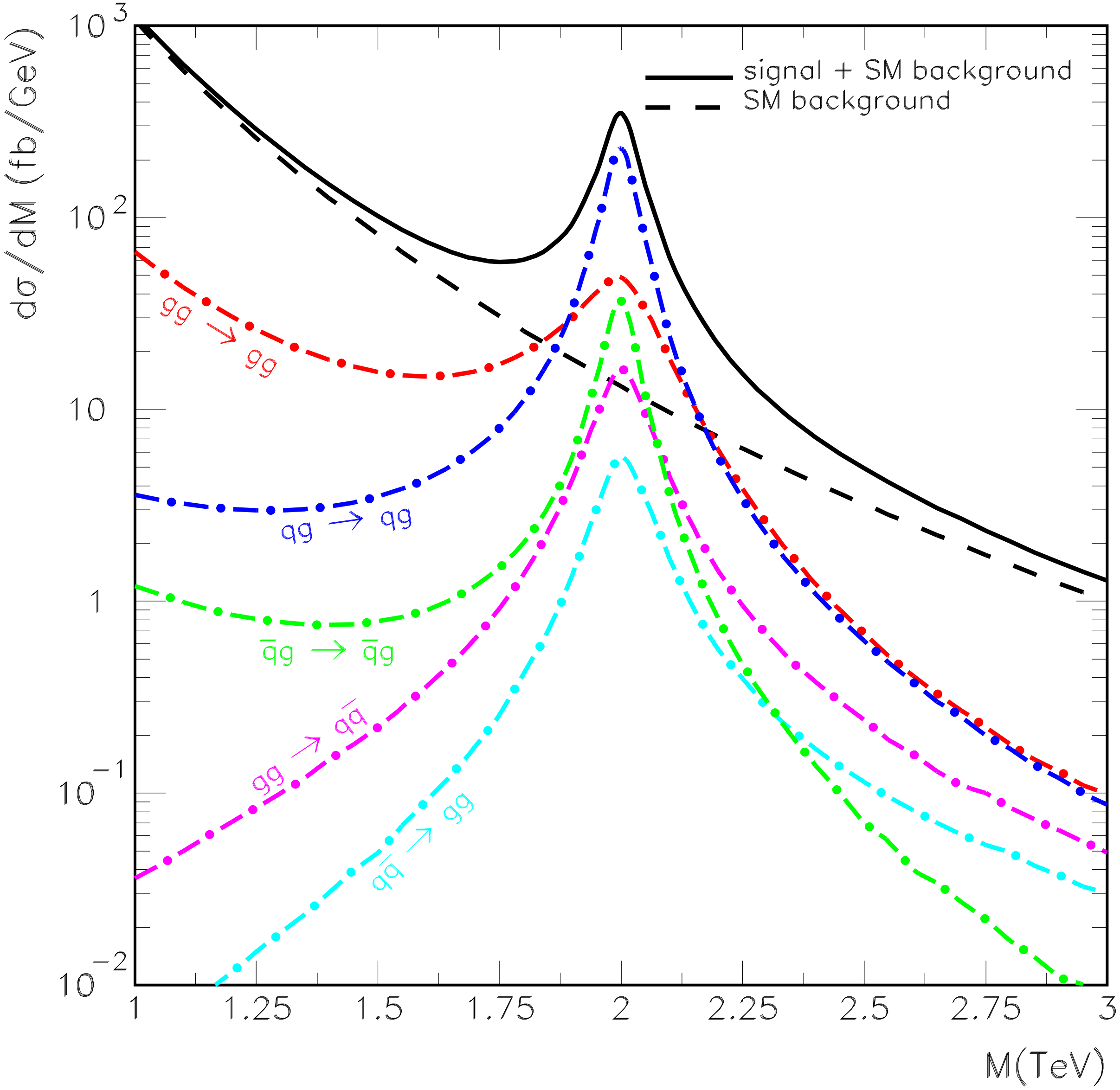
$$\boxed{|\mathcal{M}(q\bar{q} \to q\bar{q})|^2, \; |\mathcal{M}(qq \to qq)|^2}$$

depend on geometry KK and windings

however they are suppressed:

- QCD color factors favor gluons over quarks in the initial state
- Parton luminosities in pp above 1TeV are lower for $qq, q\bar{q}$ than for gg, gq





Any superstring theory with

low M_{string} and $g_{\text{string}} < 1$

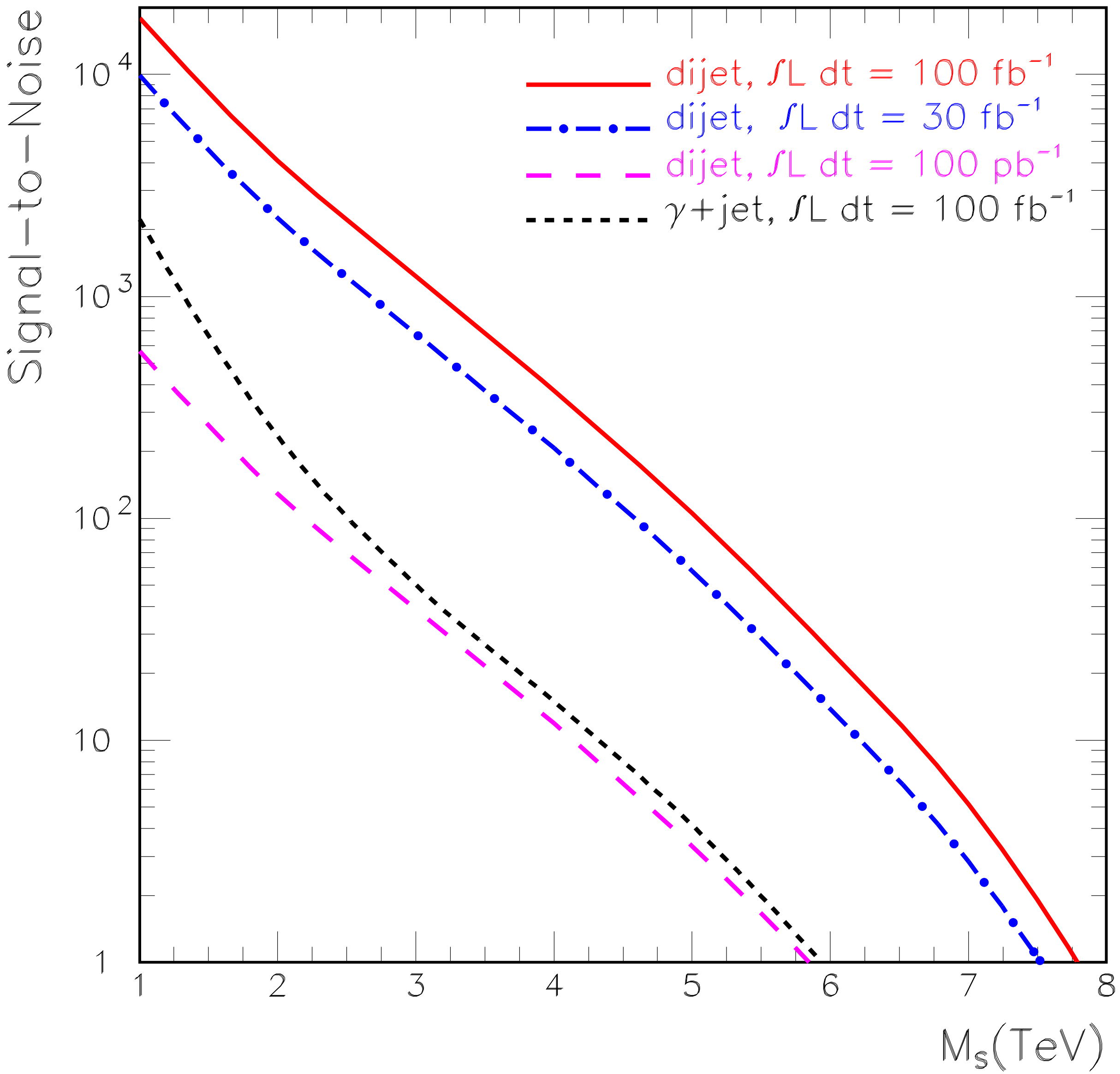
Universal deviation from SM

in jet distribution

$M_{\text{string}} = 2$ TeV

$\Gamma_{SR} = 15 - 150$ GeV

Anchordoqui, Goldberg, Lüst, Nawata, Taylor, Stieberger '08



Discovery reach

SUSY in the bulk?

- global SUSY: no need to be there   at least for hierarchy

- SUGRA: probably unbroken in the bulk $\Rightarrow$

very weakly broken (volume suppressed)

New forces at submm scales   e.g. radion, gauge fields

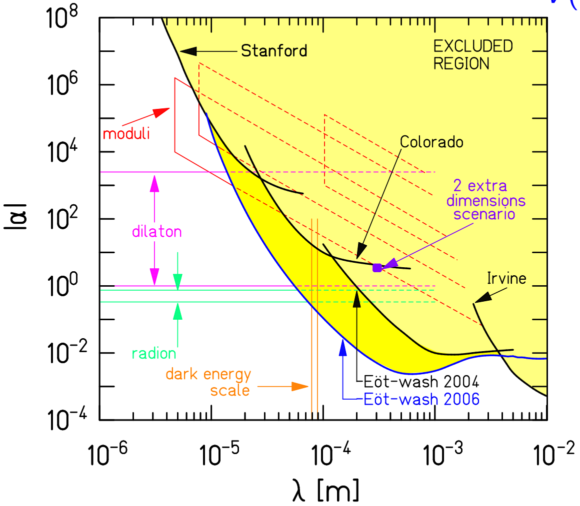
- Radion $\equiv \ln V_\perp$

- mass: $(\mathrm{TeV})^2/M_P \sim 10^{-4}$ eV $\rightarrow$ mm range
- coupling: $\frac{1}{m}\frac{\partial m}{\partial \ln V_\perp} = \sqrt{\frac{n}{n+2}} \times$ gravity

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

Experimental limits on short distance forces

$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



Radion : $M_* \gtrsim 6$ TeV   95% CL   Adelberger et al. '06

Light $U(1)$ gauge bosons

$m_A = g_A\, M$: small mass $\Rightarrow$ small coupling

A in the bulk with localized mass

$g_A \sim 1/\sqrt{V_\perp} \quad \Rightarrow m_A \gtrsim M_s^2/M_P \ \simeq \ 10^{-4}\,\mathrm{eV}$

A propagates in part of the bulk

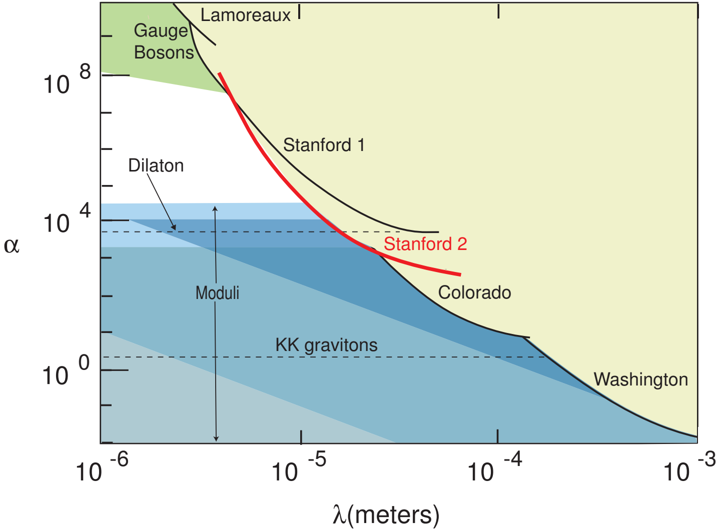
$\Rightarrow$ new submm forces: $g_A \sim 1/\sqrt{V_\perp} \gtrsim M_s/M_P \sim 10^{-16}$

$\Rightarrow \gtrsim \ 10^6 - 10^8 \times$ gravity

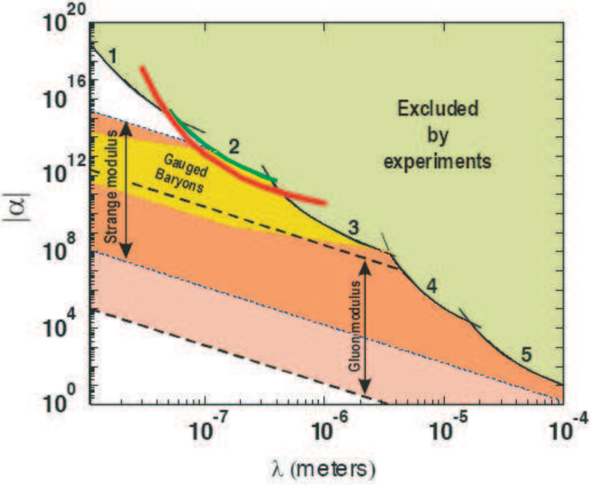
$m_{\rm proton}/M_*$

an order of magnitude improvement on bounds in the range 6-20 μm

Smullin-Geraci-Weld-Chiaverini-Holmes-Kapitulnik '05



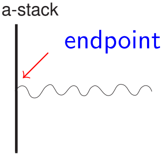
an order of magnitude improvement in the range 10-200 nm Decca et al '07



5: Colorado 4: Stanford 3: Lamoureaux 1: Mohideen et al.

A D-brane embedding of the Standard Model

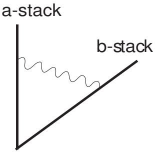
Generic spectrum: N coincident branes $\Rightarrow U(N)$



endpoint transformation: $\mathbf{N}_a$ or $\bar{\mathbf{N}}_a$ $U(1)_a$ charge: $+1$ or -1

$\Rightarrow$ "baryon" number

- open strings from the same stack $\Rightarrow$ adjoint gauge multiplets of $U(N_a)$
- stretched between two stacks $\Rightarrow$ bifundamentals of $U(N_a) \times U(N_b)$



- oriented strings : need at least 4 brane-stacks

- existence of bulk with large dimensions :

minimal choice: $U(3) \times U(2) \times U(1) \times U(1)_{\rm bulk}$

color branes (g_3) weak branes (g_2)

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

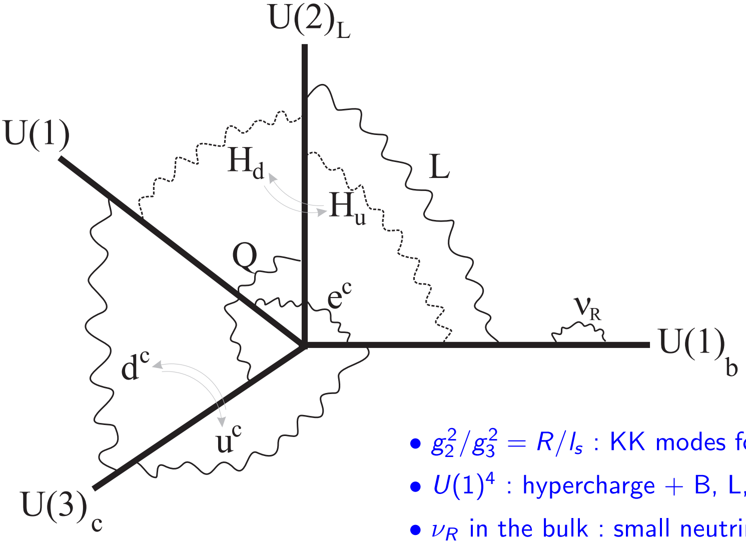
$$
\begin{array}{lll}
Q & (\mathbf{3}, \mathbf{2}; 1, w, 0)_{1/6} & w = \pm 1 \\
u^c & (\bar{\mathbf{3}}, \mathbf{1}; -1, 0, x)_{-2/3} & x = \pm 1, 0 \\
d^c & (\bar{\mathbf{3}}, \mathbf{1}; -1, 0, y)_{1/3} & y = \pm 1, 0 \\
L & (\mathbf{1}, \mathbf{2}; 0, 1, z)_{-1/2} & z = \pm 1, 0 \\
l^c & (\mathbf{1}, \mathbf{1}; 0, 0, 1)_{1} &
\end{array}
$$

hypercharge $Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow$ 2 possibilities:

$$
\begin{array}{llllll}
c_3 = -1/3 & c_2 = \pm 1/2 & x = -1 & y = 0 & w = \pm 1 & z = -1/0 \\
c_3 = 2/3 & c_2 = \pm 1/2 & x = 0 & y = 1 & w = \mp 1 & z = -1/0
\end{array}
$$

I.A.-Kiritsis-Tomaras '00; I.A.-Kiritsis-Rizos-Tomaras '02

Standard Model on D-branes



- $g_2^2/g_3^2 = R/l_s$: KK modes for $SU(2)_L$
- $U(1)^4$: hypercharge + B, L, PQ global
- ν_R in the bulk : small neutrino masses
- $U(1)$ on top of $U(2)$ or $U(3)$ $\Rightarrow$ prediction for $\sin^2\theta_W$

The remaining three $U(1)$'s : anomalous

Green-Schwarz anomaly cancellation $\Rightarrow$

- they become massive (absorb three axions)

gauge field: $\delta A = d\Lambda \quad \Rightarrow \quad$ axion: $\delta a = -M\Lambda$

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

cancel the anomaly

$\Rightarrow \;\; U(1)_A$ mass: $\;\; m_A = g_A\, M$

- the global symmetries remain in perturbation

- Baryon number $\Rightarrow$ proton stability

- Lepton number $\Rightarrow$ protect small neutrino masses

no Lepton number $\Rightarrow \frac{1}{M_s} LLHH \to$ Majorana mass: $\frac{\langle H\rangle^2}{M_s} LL$

$\sim$ GeV

R-neutrinos: open strings in the bulk

R-neutrino: $\nu_R(x, y)$ $\quad y$: bulk coordinates

Arkani Hamed-Dimopoulos-Dvali-March Russell '98
Dienes-Dudas-Gherghetta '98

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

$\langle H \rangle = v \;\Rightarrow\;$ mass-term: $\dfrac{g_s v}{R_\perp^{n/2}} \nu_L \nu_R^0 \;\leftarrow$ 4d zero-mode

Dirac neutrino masses: $m_\nu \simeq \dfrac{g_s v}{R_\perp^{n/2}} \simeq v \dfrac{M_s}{M_p}$

$\simeq 10^{-3} - 10^{-2}$ eV for $M_s \simeq 1 - 10$ TeV

$m_\nu << 1/R_\perp \Rightarrow$ KK modes unaffected

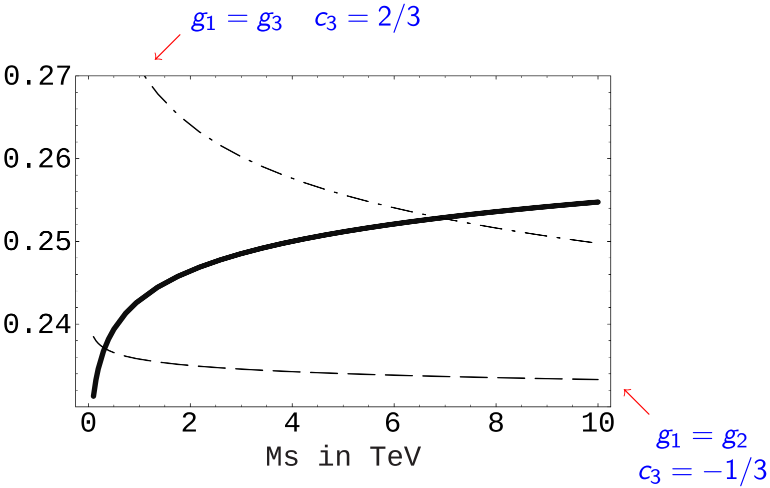
$$Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow \frac{1}{g_Y^2} = \frac{2c_1^2}{g_1^2} + \frac{4c_2^2}{g_2^2} + \frac{9c_3^2}{g_3^2}$$

$$\sin^2\theta_W = \frac{g_Y^2}{g_2^2 + g_Y^2} = \frac{1}{g_2^2/g_Y^2 + 1} = \frac{1}{1 + 4c_2 + 2c_1^2 g_2^2/g_1^2 + 6c_3^2 g_2^2/g_3^2}$$

$$= \frac{1}{2 + 2g_2^2/g_1^2 + 6c_3^2 g_2^2/g_3^2}$$

$$g_1 = g_2 = g_3 \Rightarrow \sin^2\theta_W = \begin{cases} 3/14 & c_3 = -1/3 \\ 3/20 & c_3 = 2/3 \end{cases}$$

$\sin^2\theta_W(M_s)$



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

Origin of EW symmetry breaking?

little hierarchy: $m_W/M_s \lesssim \mathcal{O}(10^{-1})$

possible solution: radiative breaking I.A.-Benakli-Quiros '00

$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$

$\mu^2 = 0$ at tree but becomes < 0 at one loop non-susy vacuum

simplest case: one Higgs from the same brane

$\Rightarrow$ tree-level V same as susy: $\lambda = \frac{1}{8}(g^2 + g'^2)$ D-terms

$\mu^2 = -g^2 \varepsilon^2 M_s^2 \leftarrow$ effective UV cutoff

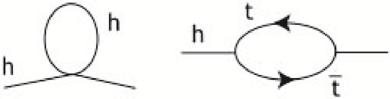
$$\varepsilon^2(R) = \frac{R^3}{2\pi^2} \int_{\underset{\text{IR}}{0}}^{\overset{\text{UV}}{\infty}} dl\, l^{3/2} \underbrace{\overbrace{\frac{\theta_2^4}{16 l^4 \eta^{12}}}^{e^{-\pi l}}}_{1} \left(il + \frac{1}{2} \right) \sum_n n^2 e^{-2\pi n^2 R^2 l}$$

Mass hierarchy problem

Higgs mass: very sensitive to high energy physics

1-loop radiative corrections:

dominant contributions:



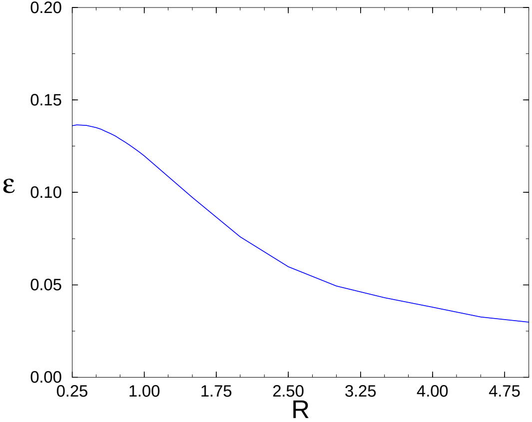
$$\mu^2_{\rm eff} = \mu^2_{\rm bare} + \left(\frac{\lambda}{8\pi^2} - \frac{3\lambda_t^2}{8\pi^2}\right)\Lambda^2 + \cdots$$

UV cutoff: $\int^\Lambda \frac{d^4k}{k^2}$ scale of new physics

High-energy validity of the Standard Model : $\Lambda >> \mathcal{O}(100)$ GeV $\Rightarrow$

"unatural" fine-tuning between $\mu^2_{\rm bare}$ and radiative corrections

order by order



$R \to 0\ :\ \varepsilon(R) \simeq 0.14$ large transverse dim $R_\perp = l_s^2/R \to \infty$

$R \to \infty :\ \varepsilon(R) M_s \sim \varepsilon_\infty / R$ $\varepsilon_\infty \simeq 0.008$ UV cutoff: $M_s \to 1/R$

Higgs = component of a higher dim gauge field

$\Rightarrow \varepsilon_\infty$ calculable in the effective field theory

Quartic Higgs coupling $\Rightarrow$ mass prediction:

- tree level : $M_H = M_Z$

- low-energy SM radiative corrections top quark sector : $M_H \sim 120$ GeV

Also M_s or $1/R \sim$ a few or several TeV

• point particle: 0-brane

charged under 1-form gauge potential $A_\mu dx^\mu$

• string: 1-brane

charged under 2-form gauge field $B_{\mu\nu} dx^\mu dx^\nu$

• p-brane: $(p+1)$-form gauge potential C_{p+1}

Dp-brane: C_{p+1} RR closed string state

Gauss-law in compact space $\Rightarrow$

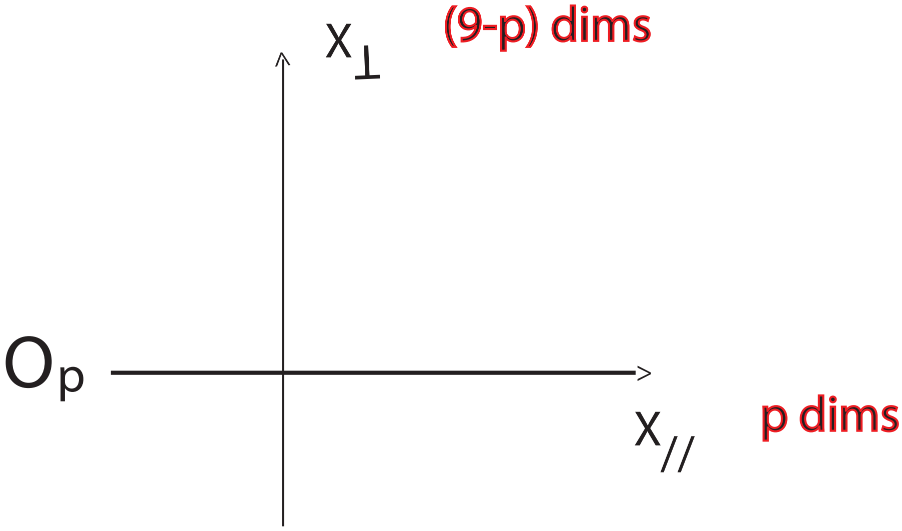
neutrality condition $\equiv$ RR tadpole cancellation

SUSY: RR charge $\leftrightarrow$ brane tension

charge neutrality $\leftrightarrow$ zero energy

Orientifold: (hyper)surface where closed strings

change orientation



$X_\perp \to -X_\perp$ p-plane localized at $X_\perp = 0$

$z \to \bar{z}$ worldsheet orientation flip

non-dynamical object with RR charge $\Rightarrow$

can have negative tension

Brane supersymmetry breaking

I.A.-Dudas-Sagnotti, Aldazabal-Uranga '99

Stable configurations of branes with orientifolds

- absence of tachyons
- bulk susy breaking suppressed by $R_\perp$

	D	$\bar{\text{D}}$	O	$\bar{\text{O}}$
RR charge	$+$	$-$	$-$	$+$
tension	$+$	$+$	$-$	$-$
linear SUSY	Q_e	Q_o	Q_e	Q_o
NL SUSY	Q_o	Q_e		

Model I: DO or $\bar{\text{D}}\bar{\text{O}}$

local charge conservation, brane SUSY (locally)

Model II: $\bar{\text{D}}$O or D$\bar{\text{O}}$

brane SUSY breaking (linear), NL SUSY

Non-linear SUSY on the brane $\Rightarrow$

(nearly) massless goldstino χ

Dudas-Mourad, Pradisi-Riccioni '01

Standard realization of Volkov-Akulov $\Rightarrow$

universal coupling to stress-tensor

$$\mathcal{L}_\chi = -\frac{i}{2}\chi\sigma^\mu \overset{\leftrightarrow}{\partial}_\mu \bar{\chi} + i\kappa^2(\chi \overset{\leftrightarrow}{\partial^\mu} \sigma^\nu \bar{\chi})T_{\mu\nu}$$

κ: goldstino decay constant

But not the most general

e.g. a new 4-fermion operator not fixed by NL SUSY

Brignole-Feruglio-Zwirner '97, I.A.-Benakli-Laugier '01

General analysis of goldstino couplings

to SM fields in D-brane models

I.A.-Tuckmantel '04

Matter on intersection of two brane stacks:

$$\frac{1}{2\kappa^2} = T_1 + T_2 \qquad T_i = \frac{M_s^4}{4\pi^2 g_i^2} N_i$$

$$\delta\mathcal{L}_\chi = i\sqrt{2}\kappa F_{\mu\nu} f \sigma^\mu \partial^\nu \bar{\chi} + 2\kappa D_\mu \phi (f \partial^\mu \chi) + \text{h.c.}$$
$$+ 2\kappa^2 (\partial_\mu \chi f_1)(\partial^\mu \bar{\chi} \bar{f}_2) + \mathcal{O}(\kappa^3)$$

F: gauge fields, f: Weyl fermions, ϕ: scalars

- universal coefficients independent of brane-angles
- 3rd term: fixes the field theory ambiguity of 4-fermion operator
- 1st term: hypercharge + fermion singlet
- 2nd term: higgs + lepton doublets

preserves lepton number if $L(\chi) = -1$

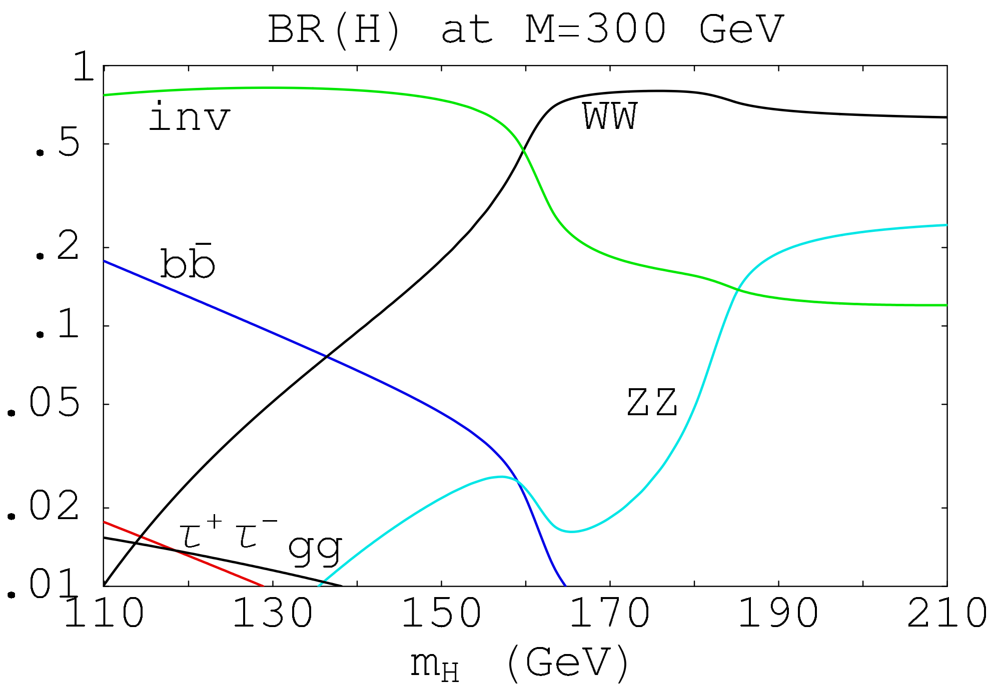
I.A.-Tuckmantel-Zwirner '04

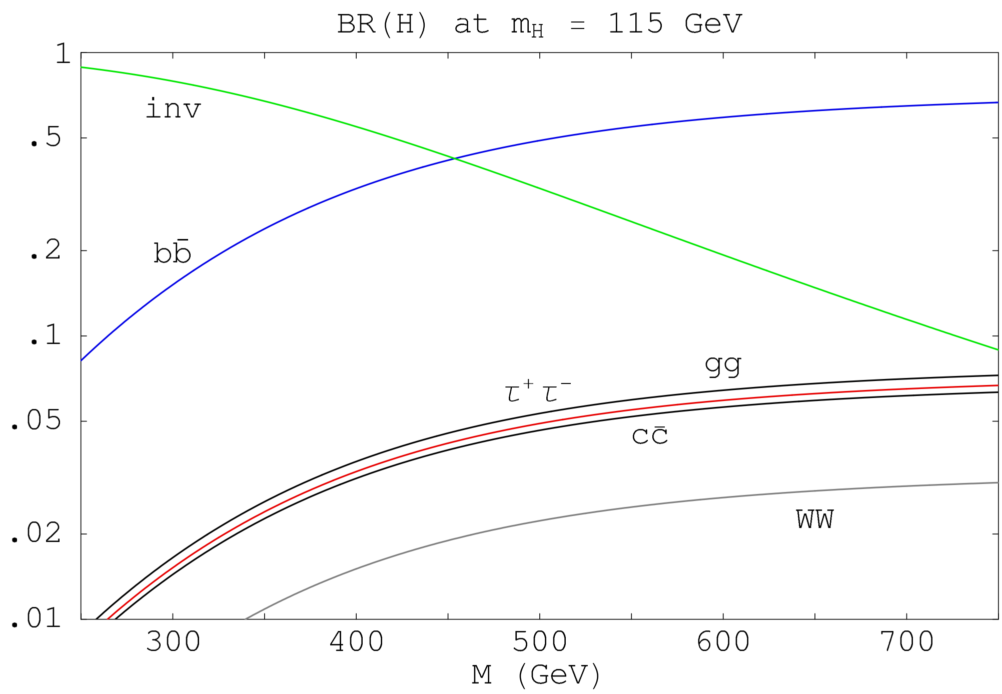
$Z, H \to \nu\chi \quad W^\pm \to l^\pm \chi \Rightarrow$

- bounds: $M_s \gtrsim 500$ GeV (e.g. invisible Z width)
- signal: invisible Higgs decay

dominant or non-negligible in a large range of (M_s, M_H)

$M_s \simeq 2M$


BR(H) at M=300 GeV
1
.5
.2
.1
.05
.02
.01
inv
WW
$b\bar{b}$
ZZ
$\tau^+\tau^-$ gg
110
130
150
170
190
210
m_H (GeV)


BR(H) at m_H = 115 GeV
1
.5
.2
.1
.05
.02
.01
inv
$b\bar{b}$
gg
$\tau^+\tau^-$
$c\bar{c}$
WW
300
400
500
600
700
M (GeV)

Conclusions

TeV strings and large extra dimensions: Physical reality or imagination?

- Well motivated theoretical framework

  with many testable experimental predictions

  new resonances, missing energy

- Stimulus for micro-gravity experiments

  look for new forces at short distances

  higher dim graviton, scalars, gauge fields

But: - unification has to be dropped

- physics is radically changed above string scale

LHC: will explore the physics beyond the Standard Model

Non-compact extra dimensions and localized gravity

- no problem with fixing the size moduli
- new approach to the hierarchy problem
- gravity modification at large distances

- curved space : Randall-Sundrum '99

- flat space : Dvali-Gabadadze-Porrati '00

  more attractive for string theory realization spacetime = slice of AdS_5 our universe = 4d flat boundary

$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ UV-brane $\rightarrow 0 \leq y \leq \pi r_c \leftarrow$ IR-brane

- fine-tuned tensions: $T = -T' = 24M^3k^2$ $\Lambda = -24M^3k^2$
- exponential hierarchy: $M_W = M_P e^{-2\pi k r_c}$
- IR-brane can move to infinity: $r_c \rightarrow \infty$

  $M_P^2 = M^3 \frac{1-e^{-2\pi k r_c}}{k} \leftarrow$ internal volume V finite $\Rightarrow$

  - always 4d gravity localized on the UV-brane

    potential: $\frac{1}{r} + \frac{1}{k^2 r^3} \leftarrow$ deviations ($r_c \rightarrow \infty$)

    $k^{-1} \lesssim 0.1$ mm : $M > 10^8$ GeV, $T^{1/4} > 1$ TeV $\Rightarrow$ matter in the bulk

viable models: AdS/CFT duals to strongly coupled 4d field theories

compositeness, technicolor-type

Magnetized branes and moduli stabilization

- SUSY breaking by internal magnetic fields

  or equivalently branes at angles

- Minimal Standard Model embedding
- Gaugino masses
- A new mechanism of gauge mediation
- Moduli stabilization

Oblique internal magnetic fields

- Effective field theory

General framework

Type I string theory with magnetic fluxes on 2-cycles of the compactification manifold

- Dirac quantization: $H = \frac{m}{nA} \equiv \frac{p}{A}$

  H: constant magnetic field

  m: units of magnetic flux

  n: brane wrapping

  A: area of the 2-cycle

- Spin-dependent mass shifts for charged states

  $\Rightarrow$ SUSY breaking

- Exact open string description:

  $qH \to \theta = \arctan qH\alpha'$ weak field $\Rightarrow$ field theory

- T-dual representation: branes at angles

(m, n): wrapping numbers around the 2-cycle directions

6d $\longrightarrow$ 4d on T^2 with abelian magnetic field H

$\delta M^2 = (2k+1)|qH| + 2qH\cdot\Sigma \leftarrow$ spin operator

$k = 0, 1, 2, \ldots$: Landau level

Landau multiplicity: mn

- spin-0: $\Sigma = 0 \Rightarrow$ mass gap

- spin-1/2: $\Sigma = \pm 1/2 \Rightarrow$ chiral 0-mode

$k = 0 \quad : \quad \delta M^2 = |qH| \pm qH$

$\Rightarrow \quad \delta M^2 = 0 \quad$ for $\Sigma = -1/2$ $(qH > 0)$

- spin-1: $\Sigma = \pm 1 \Rightarrow$ tachyon

Nielsen-Olesen instability

$k = 0 \quad : \quad \delta M^2 = |qH| \pm 2qH$

$\Rightarrow \quad \delta M^2 = -qH \quad$ for $\Sigma = -1$ $(qH > 0)$

Exact open string description:

$q \longrightarrow q_L + q_R$ endpoint charges

$qH \longrightarrow \theta_L + \theta_R \quad ; \quad \theta_{L,R} = \arctan q_{L,R} H\alpha'$

weak field limit $\Rightarrow$ field theory

H constant $\Rightarrow F_{kl} = \epsilon_{kl} H \quad A_k = -\frac{1}{2} F_{kl} x^l$

world-sheet boundary action:

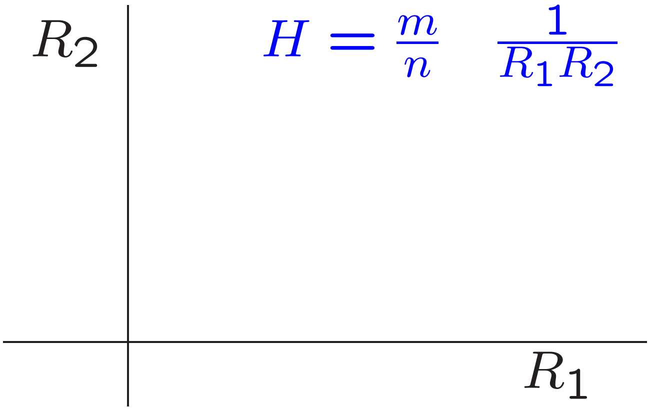
$$q \int A_k \partial x^k = -H \int \left(q_L x^k \overset{\leftrightarrow}{\partial} x^l \Big|_{\sigma=0} + q_R x^k \overset{\leftrightarrow}{\partial} x^l \Big|_{\sigma=\pi} \right)$$

internal rotation current

$\Rightarrow$ frequency shift by $\theta_{L,R}$: $\tan \theta_{L,R} = q_{L,R} H$

T-dual representation: branes at angles

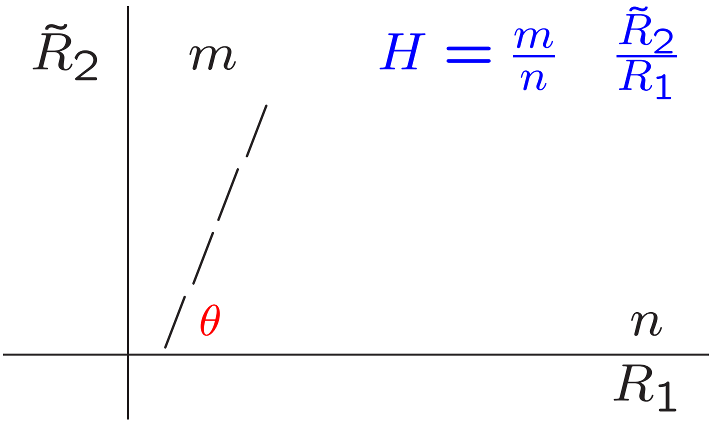
magnetized D9-brane wrapped on T^2



$$H = \frac{m}{n} \quad \frac{1}{R_1 R_2}$$

$$R_2 \to \alpha'/R_2 \equiv \tilde{R}_2 \quad \Rightarrow \text{ D8-brane}$$

wrapped around a direction of angle θ in T^2



$$H = \frac{m}{n} \quad \frac{\tilde{R}_2}{R_1} \quad = \tan\theta$$

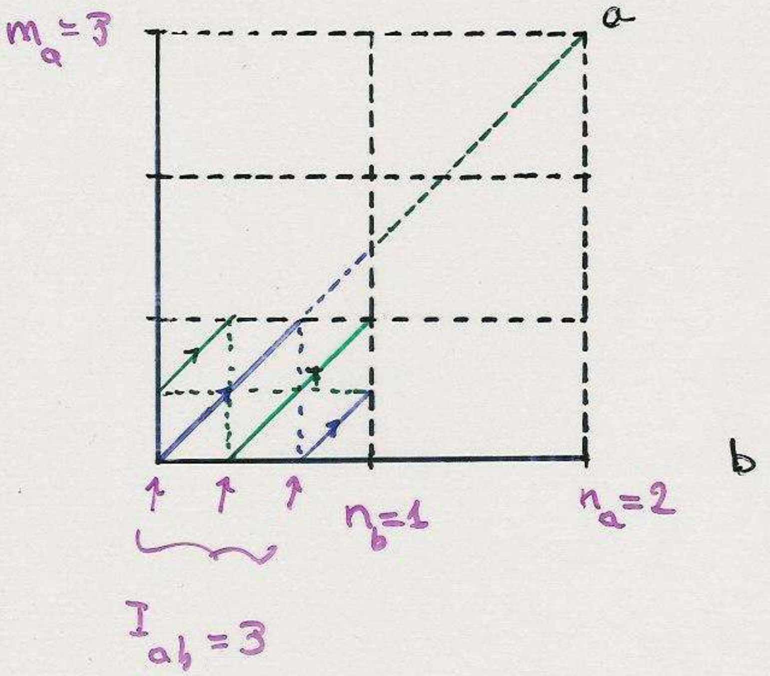
m, n : wrapping numbers

Chirality = intersection number

e.g. $I_{ab} = m_a n_b - m_b n_a$

$=$ intersection nb of branes a, b

ex. $m_b = 0 \quad n_b = 1 \quad \Rightarrow \quad I_{ab} = m_a$



$(T^2)^3$ generalization: H_I with $I = 1, 2, 3$

$\delta M^2 = \sum_I \{(2k_I + 1)|qH_I| + 2qH_I\Sigma_I\}$

- spin-1/2: one chiral 0-mode

$\delta M^2 = 0$ for $k_I = 0$ and $\Sigma_I = -1/2$ $(qH_I > 0)$

- spin-1: tachyon can be avoided Bachas 95

$$
\begin{array}{rcccccl}
 & |H_1| & + & |H_2| & - & |H_3| & > 0 \\
 & |H_1| & - & |H_2| & + & |H_3| & > 0 \\
- & |H_1| & + & |H_2| & + & |H_3| & > 0
\end{array}
$$

massless scalar $\Leftrightarrow$ partial brane susy restoration

Angelantonj-I.A.-Dudas-Sagnotti 00

$$\theta_1 + \theta_2 + \theta_3 = 0$$

Generic spectrum

Turn on H_I^a in several $U(1)_a$ directions

$\Rightarrow$ Gauge group: $\prod_a U(N_a) \leftarrow SU(N_a) \times U(1)_a$

- Neutral strings: adjoint representations

  $\Rightarrow$ massless gauge supermultiplets

- Charged strings $\Rightarrow$ massless chiral fermions

  but in general massive scalars

$\Rightarrow$ Generic spectrum of split SUSY:

- massless gauginos
- massive squarks and sleptons
- massless Higgs $\Leftrightarrow$ non chiral susy intersection

  two Higgs multiplets

Non oriented strings $\Rightarrow$ orientifold planes

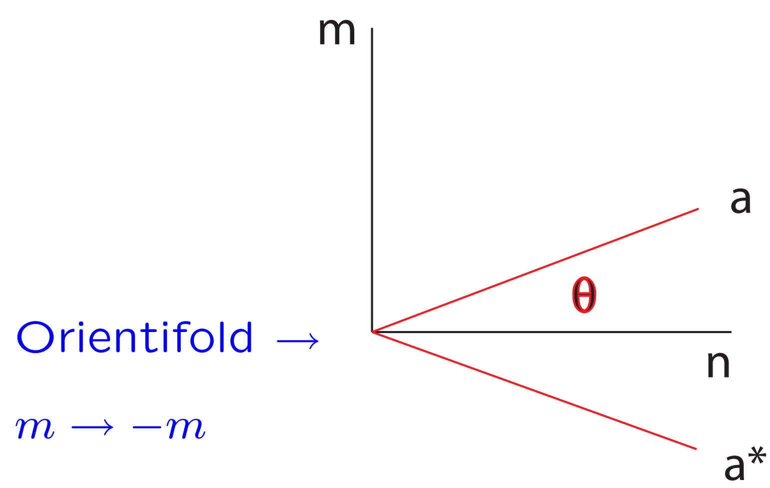
$\Rightarrow$ mirror branes

identified with branes under orientifold action

D-brane a: (m,n) ; $n > 0$ anti-brane: $(m,-n)$

Orientifold: $(0,x)$

Miirror brane a^*: $(-m,n)$



• strings stretched between two mirror stacks

$\Rightarrow$ antisymmetric or symmetric of $U(N_a)$

Minimal Standard Model embedding

New possibilities using intersecting branes

- no large dimensions for low string scale
- no need for B or L conservation
- but need $\sin^2\theta_W = \frac{3}{8}$

General analysis using 3 brane stacks

$\Rightarrow\ U(3)\times U(2)\times U(1)$

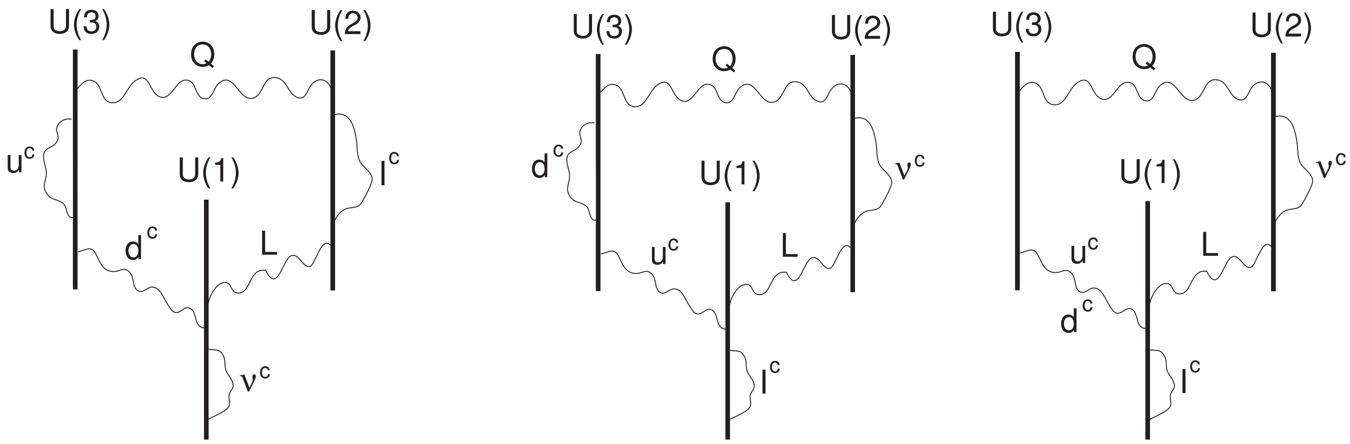
antiquarks u^c, d^c $(\bar{3},1)$:

antisymmetric of $U(3)$ or

bifundamental $U(3)\leftrightarrow U(1)$

$\Rightarrow$ 3 models: antisymmetric is u^c, d^c or none

I.A.-Dimopoulos '04

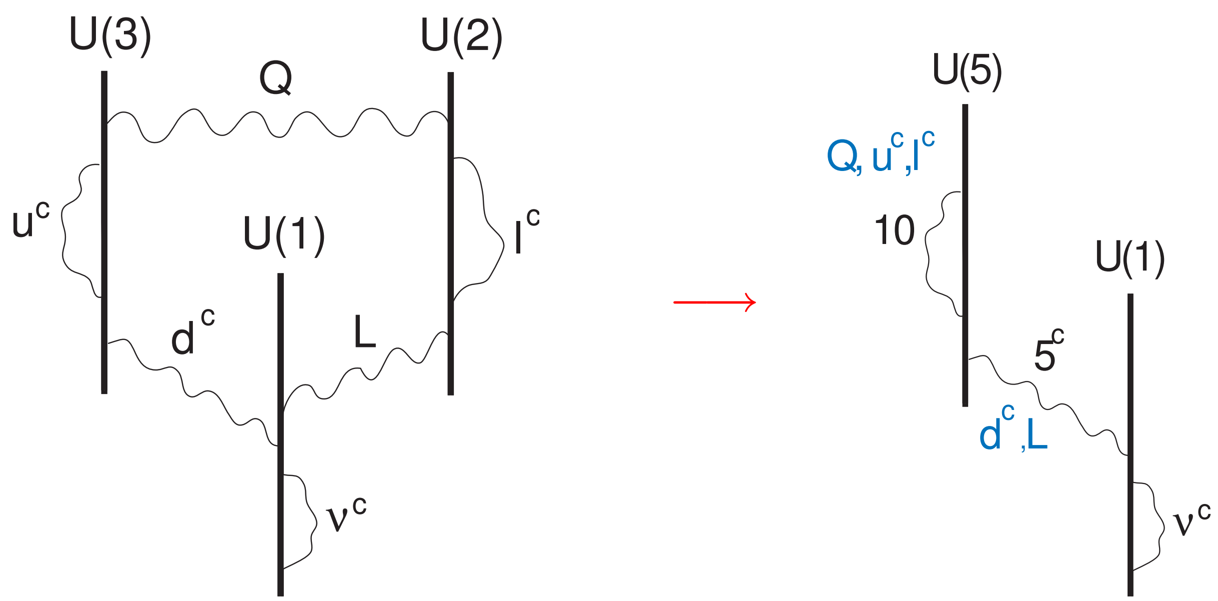


	Model A	**Model B**	**Model C**
Q	$(\mathbf{3},\mathbf{2};1,1,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$
u^c	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$
d^c	$(\bar{\mathbf{3}},\mathbf{1};-1,0,\varepsilon_d)_{1/3}$	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{1/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,-1)_{1/3}$
L	$(\mathbf{1},\mathbf{2};0,-1,\varepsilon_L)_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$
l^c	$(\mathbf{1},\mathbf{1};0,2,0)_1$	$(\mathbf{1},\mathbf{1};0,0,-2)_1$	$(\mathbf{1},\mathbf{1};0,0,-2)_1$
ν^c	$(\mathbf{1},\mathbf{1};0,0,2\varepsilon_\nu)_0$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_0$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_0$

$$Y_A = -\frac{1}{3}Q_3 + \frac{1}{2}Q_2 \qquad\qquad Y_{B,C} = \frac{1}{6}Q_3 - \frac{1}{2}Q_1$$

Model A : $$\sin^2\theta_W = \frac{1}{2+2\alpha_2/3\alpha_3}\bigg|_{\alpha_2=\alpha_3} = \frac{3}{8}$$

Model B, C : $$\sin^2\theta_W = \frac{1}{1+\alpha_2/2\alpha_1+\alpha_2/6\alpha_3}\bigg|_{\alpha_2=\alpha_3} = \frac{6}{7+3\alpha_2/\alpha_1}$$



Q	$(\mathbf{3},\mathbf{2};1,1,0)_{1/6}$
u^c	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{-2/3}$
d^c	$(\bar{\mathbf{3}},\mathbf{1};-1,0,\varepsilon_d)_{1/3}$
L	$(\mathbf{1},\mathbf{2};0,-1,\varepsilon_L)_{-1/2}$
l^c	$(\mathbf{1},\mathbf{1};0,2,0)_1$
ν^c	$(\mathbf{1},\mathbf{1};0,0,2\varepsilon_\nu)_0$

$$Y_A = -\frac{1}{3}Q_3 + \frac{1}{2}Q_2$$

$$\Rightarrow \qquad \sin^2\theta_W = \left.\frac{1}{2+2\alpha_2/3\alpha_3}\right|_{\alpha_2=\alpha_3} = \frac{3}{8}$$

- Higgs can be easily implemented

  massless $\Rightarrow$ susy intersection

  $H_1, H_2 \, : \, U(2) \leftrightarrow U(1)$ like L

	Model A	**Model B, C**
H_1	$(\mathbf{1},\mathbf{2};0,-1,\varepsilon_{H_1})_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_{H_1},\mathbf{1})_{-1/2}$
H_2	$(\mathbf{1},\mathbf{2};0,1,\varepsilon_{H_2})_{1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_{H_2},-\mathbf{1})_{1/2}$

- 2 extra $U(1)$'s

- Model A,B: one combination can be $B-L$

  broken by a SM singlet VEV at high scale

  or survive at low energies

- Model C: Baryon symmetry

- The other/both is/are anomalous

Spectrum multplicities

$(N_a, \bar{N}_b)$: $I_{ab} = \text{det}W_a \text{det}W_b \int_{T^6} \left(F^a_{(1,1)} - F^b_{(1,1)} \right)^3$

(N_a, N_b): $I_{ab^*} \leftarrow F^{b^*} = -F^b$

$$T^6 = \prod_i T_i^2 \Rightarrow I_{ab} = \prod_i (m_i^a n_i^b - n_i^a m_i^b)$$

$$I_{aa^*} = \prod_i \left\{ \frac{1}{2}(2m_i^a n_i^a \mp 2m_i^a) \pm 2m_i^a \right\}$$

number of intersections along orientifold axis $(0, x)$

$$= \begin{cases} \text{Antisymmetric}: \frac{1}{2}\left(\prod_i 2m_i^a\right)\left(\prod_j n_j^a + 1\right) \\ \text{Symmetric}: \frac{1}{2}\left(\prod_i 2m_i^a\right)\left(\prod_j n_j^a - 1\right) \end{cases}$$

- non-chiral multiplicity: extract the vanishing factors
- $I_{ab^*} = 0 \longrightarrow I_{ab}$ even $\Rightarrow$

  odd nb of generations: constant NS B-field

quantization $\longrightarrow$ magnetic fluxes m half-intergers

Magnetic fluxes can be used to stabilize moduli

I.A.-Maillard '04, I.A.-Kumar-Maillard '05, '06

e.g. T^6: 36 moduli (geometric deformations)

internal metric: $6 \times 7/2 = 21 = 9 + 2 \times 6$

type IIB RR 2-form: $6 \times 5/2 = 15 = 9 + 2 \times 3$

$$\text{complexification} \Rightarrow \begin{cases} \text{Kähler class} & J \\ \text{complex structure} & \tau \end{cases}$$

9 complex moduli for each

magnetic flux: 6×6 antisymmetric matrix F

complexification $\Rightarrow$

$F_{(2,0)}$ on holomorphic 2-cycles: potential for τ

$F_{(1,1)}$ on mixed (1,1)-cycles: potential for J

T^6 parametrization/complexification

$x^i \equiv x^i + 1 \quad y_i \equiv y_i + 1 \quad i = 1, 2, 3$

$z^i = x^i + \tau^{ij} y_i$

τ: 3×3 complex structure matrix

$\delta g_{i\bar{j}}$: Kähler deformations

$\rightarrow J = \delta g_{i\bar{j}} i dz_i \wedge d\bar{z}_j$

W : covering map

of the brane world-volume over T^6

$N = 1$ SUSY conditions:

1. $F_{(2,0)} = 0 \quad \Rightarrow \tau$

   $\tau^\top p_{xx} \tau - (\tau^\top p_{xy} + p_{yx}\tau) + p_{yy} = 0$

2. $J \wedge J \wedge F_{(1,1)} = F_{(1,1)} \wedge F_{(1,1)} \wedge F_{(1,1)} \quad \Rightarrow J$

   vanishing of a Fayet-Iliopoulos term

   $\xi \sim F \wedge F \wedge F - J \wedge J \wedge F$

   e.g. $T^6 = \prod_{i=1}^3 T_i^2 \leftarrow$ orthogonal 2-torus

   $\tau_i = iR_i^x / R_i^y \quad J_i = R_i^x R_i^y \quad H_i^a = F_i^a / J_i$

   $H_1 + H_2 + H_3 = H_1 H_2 H_3 \Leftrightarrow \theta_1 + \theta_2 + \theta_3 = 0$

3. $\det W(J \wedge J \wedge J - J \wedge F \wedge F) > 0$

   action positivity

Main ingredients for moduli stabilization

- “oblique” (non-commuting) magnetic fields

  $\Rightarrow$ fix off-diagonal components of the metric

  e.g. can be made diagonal

- Non linear DBI action $\Rightarrow$ fix overall volume

  not valid in six dimensions: $J \wedge F = 0$

- Kähler class RR moduli:

  absorbed by magnetized $U(1)$'s $\rightarrow$ massive

  $\Rightarrow$ need at least 9 brane stacks

Stack $\sharp$	Fluxes	Fixed moduli	$5-$brane localization
$\sharp 1$ $N_1 = 1$	$(F^1_{x_1 y_2}, F^1_{x_2 y_1}) = (1,1)$	$\tau_{31} = \tau_{32} = 0$ $\tau_{11} = \tau_{22}$ $\mathrm{Re} J_{1\bar{2}} = 0$	$[x_3, y_3]$
$\sharp 2$ $N_2 = 1$	$(F^2_{x_1 y_3}, F^2_{x_3 y_1}) = (1,1)$	$\tau_{21} = \tau_{23} = 0$ $\tau_{11} = \tau_{33}$ $\mathrm{Re} J_{1\bar{3}} = 0$	$[x_2, y_2]$
$\sharp 3$ $N_3 = 1$	$(F^3_{x_1 x_2}, F^3_{y_1 y_2}) = (1,1)$	$\tau_{13} = 0\,,\ \tau_{11}\tau_{22} = -1$ $\mathrm{Im} J_{1\bar{2}} = 0$	$[x_3, y_3]$
$\sharp 4$ $N_4 = 1$	$(F^4_{x_2 x_3}, F^4_{y_2 y_3}) = (1,1)$	$\tau_{12} = 0$ $\mathrm{Im} J_{2\bar{3}} = 0$	$[x_1, y_1]$
$\sharp 5$ $N_5 = 1$	$(F^5_{x_1 x_3}, F^5_{y_1 y_3}) = (1,1)$	$\mathrm{Im} J_{1\bar{3}} = 0$	$[x_2, y_2]$
$\sharp 6$ $N_6 = 1$	$(F^6_{x_2 y_3}, F^6_{x_3 y_2}) = (1,1)$	$\mathrm{Re} J_{2\bar{3}} = 0$	$[x_1, y_1]$

Last column: 5-brane charge localization on the 2-cycles $[x_i, y_i]$

Fix areas of the 3 T^2's $\Rightarrow$ add 3 more stacks:

Stack $\sharp$	Multiplicity	Fluxes
$\sharp 7$	$N_7 = 1$	$(F^7_{x_1y_1}, F^7_{x_2y_2}, F^7_{x_3y_3}) = (-4, -4, 3)$
$\sharp 8$	$N_8 = 2$	$(F^8_{x_1y_1}, F^8_{x_2y_2}, F^8_{x_3y_3}) = (-3, 1, 1)$
$\sharp 9$	$N_9 = 3$	$(F^9_{x_1y_1}, F^9_{x_2y_2}, F^9_{x_3y_3}) = (-2, 3, 0)$

$$\Rightarrow \begin{pmatrix} F^7_1 & F^7_2 & F^7_3 \\ F^8_1 & F^8_2 & F^8_3 \\ F^9_1 & F^9_2 & F^9_3 \end{pmatrix} \begin{pmatrix} J_2 J_3 \\ J_1 J_3 \\ J_1 J_2 \end{pmatrix} = \begin{pmatrix} F^7_1 F^7_2 F^7_3 \\ F^8_1 F^8_2 F^8_3 \\ F^9_1 F^9_2 F^9_3 \end{pmatrix}$$

here: $i = 1, 2, 3 \equiv i\bar{i}$

$$\Rightarrow \tau_{ij} = i\delta_{ij} \quad (J_{x_1y_1}, J_{x_2y_2}, J_{x_3y_3}) = 4\pi^2\alpha' \sqrt{\frac{3}{22}}(44, 66, 19)$$

- large volume:

- rescale all fluxes and all J_i $\Rightarrow$ three large T^2

  tadpole conditions remain invariant

Tadpole conditions

$Q_9 = \sum_a N_a \det W_a = 16 \leftarrow$ O9 charge

$Q_5 = \sum_a N_a \det W_a \epsilon^{\alpha\beta\gamma\delta\sigma\tau} p^a_{\gamma\delta} p^a_{\sigma\tau} = 0$

$\forall$ 2-cycle $\alpha, \beta = 1, \ldots, 6$

SUSY + tadpole conditions seem incompatible

- use 9 magnetized branes to fix all moduli

  impose SUSY conditions

- introduce an extra brane(s)

  to satisfy RR tadpole cancellation

  $\Rightarrow$ dilaton potential from the FI D-term

$\Rightarrow$ two possibilities:

• keep SUSY by turning on charged scalar VEVs

I.A.-Kumar-Maillard '06

D-term condition (2) is modified to:

$$qv^2(J\wedge J\wedge J - J\wedge F\wedge F) = -(F\wedge F\wedge F - F\wedge J\wedge J)$$

- EFT validity $\Rightarrow$ $v < 1$ in string units

- Infinite family of (large volume) solutions

invariance: $\{F_a, J\} \to \{\Lambda F_a, \Lambda J\}$ for $\Lambda \in \mathbb{N}$

• break SUSY in a dS or AdS vacuum

I.A.-Derendinger-Maillard '08

Tadpole cancellations + fix charged scalar VEVs

Stack $\sharp$	Multiplicity	Fluxes
$\sharp 7$	$N_7 = 1$	$(F^7_{x_1y_1}, F^7_{x_2y_2}, F^7_{x_3y_3}) = (-4, -4, 3)$
$\sharp 8$	$N_8 = 2$	$(F^8_{x_1y_1}, F^8_{x_2y_2}, F^8_{x_3y_3}) = (-3, 1, 1)$
$\sharp 9$	$N_9 = 3$	$(F^9_{x_1y_1}, F^9_{x_2y_2}, F^9_{x_3y_3}) = (-2, 3, 0)$
$\sharp 10$	$N_{10} = 2$	$(F^{10}_{x_1y_1}, F^{10}_{x_2y_2}, F^{10}_{x_3y_3}) = (5, 1, 2)$
$\sharp 11$	$N_{11} = 2$	$(F^{11}_{x_1y_1}, F^{11}_{x_2y_2}, F^{11}_{x_3y_3}) = (0, 4, 1)$

$$\Rightarrow \; \tau_{ij} = i\delta_{ij} \quad (J_{x_1y_1}, J_{x_2y_2}, J_{x_3y_3}) = 4\pi^2\alpha'\sqrt{\frac{3}{22}}(44, 66, 19)$$

$$v_{10}^2\alpha' \simeq \frac{0.71}{q} \simeq 0.35 \qquad v_{11}^2\alpha' \simeq \frac{0.31}{q} \simeq 0.15$$

v_{10}, v_{11}: antisymmetric reps $(q = 2) \Rightarrow$

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

D-term SUSY breaking $\Rightarrow$

problem with Majorana gaugino masses

- lowest order: exact R-symmetry

- higher orders: suppressed by the string scale

I.A.-Taylor '04, I.A.-Narain-Taylor '05

However in toroidal models:

- gauge multiplets have extended SUSY

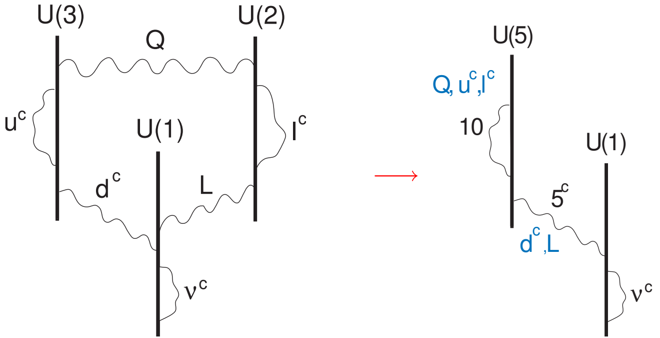
  $\Rightarrow$ Dirac gaugino masses without $\not{R}$

- non chiral intersections have $N = 2$ SUSY

  $\Rightarrow$ Higgs in $N = 2$ hypermultiplet

$\Rightarrow$ New gauge mediation mechanism

I.A.-Benakli-Delgado-Quiros '07



Full string embedding with all geometric moduli stabilized:

I.A.-Panda-Kumar '07

- all extra $U(1)$'s broken $\Rightarrow$ gauge group just susy $SU(5)$
- gauge non-singlet chiral spectrum: 3 generations of quarks + leptons
- SUSY can be broken in an extra $U(1)$ factor by D-term $\Rightarrow$

  new mechanism of gauge mediation: Dirac gauginos, $N = 2$ Higgs potential

High string scale: $M_s \sim M_{\rm GUT}$

Appropriate framework for SUSY + unification:

- intersecting branes in extra dimensions: IIA, IIB, F-theory
- internal magnetic fields in type I
- Heterotic M-theory

2 approaches: - Standard Model directly from strings

- 'orbifold' GUTs: matter in incomplete representations

Main problems: - gauge coupling unification is not automatic

different coupling for every brane stack

- extra states: vector like 'exotics' or worse

they also destroy unification in orbifold GUTs

Main steps of model building:

1. obtain MSSM spectrum and couplings
   - MSSM: part of total massless spectrum
   - 'fit' Yukawa couplings using moduli freedom (flat directions)
     that can be fixed by turning on fluxes (discrete parameters)
2. dynamical SUSY breaking in a 'hidden' sector
   $\Rightarrow$ gravity or gauge mediation to the MSSM sector

What can we learn from the LHC?

If SUSY is found use experimental data on sparticle masses and couplings to constrain classes of models/compactifications