String phenomenology

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Workshop on string theory
Kanha, India, 12-16 February 2009

1. main questions and list of possibilities
2. phenomenology of low string scale
3. extra $U(1)$'s
4. general issues of high string scale
5. string GUTs
6. framework of magnetized branes

- Are there low energy string predictions testable at LHC ?
- What can we hope from LHC on string phenomenology ?

STRINGS 2008
CERN | Geneva

18-23 August 2008

Organizers:

A. Alekseev (U Geneva)
L. Alvarez-Gaumé (CERN)
I. Antoniadis (CERN)
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http://cern.ch/strings2008/

Very different answers depending mainly on the value of the string scale M_s

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV

- physical motivations $\Rrightarrow$ favored energy regions:

- High : $\left\{ \begin{array}{ll} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\rm GUT} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{array} \right.$

- Intermediate : around 10^{11} GeV ($M_s^2/M_P \sim$ TeV)

  SUSY breaking, strong CP axion, see-saw scale

- Low : TeV (hierarchy problem)

Low string scale ⇒ experimentally testable framework

- spectacular model independent predictions

perturbative type I string setup

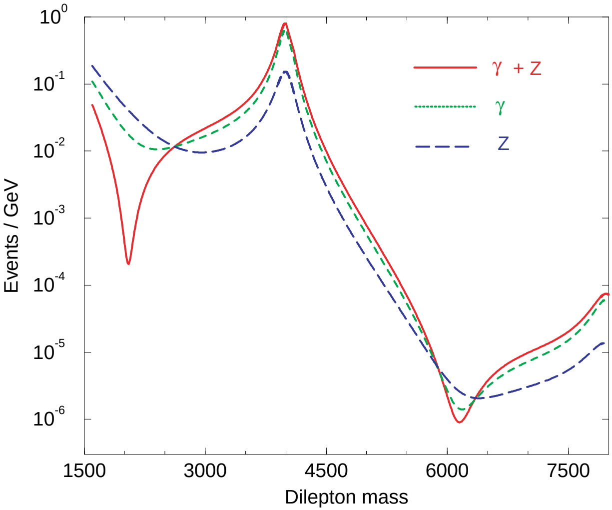
- radical change of high energy physics at the TeV scale

explicit model building is not necessary at this moment

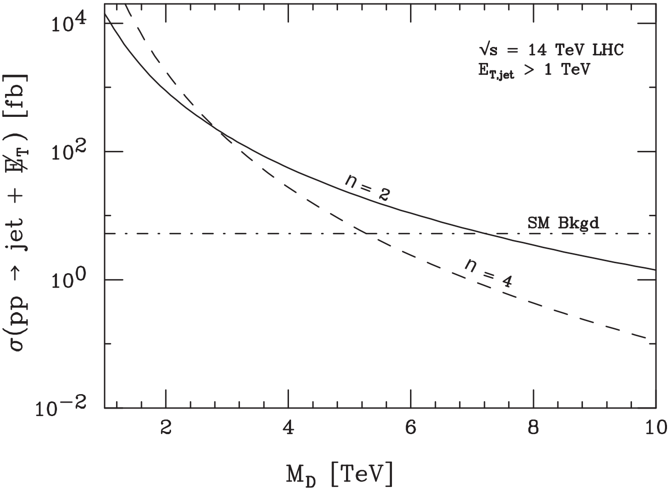
but unification has to be probably dropped

- particle accelerators
  - TeV extra dimensions ⇒ · KK resonances of SM gauge bosons
    · Extra $U(1)$'s
  - Extra large submm dimensions ⇒
    missing energy from gravity radiation in the bulk [6]
  - string physics and possible strong gravity effects :
    · string Regge excitations [7]
    · production of micro-black holes ? [12]

$R^{-1} = 4$ TeV I.A.-Benakli-Quiros '94, '99

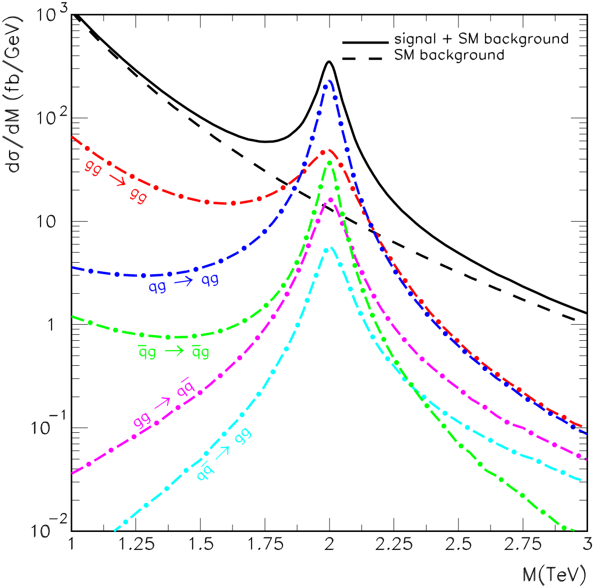


Giudice-Rattazzi-Wells '98



Angular distribution ⇒ spin of the graviton [4]

Universal deviation from Standard Model in jet distribution



$M_s = 2$ TeV

Width = 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08 [4]

Tree *N*-point superstring amplitudes in 4 dims

involving at most 2 fermions and gluons:

completely model independent for any string compactification

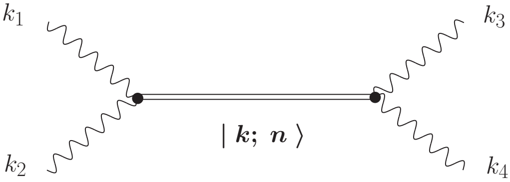
any number of supersymmetries, even none

No intermediate exchange of KK, windings or graviton emmission

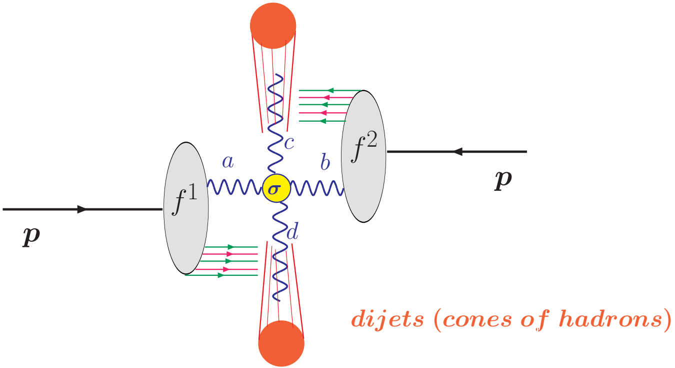
Universal sum over infinite exchange of string Regge (SR) excitations:

masses: $M_n^2 = M_s^2\, n$

maximal spin: $n + 1$



Dijet signals at LHC



dijets (cones of hadrons)

$$\boxed{\sigma(pp \to 2\ \text{jets}) = \sum_{a,b,c,d} \int dx_1\, dx_2\, f_a^1(x_1; Q^2)\, f_b^2(x_2; Q^2)\, \sigma_{ab\to cd}(\underbrace{x_1 x_2 s}_{\hat{s}}, \underbrace{Q^2}_{\hat{t}}; M_s)}$$

⇒ Look for SR excitations propagating in s–channel

Cross sections

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

model independent
for any compactification

Lüst-Stieberger-Taylor '08

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

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

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

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

In addition we need:

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

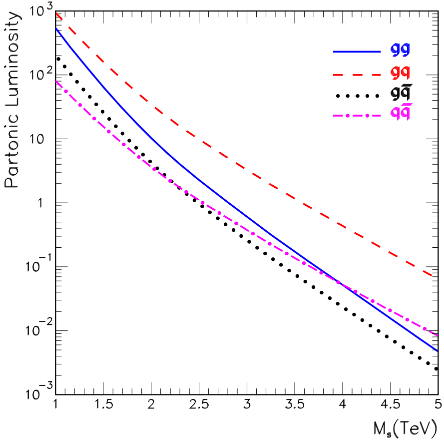
model dependent:

geometry, KK, windings

however they are suppressed:

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

[7]



Energy threshold for black hole production :

$$E_{\mathrm{BH}} \simeq M_s/g_s^2 \quad \leftarrow \text{ string coupling}$$

Horowitz-Polchinski '96, Meade-Randall '07

weakly coupled theory $\Rightarrow$

strong gravity effects occur much above M_s, $M_P^* \simeq M_s/g_s^{2/(2+d_\perp)}$

higher-dim Planck scale ↗ bulk dimensionality ↑

$g_s \simeq \alpha_{\mathrm{YM}} \sim 0.1$; Regge excitations : $M_n^2 = M_s^2 n \Rightarrow$

↖ gauge coupling

production of $n \sim 1/g_s^4 \sim 10^4$ string states before reach E_{BH}

- Newton constant: $G_N \sim g_s^2$ in string units

- string size black hole: $r_H \sim 1$

  $\Rightarrow$ black hole mass: $M_{\mathrm{BH}} \sim 1/G_N \simeq 1/g_s^2$

  $\uparrow$

  valid in any dimension d: $r_H^{d/2-1}$

- black hole entropy $S_{\mathrm{BH}} \sim 1/G_N \sim 1/g_s^2 \sim \sqrt{n}$: string entropy

- microgravity experiments

  - change of Newton's law at short distances

    detectable only in the case of two large extra dimensions

  - new short range forces

    light scalars and gauge fields if SUSY in the bulk

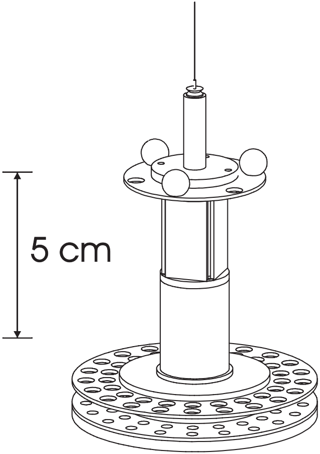
    such as radion and lepton number

    volume suppressed mass: $(\mathrm{TeV})^2/M_P \sim 10^{-4}$ eV → mm range

    can be experimentally tested for any number $d_\perp$ [16]

    of submm extra dimensions

Adelberger et al. '06

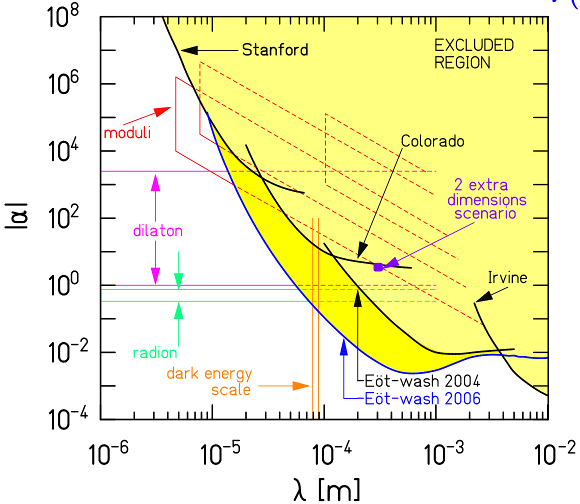


$R_\perp \lesssim 45\ \mu$m at 95% CL

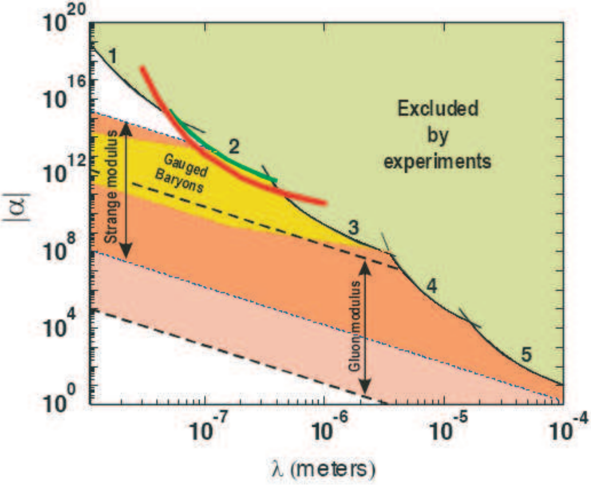
- dark-energy length scale $\approx 85\mu$m

Experimental limits on short distance forces

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

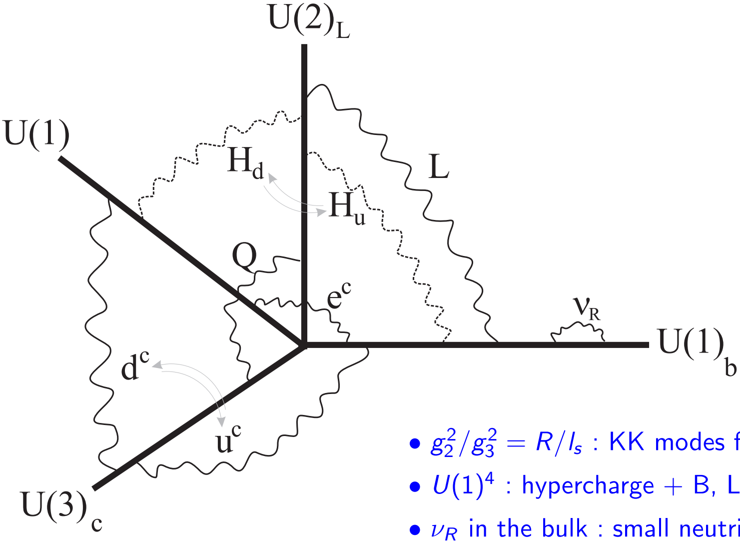


Radion : $M_P^* \gtrsim 6$ TeV   95% CL   Adelberger et al. '06 an order of magnitude improvement in the range 10-200 nm Decca et al '07



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

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 [32]

- $U(1)$ on top of $U(2)$ or $U(3)$ ⇒ prediction for $\sin^2\theta_W$

Extra $U(1)$'s: $SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_X$

- SM fermions charged under $X \Rightarrow$ new resonances
- SM fermions neutral under X $\Rightarrow U(1)_X$ hidden

  unless new heavy fermions f with mixed quantum numbers

  Consider the case: fermion mass $M_f >> M_X$

  decoupling $\Rightarrow$ X-production suppressed by powers of E/M_f

  exception: if there are mixed anomalies

$$U(1)_X \text{ - SM - SM} \quad , \quad U(1)_X \text{ - } U(1)_X \text{ - } U(1)_Y$$

1) fermions f vector-like with respect to SM but chiral w.r.t. $U(1)_X \Rightarrow$

Green-Scwarz anomaly cancellation: axion θ_X $\delta X = d\Lambda$ $\delta\theta_X = -M\Lambda$

$$-\frac{1}{4g_X^2}F_X^2 - \frac{1}{2}(d\theta_X + MX)^2 + \frac{\theta_X}{M}k_I F_I \wedge F_I \qquad M_X = g_X M$$

axion coupling + 1-loop anomaly $\Rightarrow 1/M_f^2$ suppression

2) avoid mass suppression: non-trivial anomaly cancellation

D'Hoker-Farhi terms: two sets of heavy fermions $f = \{\psi, \chi\}$

ψ : vector-like w.r.t. SM but chiral w.r.t. $U(1)_X$

χ : chiral w.r.t. SM but vector-like w.r.t. $U(1)_X$

$\Rightarrow$ dim-4 effective interaction : $D\theta_X \wedge D\theta_I \wedge F_I$

I.A-Boyarsky-Rucharsky '06, '07: $I \equiv \gamma, U(1)_X \equiv \mathrm{PQ}$, $M_X \sim$ subeV

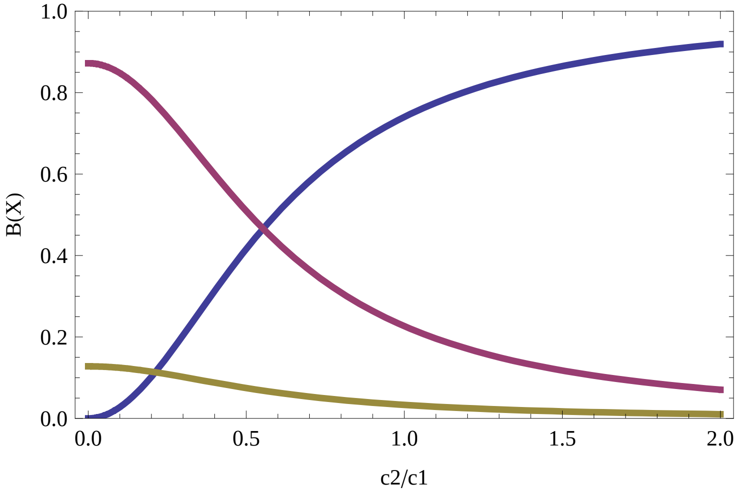
$$\theta_I \equiv \text{SM Higgs} \;\Rightarrow\; \mathcal{L}_{\text{eff}} = c_1 D\theta_X \frac{H^\dagger DH}{|H|^2} F_Y + c_2 D\theta_X \frac{HF_W DH^\dagger}{|H|^2}$$

$c_2 \rightarrow XW^+W^-$ $\quad$ $c_1 \rightarrow XZY$ $\quad$ $(XZ\gamma, XZZ)$ $\quad$ vertices

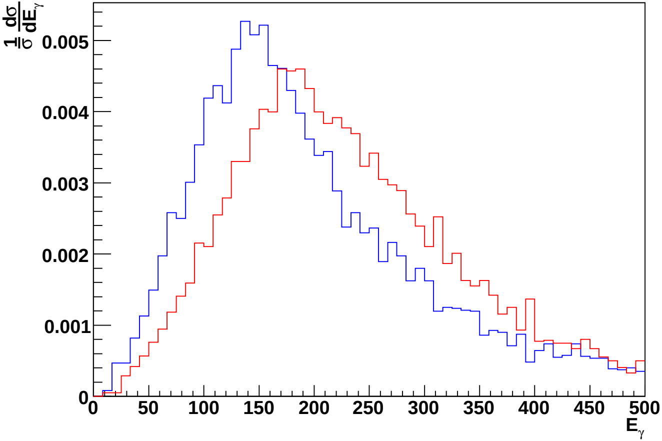
interesting LHC signatures : 3 vector boson final state (even $WZ\gamma$)

I.A-Boyarsky-Espahbodi-Rucharsky-Wells '09

Branching ratios: $X \to WW$, $X \to \gamma Z$, $X \to ZZ$



Photon E_T distribution for X = vector versus X = scalar



$$pp \to WX \qquad X \to Z\gamma$$

Intermediate string scale :

not directly testable but interesting possibility with several implications

→ 'large volume' compactifications

High string scale :

perturbative heterotic string : the most natural for SUSY and unification

prediction for GUT scale but off by almost 2 orders of magnitude

$M_s = g_H\, M_P \simeq 50\, M_{\rm GUT} \qquad g_H^2 \simeq \alpha_{\rm GUT} \simeq 1/25$

introduce large threshold corrections or strong coupling $\rightarrow\ M_s \simeq M_{\rm GUT}$

but loose predictivity

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

Appropriate framework for SUSY + unification:

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

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
   ⇒ 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

- different input for each step ⇒ predictivity is highly reduced

Maximal predictive power if there is common framework for :

- moduli stabilization
- model building (spectrum and couplings)
- SUSY breaking (calculable soft terms)
- computable radiative corrections (crucial for comparing models)

Possible candidate of such a framework: **magnetized branes** [37]

string inspired vs string derived

inspired: impose general constraints from a particular string framework

→ phenomenological analysis

e.g. heterotic (KM level-1): no adjoints ⇒

flipped $SU(5)$, Pati-Salam, orbifold GUTs, etc

intersecting branes, F-theory: 'local' models (decoupled gravity)

derived: 'complete' models taking into account global/string constraints

e.g. heterotic: modular invariance

type IIA/B orientifolds: tadpole cancellation

string inspired/local models

advantages: simplicity, Field-theory framework

disadvantages: miss (important) consequences of the global constraints

- not every local → global e.g. swampland
- no information on the hidden sector
- do not address moduli stabilization ⇒ predictivity is weak
- no control on extra states:
  - chiral or non-chiral exotics, fractional electric charges, extra $U(1)$'s
  - conditions for dynamical SUSY breaking: gravity or gauge mediation?
- cannot do precise computations:
  - couplings, thresholds, radiative corrections

→ examples [36]

Heterotic models revived: Orbifold GUTs

string constructions based on $Z'_6 = Z_3 \times Z_2$ orbifold

groups in Munich, Bonn, Hamburg, Ohio, U Penn

- GUT breaking to SM by discrete Wilson lines

  on non-contractible cycles
- 2 'large' dimensions $\Rightarrow M_{\mathrm{GUT}} =$ compactification scale

  solve GUT scale problem: need universal thresholds above M_{GUT}
- local GUTs: $SO(10)$ or $SU(5)$ unbroken in one (or two) fixed points

  $\Rightarrow$ lightest generation(s) in complete GUT multiplet(s)
- $U(1)_{B-L} \to$ matter parity $\Rightarrow$ EW Higgs identification
- Higgs from untwisted sector $\Rightarrow$ gauge-Higgs unification

  $\lambda_{\mathrm{top}} = g_{\mathrm{GUT}} \Rightarrow m_{\mathrm{top}} \sim$ IR fixed point $\simeq$ 170 GeV

- Yukawa couplings: hierarchies à le Froggatt-Nielsen

  discrete symmetries $\Rightarrow$ couplings allowed with powers of a singlet field

  $\lambda_n \sim \Phi^n \qquad \langle\Phi\rangle \sim 0.1\, M_s \rightarrow$ hierarchies

  A single anomalous $U(1) \Rightarrow \langle\Phi\rangle \neq 0$ to cancel the FI D-term

- R-neutrinos: natural framework for see-saw mechanism

  $\langle h\rangle\nu_L\nu_R + M\nu_R\nu_R \qquad \langle h\rangle = v << M \Rightarrow m_R \sim M\, ;\, m_L \sim v^2/M$

- proton decay: problematic dim-5 operators

  in general need suppression higher than M_s or small couplings

- SUSY breaking in a hidden sector from the other E_8

  → gravity mediation

Intersecting branes: 'perfect' for SM embedding

gauge group and representations but no unification

→ hypercharge normalization

GUTs: problematic

- no perturbative $SO(10)$ spinors
- no top-quark Yukawa coupling in $SU(5)$: $10\,10\,5_H$

  $SU(5)$ is part of $U(5) \Rightarrow U(1)$ charges : 10 charge 2 ; 5_H charge ± 1

  $\Rightarrow$ cannot balance charges with $SU(5)$ singlets

  can be generated by D-brane instantons but ...
- no Majorana neutrino masses

  same reason but instantons can do

  or alternatively generate exp suppressed Dirac masses

Minimal Standard Model embedding

General analysis using 3 brane stacks [18]

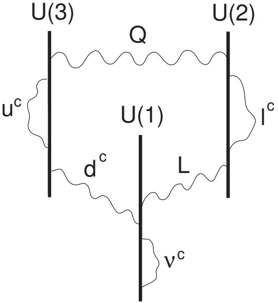
$$\Rightarrow \; U(3) \times U(2) \times U(1)$$

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

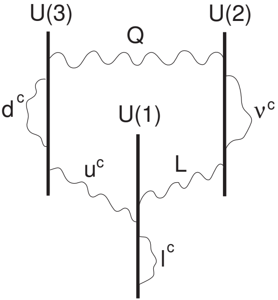
antisymmetric of $U(3)$ or bifundamental $U(3) \leftrightarrow U(1)$

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

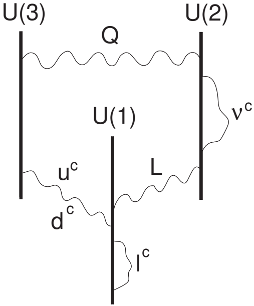
I.A.-Dimopoulos '04



Model A



Model B



Model C

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

$$Y_{B,C} = \frac{1}{6}Q_3 - \frac{1}{2}Q_1$$

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

$$\left.\frac{1}{1+\alpha_2/2\alpha_1+\alpha_2/6\alpha_3}\right|_{\alpha_2=\alpha_3} = \frac{6}{7+3\alpha_2/\alpha_1}$$

F-theory GUTs

$N = 1$ SUSY $\Rrightarrow$ elliptically fibered CY 4-fold with (p, q) 7-branes

located at 4-cycles where the type IIB complex dilaton degenerates

→ monodromy under $SL(2, Z)$ S-duality

unlike D7-branes, they are mutually non-local $\Rrightarrow$ $U(N), SO(2N), E_N$

selection criterium (for calculability): local models decoupled from gravity

Donagi-Wijnholt, Beasley-Heckman-Vafa '08

$V_6 \to \infty$: g_s strong but $\alpha_{\rm GUT}$ finite and small $\sim 1/25$

or equivalently for fixed V_6: contractible 4-cycles wrapped by the 7-branes

$\Rrightarrow$ del Pezzo manifolds dP_n with $n = 0, \dots, 8$ (also $S^2 \times S^2$)

→ $SU(5)$ or $SO(10)$ SUSY GUTs

Construction rules and some of the main properties

- one 7-brane stack on a 4-cycle determines the GUT group

  other 'matter' 7-branes are also needed

- pairs of 4-cycles intersect on 2-cycles:

  Riemann surfaces associated to chiral matter

- three 2-cycles can intersect at points → Yukawa couplings

$\Rightarrow$ gauge fields in 8 dims, matter in 6 dims, Yukawa interactions in 4 dims

- no non-contractible cycles $\Rightarrow$ no Wilson lines

  $SU(5)$ breaking to SM by $U(1)_Y$ flux

- can have complete or incomplete $SU(5)$ representations

  families: complete, Higgs: incomplete $\Rightarrow$ doublet-triplet splitting

- Yukawa couplings: $\lambda_t \sim \mathcal{O}(1)$, others suppressed by powers of $\alpha_{\rm GUT}$

  Froggatt-Nielsen without dynamical singlet

Open questions

- weakness of all local models [28]
- can one decouple gravity? $M_{\mathrm{GUT}}/M_{\mathrm{SUGRA}} \simeq 1/50$

  certainly valid condition for low string scale!
- $U(1)_Y$ flux seems to destroy unification

  $\mathcal{O}(1)$ contribution to α_1, α_2 but not α_3 R. Blumenhagen '08
- type IIB orientifold limit: non-trivial global constraints
- SUSY breaking must be gauge mediated but not guaranteed [26]

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

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

  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: $\Rightarrow$ calculability

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

- T-dual representation: branes at angles $\Rightarrow$ model building

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

Magnetic fluxes can be used to stabilize moduli

I.A.-Maillard ’04, I.A.-Kumar-Maillard ’05, ’06, Bianchi-Trevigne ‘05

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

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

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

$$\text{complexification:} \begin{cases} \text{Kähler class} & J \\ \text{complex structure} & \tau \end{cases} \quad \text{9 complex moduli for each}$$

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

$N = 1$ SUSY conditions $\Rightarrow$ moduli stabilization

1. $F_{(2,0)} = 0 \;\Rightarrow \tau$ matrix equation for every magnetized $U(1)$

   need 'oblique' (non-commuting) magnetic fields to fix off-diagonal components of the metric ← but can be made diagonal

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

   vanishing of a Fayet-Iliopoulos term: $\xi \sim F \wedge F \wedge F - J \wedge J \wedge F$

   magnetized $U(1) \rightarrow$ massive absorbs RR axion

   one condition $\Rightarrow$ need at least 9 brane stacks

3. Tadpole cancellation conditions : introduce an extra brane(s)

   $\Rightarrow$ dilaton potential from the FI D-term $\rightarrow$ two possibilities:

   - keep SUSY by turning on charged scalar VEVs
   - break SUSY in a dS or AdS vacuum $d = \xi/\sqrt{1+\xi^2}$ [41]

I.A.-Derendinger-Maillard '08

$$F_{(2,0)} = 0 \;\Rightarrow \qquad \tau^{\mathrm{T}} p_{xx} \tau - (\tau^{\mathrm{T}} p_{xy} + p_{yx} \tau) + p_{yy} = 0$$

Non-trivial VEVs v for charged brane scalars ⇒

D-term condition is modified to:

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

New gauge mediation mechanism

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

D-term SUSY breaking:

- problem with Majorana gaugino masses   lowest order R-symmetry broken at higher orders but suppressed by the string scale

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

- tachyonic squark masses

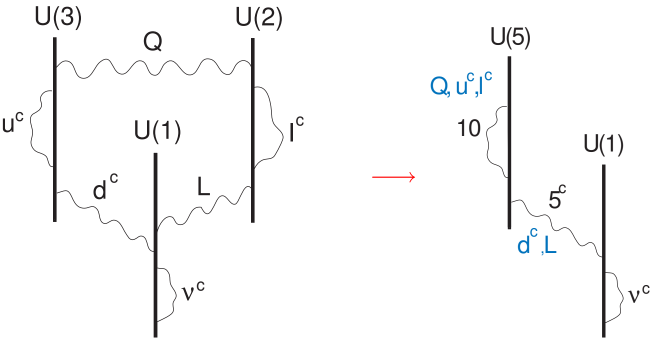
However in toroidal models gauge multiplets have extended SUSY $\Rightarrow$

Dirac gauginos without $\not{R}$ $\Rightarrow$ $m_{1/2} \sim d/M$; $m_0^2 \sim d^2/M^2$ from gauginos

Also non-chiral intersections have $N = 2$ SUSY $\Rightarrow$ $N = 2$ Higgs potential

Model building

I.A.-Panda-Kumar '07



Full string embedding with all geometric moduli stabilized:

- 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