Aspects of string phenomenology

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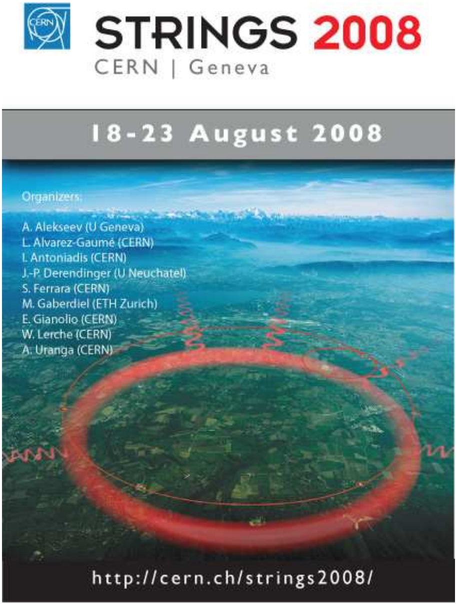
1. main questions and list of possibilities
2. phenomenology of low string scale
3. general issues of high string scale
4. string GUTs
5. framework of magnetized branes

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



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 : $\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\mathrm{GUT}} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$
- 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

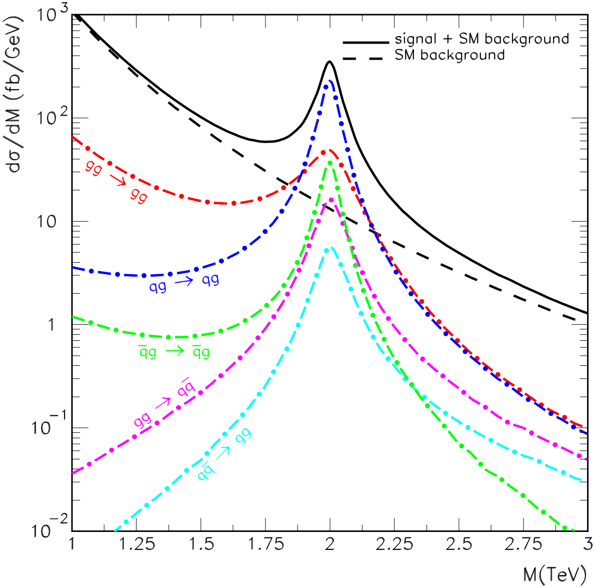
- radical change of high energy physics at the TeV scale

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 large submm dimensions ⇒ missing energy: gravity radiation
  - string physics and possible strong gravity effects :
    - · string Regge excitations
    - · production of micro-black holes ? [9]
- microgravity experiments
  - change of Newton's law, new forces at short distances

Universal deviation from Standard Model in jet distribution



$M_s = 2$ TeV

Width = 15-150 GeV

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

Tree N-point superstring amplitudes in 4 dims

involving at most 2 fermions and gluons:

completely model independent for any string compactification

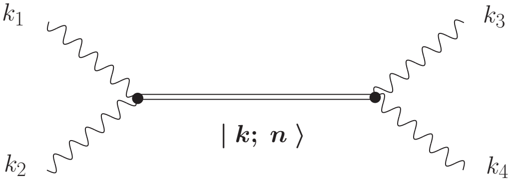
any number of supersymmetries, even none

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: $n + 1$



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

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

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

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

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

In addition we need:

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

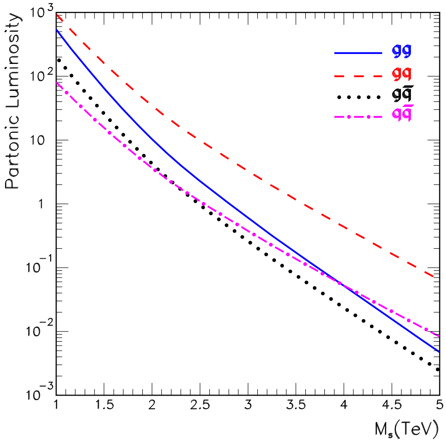
model dependent:

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

[5]



Energy threshold for black hole production :

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

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

$g_s \simeq \alpha_{\rm YM} \sim 0.1$; 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 $E_{\rm BH}$

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

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

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

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

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

Intermediate string scale :

not directly testable but interesting possibility with several implications

$\rightarrow$ '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

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** [23]

From string inspired to string derived

inspired: impose general constraints from a particular string framework

$\rightarrow$ phenomenological analysis

e.g. heterotic (KM level-1): no adjoints, extra $U(1)$'s, $\ldots \Rightarrow$

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

local: $V_6, M_p \rightarrow \infty$, gauge couplings fixed (decoupled gravity)

$\rightarrow$ only a few local constraints (anomaly cancellation)

e.g. intersecting branes at singularities, F-theory GUTs

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 $\rightarrow$ global e.g. swampland
- no information on the hidden sector
- do not address moduli stabilization $\Rrightarrow$ 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 [22]

$\rightarrow$ examples: Heterotic orbifold GUTs, Intersecting branes, F-theory GUTs

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 $\Rightarrow M_{\rm GUT}$ = compactification scale

  solve GUT scale problem: need universal thresholds above $M_{\rm GUT}$

- Higgs from untwisted sector $\Rightarrow$ gauge-Higgs unification

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

- Yukawa couplings: hierarchies à le Froggatt-Nielsen

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

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

  $\to$ gravity mediation

Intersecting branes: ‘perfect’ for SM embedding

gauge group and representations but no unification

$\longrightarrow$ hypercharge normalization

GUTs: problematic

- no perturvative $SO(10)$ spinors
- no top-quark Yukawa coupling in $SU(5)$: $\mathbf{10}\,\mathbf{10}\,\mathbf{5}_H$

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

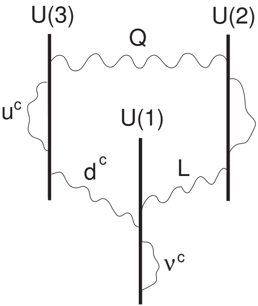
$$\Rightarrow \; U(3) \times U(2) \times U(1)$$

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

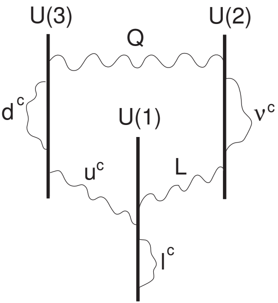
antisymmetric of $U(3)$ or bifundamental $U(3) \leftrightarrow U(1)$

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

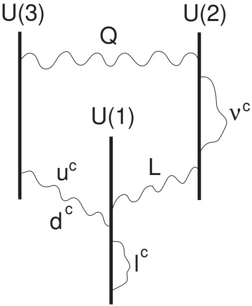
I.A.-Dimopoulos '04



Model A



Model B



Model C

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

$$\sin^2\theta_W = \left.\frac{1}{2 + 2\alpha_2/3\alpha_3}\right|_{\alpha_2=\alpha_3} = \frac{3}{8} \qquad \left.\frac{1}{1 + \alpha_2/2\alpha_1 + \alpha_2/6\alpha_3}\right|_{\alpha_2=\alpha_3} = \frac{6}{7 + 3\alpha_2/\alpha_1}$$

F-theory GUTs

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

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

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

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

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

$\to SU(5)$ or $SO(10)$ SUSY GUTs

Main properties and open questions

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

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

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

  Froggatt-Nielsen without dynamical singlet

- SUSY breaking must be gauge mediated but not guaranteed

  - weakness of all local models [15]
  - 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 [13]

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

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

  $qH \to \theta = \arctan qH\alpha'$ 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 $\leftarrow$ 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 $d = \xi/\sqrt{1+\xi^2}$

I.A.-Derendinger-Maillard '08

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

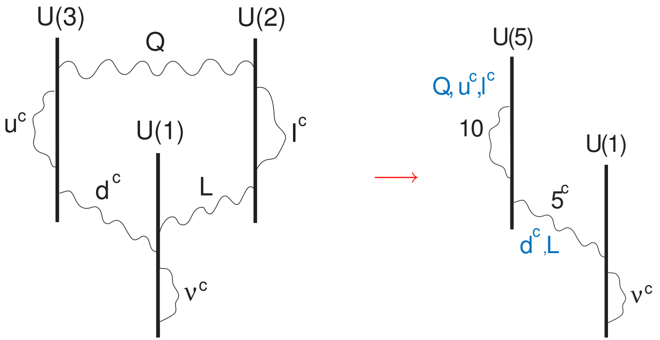
- tachyonic squark masses

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

 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