Aspects of string phenomenology in the LHC era

I. Antoniadis

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- High string scale, SUSY and 125 GeV Higgs
- Low scale strings and extra dimensions
- Extra $U(1)$'s
- Tiny string coupling and linear dilaton background
Connect string theory to the real world:

**What is the value of the string scale \( M_s \)?**

- arbitrary parameter: Planck mass \( M_P \rightarrow \) TeV

- physical motivations \( \Rightarrow \) favored energy regions:

  - **High**: \( M_P^* \approx 10^{18} \text{ GeV} \) \( M_{\text{GUT}} \approx 10^{16} \text{ GeV} \)
    - Heterotic scale
    - Unification scale

  - **Intermediate**: around \( 10^{11} \text{ GeV} \) \( (M_s^2/M_P \sim \text{TeV}) \)
    - SUSY breaking, strong CP axion, see-saw scale

  - **Low**: TeV \( (\text{hierarchy problem}) \)
Beyond the Standard Model of Particle Physics: 
driven by the mass hierarchy problem

Standard picture: low energy supersymmetry

Natural framework: Heterotic string (or high-scale M/F) theory

Advantages:
- natural elementary scalars
- gauge coupling unification
- LSP: natural dark matter candidate
- radiative EWSB

Problems:
- too many parameters: soft breaking terms
- MSSM: already a % - %₀ fine-tuning  ‘little’ hierarchy problem
CMS Total Integrated Luminosity, p-p

- 2010, $\sqrt{s} = 7$ TeV
- 2011, $\sqrt{s} = 7$ TeV
- 2012, $\sqrt{s} = 8$ TeV

Time in year

Total Integrated Luminosity (fb$^{-1}$)
$m_H = 126 \pm 0.4 \, \text{(stat.)} \pm 0.4 \, \text{(syst.)}$

$5.9 \, \sigma$

$m_H = 125.3 \pm 0.4 \pm 0.5 \, \text{GeV}$

$5 \, \sigma \, \text{significance}$
some remarks

Higgs-like particle discovery around 125 GeV:

- consistent with expectation from precision tests of the SM
- favors perturbative physics quartic coupling $\lambda = \frac{m_H^2}{v^2} \approx 1/8$

If confirmed:

- supersymmetry becomes ‘severely’ fine-tuned, in its minimal version
- but still early to draw a general conclusion before LHC13/14
  an extra singlet or split families can remediate the fine tuning to $\lesssim 10$
- very important to measure Higgs couplings $^{[8]}$
  any deviation of its couplings to top, bottom and EW gauge bosons
  implies new light states involved in the EWSB altering the fine-tuning
Δα_{had}^{(5)} = 0.02761 ± 0.00036
Couplings of the new boson vs SM Higgs

Agreement with Standard Model Higgs expectation at 1.5 $\sigma$
ATLAS SUSY Searches* - 95% CL Lower Limits (Status: ICHEP 2012)

\[ \int L dt = (0.03 - 4.8) \, fb^{-1} \]
\[ \sqrt{s} = 7 \, TeV \]

**ATLAS Preliminary**

Only a selection of the available mass limits on new states or phenomena shown.
Can the SM be valid at high energies?

Instability of the SM Higgs potential $\Rightarrow$ metastability of the EW vacuum
Dropping the hierarchy motivation...

Next scale of new physics at $M_I \sim 10^{11}$ GeV?

- Dark Matter $\rightarrow$ could be an axion
- Unification $\rightarrow$ perhaps different realization
- What could be the physics at $M_I$? $\rightarrow$ susy, string scale, ...
If the weak scale is tuned $\Rightarrow$ split supersymmetry is a possibility

Arkani Hamed-Dimopoulos '04, Giudice-Romaninio '04

- natural splitting: gauginos, higgsinos carry R-symmetry, scalars do not
- main good properties of SUSY are maintained
  - gauge coupling unification and dark matter candidate
- also no dangerous FCNC, CP violation, . . .
- experimentally allowed Higgs mass $\Rightarrow$ 'moderate' split

$m_S \sim \text{few - thousands TeV}$

gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)

- natural string framework: intersecting (or magnetized) branes

IA-Dimopoulos '04

D-brane stacks are supersymmetric with massless gauginos

intersections have chiral fermions with broken SUSY & massive scalars
Predicted range for the Higgs mass

- Split SUSY
- High-Scale SUSY
- Experimentally favored

Higgs mass $m_h$ in GeV vs. Supersymmetry breaking scale in GeV

- $\tan\beta = 50$
- $\tan\beta = 4$
- $\tan\beta = 2$
- $\tan\beta = 1$
Alternative answer: Low UV cutoff $\Lambda \sim \text{TeV}$

- low scale gravity $\Rightarrow$ extra dimensions: large flat or warped
- low string scale $\Rightarrow$ low scale gravity, ultra weak string coupling

Experimentally testable framework:

- spectacular model independent predictions
- radical change of high energy physics at the TeV scale

Moreover no little hierarchy problem:

radiative electroweak symmetry breaking with no logs

$\Lambda \sim \text{a few TeV}$ and $m_H^2 = \text{a loop factor} \times \Lambda^2$ \cite{17}

But unification has to be probably dropped

New Dark Matter candidates e.g. in the extra dims
Framework of type I string theory $\Rightarrow$ D-brane world

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

- gravity: closed strings propagating in 10 dims
- gauge interactions: open strings with their ends attached on D-branes

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

Calculability $\Rightarrow R_{||} \simeq l_{\text{string}}$; $R_{\perp}$ arbitrary

\[
M_P^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_{\perp}^n
\]

$g_s = \alpha$: weak string coupling

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

\[
M_s \sim 1 \text{ TeV} \Rightarrow R_{\perp}^n = 10^{32} l_s^n \quad [33]
\]

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

\[
R_{\perp} \sim .1 - 10^{-13} \text{ mm for } n = 2 - 6
\]

distances $< R_{\perp}$: gravity $(4+n)$-dim $\rightarrow$ strong at $10^{-16} \text{ cm}$
Origin of EW symmetry breaking?

possible answer: radiative breaking

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

$$\mu^2 = 0 \text{ at tree but becomes } < 0 \text{ at one loop}$$

non-susy vacuum

simplest case: one scalar doublet from the same brane

$$\Rightarrow \text{tree-level } V \text{ same as susy: } \lambda = \frac{1}{8}(g_2^2 + g'^2)$$

D-terms

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

$$\varepsilon^2(R) = \frac{R^3}{2\pi^2} \int_0^\infty d\ell^{3/2} \frac{\theta_2^4}{16\ell^4\eta^{12}} \left( i\ell + \frac{1}{2} \right) \sum_n n^2 e^{-2\pi n^2 R^2\ell}$$
$R \rightarrow 0 : \varepsilon(R) \approx 0.14$ \quad large \ transverse \ dim \quad R_\perp = l_s^2/R \rightarrow \infty$

$R \rightarrow \infty : \varepsilon(R)M_s \sim \varepsilon_\infty/R \quad \varepsilon_\infty \approx 0.008$ \quad UV \ cutoff: \quad M_s \rightarrow 1/R$

Higgs scalar = component of a higher dimensional gauge field

$\Rightarrow \varepsilon_\infty$ calculable in the effective field theory
Quartic coupling $\Rightarrow$ mass prediction:

- tree level: $M_H = M_Z$

- low-energy SM radiative corrections (from top quark): $M_H \sim 120$ GeV

  Casas-Espinosa-Quiros-Riotto, Carena-Espinosa-Quiros-Wagner ’95

Increasing $\lambda \rightarrow g^2/4 \sim 1/8 \Rightarrow M_H \sim v/2 = 125$ GeV

Also $M_s$ or $1/R \sim$ a few or several TeV
Gravitational radiation in the bulk $\Rightarrow$ missing energy

Angular distribution $\Rightarrow$ spin of the graviton

<table>
<thead>
<tr>
<th>Collider bounds on $R_\perp$ in mm</th>
<th>$n = 2$</th>
<th>$n = 4$</th>
<th>$n = 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP 2</td>
<td>$4.8 \times 10^{-1}$</td>
<td>$1.9 \times 10^{-8}$</td>
<td>$6.8 \times 10^{-11}$</td>
</tr>
<tr>
<td>Tevatron</td>
<td>$5.5 \times 10^{-1}$</td>
<td>$1.4 \times 10^{-8}$</td>
<td>$4.1 \times 10^{-11}$</td>
</tr>
<tr>
<td>LHC</td>
<td>$4.5 \times 10^{-3}$</td>
<td>$5.6 \times 10^{-10}$</td>
<td>$2.7 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

present LHC bounds: $M_\star \gtrsim 2.5 - 4$ TeV
Micro-black hole production?

String-size black hole energy threshold: $M_{\text{BH}} \sim M_s/g_s^2$

Horowitz-Polchinski '96, Meade-Randall '07

weakly coupled theory $\Rightarrow$ strong gravity effects occur much above $M_s$, $M_*$

$g_s \sim 0.1$ (gauge coupling) $\Rightarrow$ $M_{\text{BH}} \sim 100M_s$

Comparison with Regge excitations: $M_j = M_s \sqrt{j}$ $\Rightarrow$

production of $j \sim 1/g_s^4 \sim 10^4$ string states before reach $M_{\text{BH}}$
Other accelerator signatures: 3 different scales

- string physics
  
  Massive string vibrations ⇒ e.g. resonances in dijet distribution

  \[ M_j^2 = M_0^2 + M_s^2 j \quad ; \quad \text{maximal spin: } j + 1 \]

  higher spin excitations of quarks and gluons with strong interactions

- Large TeV dimensions seen by SM gauge interactions

  ⇒ KK resonances of SM gauge bosons

  \[ M_k^2 = M_0^2 + \frac{k^2}{R^2} \quad ; \quad k = \pm 1, \pm 2, \ldots \quad R = V_1^{1/d} \quad ; \quad g^2 = 1/(V_1 M_s^{d}) \]

  experimental limits: \( R^{-1} \gtrsim 0.5 - 4 \text{ TeV} \) (UED - localized fermions)

- extra \( U(1)'s \) and anomaly induced terms

  masses suppressed by a loop factor from \( M_s \) \(^{[24]}\)
Universal deviation from Standard Model in dijet distribution

$M_s = 2$ TeV

Width $= 15-150$ GeV

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

present LHC limits: $M_s \gtrsim 4.5$ TeV
Extra $U(1)$’s and anomaly induced terms

masses suppressed by a loop factor

usually associated to known global symmetries of the SM

(anomalous or not) such as (combinations of)

Baryon and Lepton number, or PQ symmetry

Two kinds of massive $U(1)$’s: I.A.-Kiritsis-Rizos ’02

- 4d anomalous $U(1)$’s: $M_A \simeq g_A M_s$

- 4d non-anomalous $U(1)$’s: (but masses related to 6d anomalies)

$$M_{NA} \simeq g_A M_s V_2 \leftarrow (6d\to4d)\text{ internal space} \quad \Rightarrow M_{NA} \geq M_A$$

or massless in the absence of such anomalies
Standard Model on D-branes: $\text{SM}^{++}$

$\text{Sp}(1) \equiv SU(2)$

$U(1)_L$ (Leptonic)

$U(1)_R$, $D_R$ (Baryonic)

1-Right

U(3)

2-Left

Q_L

W

gluon

$SU(2)$ global

$I. \text{ Antoniadis} \ (\text{CERN})$
$B$ and $L$ become massive due to anomalies

Green-Schwarz terms

the global symmetries remain in perturbation

- Baryon number $\Rightarrow$ proton stability
- Lepton number $\Rightarrow$ protect small neutrino masses

no Lepton number $\Rightarrow$ \( \frac{1}{M_s} LLHH \rightarrow \text{Majorana mass: } \frac{\langle H \rangle^2}{M_s} LL \sim \text{GeV} \)

$B, L \Rightarrow$ extra $Z'$s

with possible leptophobic couplings leading to CDF-type $Wjj$ events

$Z' \sim B$ lighter than 4d anomaly free $Z'' \sim B - L$
$Z' \simeq B$ anomalous and superheavy

$Z'' \simeq B - L$ massless at the string scale (no associated 6d anomaly)

but broken at TeV by a Higgs VEV with the quantum numbers of $N_R$

$L$-violation from higher-dim operators suppressed by the string scale

$U(3)$ unification, $Y$ combination $\Rightarrow$ 2 parameters: 1 coupling $+ m_{Z''}$

perturbativity $\Rightarrow 0.5 \lesssim g_{U(1)_R} \lesssim 1$

present LHC limits: $m_{Z''} \gtrsim 3 - 4$ TeV (for $Z'' \simeq B - L$ or $U(1)_R$)

interesting LHC phenomenology and cosmology
Rotation of $U(1)$’s from the string to low energy basis $Y, Y', Y''$: completely fixed in terms of the couplings

- Decoupling of anomalous $Y'$
- $Y''$ linear combination of $B - L$ and $U(1)_R$

LHC14 discovery potential: $M_{Z''}$ up to $\sim 5$ TeV

Recent cosmological observations indicate an extra relativistic component dark radiation parametrized by an effective neutrino number close to 4 → use the 3 $\nu_R$’s interacting with SM fermions via $Z''$

data: their decoupling during the quark-hadron transition

$$3.5 \lesssim M_{Z''} \lesssim 7 \text{ TeV}$$
The diagram shows the relationship between $g'_1(M_s)$ and BR $Z''$ for the $U(1)_R$ and $B - L$ sectors. The axes are labeled as follows:

- **Y-axis (Vertical):** BR $Z''$
- **X-axis (Horizontal):** $g'_1(M_s)$

The curves indicate the behavior of BR $Z''$ as $g'_1(M_s)$ varies, with distinct patterns for each sector.
Stability analysis in (non-susy) SM$^{++}$

Scalar potential:

\[ V(H, H'') = \mu^2 |H|^2 + \mu'^2 |H''|^2 + \lambda_1 |H|^4 + \lambda_2 |H''|^4 + \lambda_3 |H|^2 |H''|^2 \]

5 parameters $\Rightarrow v, m_h, v'', m_{h''} +$ a Higgs mixing angle $\alpha$

$\Rightarrow$ 3 free parameters : $m_{h''}, \alpha, v'' \leftrightarrow M_{Z''}$

Stability conditions: $\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_1 \lambda_2 > \frac{1}{4} \lambda_3^2$

RGE analysis up to $M_s \Rightarrow$ stability is possible in SM$^{++}$

for $0.05 \lesssim \alpha \lesssim 0.35$ and $500 \text{ GeV} \lesssim m_{h''} \lesssim 5 \text{ TeV}$
$M_{Z''} = 4.5$ TeV; $M_s = 10^{14}, 10^{16}, 10^{19}$ GeV
\( M_s = 10^{16} \) GeV; \( M_{Z''} = 6, 4.5, 3.5 \) TeV
More general framework: large number of species

\( N \) particle species \( \Rightarrow \) lower quantum gravity scale: \( M_*^2 = \frac{M_p^2}{N} \)

Dvali ’07, Dvali, Redi, Brustein, Veneziano, Gomez, Lüst ’07-’10
derivation from: black hole evaporation or quantum information storage

\( M_* \simeq 1 \text{ TeV} \Rightarrow N \sim 10^{32} \) particle species!

2 ways to realize it lowering the string scale

1. Large extra dimensions \( \text{SM on D-branes} \) [16]

\[ N = R^n \perp l^n_s : \text{number of KK modes up to energies of order } M_* \simeq M_s \]

2. Effective number of string modes contributing to the BH bound

\[ N = \frac{1}{g_s^2} \text{ with } g_s \simeq 10^{-16} \text{ SM on NS5-branes} \]

I.A.-Pioline ’99, I.A.-Dimopoulos-Giveon ’01
Gauge/Gravity duality \( \Rightarrow \) toy 5d bulk model

Gravity background: near horizon geometry (holography) \( \rightarrow \) Maldacena '98

Analogy from D3-branes: \( AdS_5 \)

NS-5 branes: \( (M_6 \otimes \mathbb{R}_+) \uparrow \)

linear dilaton background in 5d flat string-frame metric \( \Phi = -\alpha |y| \)

Aharony-Berkooz-Kutasov-Seiberg '98

"cut" the space of the extra dimension \( \Rightarrow \) gravity on the brane

\[
S_{\text{bulk}} = \int d^4x \int_0^{r_c} dy \sqrt{-g} \ e^{-\Phi} \left( M_5^3 R + M_5^3 (\nabla \Phi)^2 - \Lambda \right)
\]

\[
S_{\text{vis(hid)}} = \int d^4x \sqrt{-g} \ (e^{-\Phi}) \left( L_{SM(hid)} - T_{\text{vis(hid)}} \right)
\]

Tuning conditions: \( T_{\text{vis}} = -T_{\text{hid}} \leftrightarrow \Lambda < 0 \) \[36\]}
Constant dilaton and AdS metric: Randal Sundrum model

**spacetime = slice of AdS$_5$:**

\[ ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2 \]

\[ k^2 \sim \Lambda / M_5^3 \]

- **UV-brane** \( y = 0 \)
- **bulk** \( -|\Lambda| \)
- **IR-brane** \( y = \pi r_c \)

- Exponential hierarchy:
  \[ M_W = M_P e^{-2kr_c} \]
  \[ M_P^2 \sim M_5^3 / k \]
  \[ M_5 \sim M_{GUT} \]

- 4d gravity localized on the UV-brane, but KK gravitons on the IR

\[ m_n = c_n k e^{-2kr_c} \sim \text{TeV} \]

\[ c_n \approx (n + 1/4) \text{ for large } n \]

\( \Rightarrow \) spin-2 TeV resonances in di-lepton or di-jet channels
dilaton $\Phi = -\alpha |y|$ and flat metric $\Rightarrow$

$$g_s^2 = e^{-\alpha |y|} ; \quad ds^2 = e^{\frac{2}{3}\alpha |y|}(\eta_{\mu\nu} dx^\mu dx^\nu + dy^2) \quad \leftarrow \text{Einstein frame}$$

$$z \sim e^{\alpha y/3} \Rightarrow \text{polynomial warp factor + log varying dilaton}$$

- exponential hierarchy: $g_s^2 = e^{-\alpha |y|}$, $M_P^2 \sim \frac{M_5^3}{\alpha} e^{\alpha r_c}$, $\alpha \equiv k_{RS}$

- 4d graviton flat, KK gravitons localized near SM
LST KK graviton phenomenology

- KK spectrum: \[ m_n^2 = \left( \frac{n \pi}{r_c} \right)^2 + \frac{\alpha^2}{4} ; \ n = 1, 2, \ldots \]
  \[ \Rightarrow \text{mass gap + dense KK modes} \quad \alpha \sim 1 \ \text{TeV} \quad r_c^{-1} \sim 30 \ \text{GeV} \]

- couplings: \[ \frac{1}{\Lambda_n} \sim \frac{1}{(\alpha r_c) M_5} \]
  \[ \Rightarrow \text{extra suppression by a factor} \ (\alpha r_c) \sim 30 \]

- width: \[ 1/(\alpha r_c)^2 \text{ suppression} \sim 1 \ \text{GeV} \]
  \[ \Rightarrow \text{narrow resonant peaks in di-lepton or di-jet channels} \]

- extrapolates between RS and flat extra dims \((n = 1)\)
  \[ \Rightarrow \text{distinct experimental signals} \]
Conclusions

- Possible discovery of the Higgs scalar at the LHC: big step forward
- Precise measurement of its couplings is of primary importance
- Hint on the origin of mass hierarchy and of BSM physics
  - Natural or unnatural SUSY?
  - Low string scale in some realization?
  - Something new and unexpected?
- Good chance that next phase of LHC run will provide the answer