Aspects of string phenomenology in the LHC era

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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:
  \[
  \begin{align*}
  M_P^* &\approx 10^{18} \text{ GeV} & \text{Heterotic scale} \\
  M_{\text{GUT}} &\approx 10^{16} \text{ GeV} & \text{Unification scale}
  \end{align*}
  \]

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

  SUSY breaking, strong CP axion, see-saw scale

  Low: TeV (hierarchy problem)
Excellent LHC performance

Number of events = Cross section × Luminosity

LHC 2011 RUN (3.5 TeV/beam)

LHC 2012 RUN (4 TeV/beam)

(generated 2012-06-21 00:39 including fill 2267)

(generated 2012-12-07 08:25 including fill 3378)
$m_H = 125.5 \pm 0.2 \text{ (stat.)} \pm 0.5 \text{ (syst.)}$   \hspace{1cm}   $m_H = 125.7 \pm 0.3 \pm 0.3 \text{ GeV}$
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
Remarks on the value of the Higgs mass $\sim 125$ GeV

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

Window to new physics

- compatible with supersymmetry
  but appears fine-tuned in its minimal version \[^{[10]}\]
  early to draw a general conclusion before LHC13/14
  e.g. an extra singlet or split families can alleviate the fine tuning \[^{[11]}\]

- very important to measure its properties and couplings \[^{[15]}\]
  any deviation of its couplings to top, bottom and EW gauge bosons
  implies new light states involved in the EWSB altering the fine-tuning
Δχ²
[région exclue]

Δα

Δα^{(5)}_{had} = 0.02761 ± 0.00036

incertitude théorique

95% CL

m_H [GeV]
Fine-tuning in MSSM

Upper bound on the lightest scalar mass:

\[
m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[ \ln \frac{m_t^2}{m_Z^2} + \frac{A_t^2}{m_t^2} \left( 1 - \frac{A_t^2}{12m_t^2} \right) \right] \lesssim (130\text{GeV})^2
\]

\[
m_h \simeq 126\text{ GeV} \Rightarrow m_\tilde{t} \simeq 3\text{ TeV} \text{ or } A_t \simeq 3m_\tilde{t} \simeq 1.5\text{ TeV}
\]

\Rightarrow \% \text{ to a few \%\% fine-tuning}

minimum of the potential: 

\[
m_Z^2 = 2 \frac{m_1^2 - m_2^2 \tan^2 \beta}{\tan^2 \beta - 1} \sim -2m_Z^2 + \cdots
\]

RG evolution: 

\[
m_Z^2 = m_Z^2(M_{\text{GUT}}) - \frac{3\lambda_t^2}{4\pi^2} m_t^2 \ln \frac{M_{\text{GUT}}}{m_\tilde{t}} + \cdots \text{ [26]}
\]

\[
\sim m_Z^2(M_{\text{GUT}}) - \mathcal{O}(1)m_\tilde{t}^2 + \cdots \text{ [8]}
\]
MSSM with dim-5 and 6 operators

parametrize new physics above MSSM by higher-dim effective operators

relevant super potential operators of dimension-5:

\[ \mathcal{L}^{(5)} = \frac{1}{M} \int d^2 \theta (\eta_1 + \eta_2 S) (H_1 H_2)^2 \]

\( \eta_1 \): generated for instance by a singlet

\[ W = \lambda \sigma H_1 H_2 + M \sigma^2 \quad \rightarrow \quad W_{\text{eff}} = \frac{\lambda^2}{M} (H_1 H_2)^2 \]

Strumia '99 ; Brignole-Casas-Espinosa-Navarro '03

Dine-Seiberg-Thomas '07

\( \eta_1 \): corresponding soft breaking term

spurion \( S \equiv m_S \theta^2 \)
**Physical consequences of MSSM$_5$: Scalar potential**

\[ \mathcal{V} = m_1^2 |h_1|^2 + m_2^2 |h_2|^2 + B\mu (h_1 h_2 + \text{h.c.}) + \frac{g_2^2 + g_Y^2}{8} (|h_1|^2 - |h_2|^2)^2 \\
+ (|h_1|^2 + |h_2|^2) (\eta_1 h_1 h_2 + \text{h.c.}) + \frac{1}{2} [\eta_2 (h_1 h_2)^2 + \text{h.c.}] + \mathcal{O}(\eta_i^2) \]

- $\eta_{1,2} \Rightarrow$ quartic terms along the D-flat direction $|h_1| = |h_2|

- potential stability $\Rightarrow \eta_2 \geq 4|\eta_1|

requiring $\eta$-corrections to be smaller than MSSM mass matrix elements $\Rightarrow$

only $\eta_2$ can change the tree-level bound $m_h \leq m_Z$ but marginally
Relaxing the condition on potential positivity: guaranteed by dim-6 ops

only one dim-6 along the D-flat direction induced by dim-5: \( \propto \eta_1^2 \)

\[ W = \eta_1 (H_1 H_2)^2 \longrightarrow V = \left| \frac{\partial W}{\partial H_i} \right|^2 \sim \eta_1^2 |H_1 H_2|^2 (|H_1|^2 + |H_2|^2) \]

- tree-level mass can increase significantly
- bigger parameter space for LSP being dark matter

Bernal-Blum-Nir-Losada ’09
dim-6 operators can have an independent scale from dim-5

Classification of all dim-6 contributing to the scalar potential

\[ \delta_6 m_h^2 = f v^2 + \ldots \]

large tan $\beta$ expansion: constant receiving contributions from several operators

\[ f \sim f_0 \times \left( \frac{\mu^2}{M^2}, \frac{m_S^2}{M^2}, \frac{\mu m_S}{M^2}, \frac{v^2}{M^2} \right) \]

$m_S = 1$ TeV, $M = 10$ TeV, $f_0 \sim 1 - 2.5$ for each operator

$\Rightarrow m_h \simeq 103 - 119$ GeV

$\Rightarrow$ MSSM with dim-5 and dim-6 operators:
possible resolution of the MSSM fine-tuning problem \[^8\]
**Couplings of the new boson vs SM**

**ATLAS Preliminary**

- $W,Z,H \to bb$
  - $\sqrt{s} = 7$ TeV: $Ldt = 4.7$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV: $Ldt = 13$ fb$^{-1}$
- $H \to \tau\tau$
  - $\sqrt{s} = 7$ TeV: $Ldt = 4.6$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV: $Ldt = 13$ fb$^{-1}$
- $H \to WW^{(*)} \to lvlv$
  - $\sqrt{s} = 7$ TeV: $Ldt = 4.6$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV: $Ldt = 20.7$ fb$^{-1}$
- $H \to \gamma\gamma$
  - $\sqrt{s} = 7$ TeV: $Ldt = 4.8$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV: $Ldt = 20.7$ fb$^{-1}$
- $H \to ZZ^{(*)} \to 4l$
  - $\sqrt{s} = 7$ TeV: $Ldt = 4.6$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV: $Ldt = 20.7$ fb$^{-1}$

**Combined**

$\mu = 1.30 \pm 0.20$

**CMS preliminary**

- $VH \to bb$
  - CMS HIG-12-044
  - $\sqrt{s} = 7$ TeV, $L = 4.9$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV, $L = 12.1$ fb$^{-1}$
- $H \to \tau\tau$
  - CMS HIG-13-004
  - $\sqrt{s} = 7$ TeV, $L = 4.9$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV, $L = 19.4$ fb$^{-1}$
- $H \to \gamma\gamma$
  - CMS HIG-13-001
  - $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV, $L = 19.6$ fb$^{-1}$
- $H \to ZZ^{(*)} \to 4l$
  - CMS HIG-13-002
  - $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV, $L = 19.6$ fb$^{-1}$
- $H \to WW^{(*)} \to 2l2\nu$
  - CMS HIG-13-003
  - $\sqrt{s} = 7$ TeV, $L = 4.9$ fb$^{-1}$
  - $\sqrt{s} = 8$ TeV, $L = 19.5$ fb$^{-1}$

**exclusion**: spin 2 and pseudoscalar at 95% CL

**Agreement with Standard Model expectation at $\sim 2\sigma$**
Can the SM be valid at high energies?

Degrassi-Di Vita-Elias Miró-Espinosa-Giudice-Isidori-Strumia ’12

Instability of the SM Higgs potential $\Rightarrow$ metastability of the EW vacuum
SUSY: $\lambda = 0 \Rightarrow \tan \beta = 1$

$$H_{SM} = \sin \beta H_u - \cos \beta H^*_d \quad \lambda = \frac{1}{8} (g_2^2 + g'^2) \cos^2 2\beta$$

$\lambda = 0$ at a scale $\geq 10^{10}$ GeV $\Rightarrow m_H = 126 \pm 3$ GeV

Ibanez-Valenzuela ’13

e.g. for universal $\sqrt{2} m = M = M_{SS}, A = -3/2 M$
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

- $\tan\beta = 50$
- $\tan\beta = 4$
- $\tan\beta = 2$
- $\tan\beta = 1$
An extra $U(1)$ can also cure the instability problem

Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor-Vlcek ’12

- $B$ anomalous and superheavy
- $B - L$ massless at the string scale (no associated 6d anomaly)
  but broken at TeV by a scalar 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 $\Rightarrow$ $0.5 \lesssim g_{U(1)_R} \lesssim 1$
- interesting LHC phenomenology and cosmology [23]
Standard Model on D-branes: SM$$^{++}$$

3-Baryonic

2-Left

U(3)

1-Right

U(1)$$^L$$

E$$^R$$, N

Gluon

Q$$^L$$

W

L$$^L$$

U(1)$$^R$$

Sp(1) \equiv SU(2)

\[ U(1)^3 \Rightarrow \text{hypercharge} + B, L \] [31]
$g'_{1}(M_{s})$ vs. $BR Z''$ for $U(1)_{R}$ and $B - L$. The graph shows the behavior of $BR Z''$ as a function of $g'_{1}(M_{s})$ for different values of $U(1)_{R}$ and $B - L$. The solid line represents $U(1)_{R}$, while the dashed line represents $B - L$. The graph illustrates the variation in $BR Z''$ with changes in $g'_{1}(M_{s})$. For further details, please refer to the text accompanying the figure.
Rotation of $U(1)$’s from the string to low energy basis $Z, Z', Z''$: 
completely fixed in terms of the couplings

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

Recent cosmological observations indicate extra relativistic component
dark radiation parametrized by an effective $\nu$-number close to 4 *

$\rightarrow$ use the 3 $\nu_R$’s interacting with SM fermions via $Z''$
data: their decoupling during the quark-hadron transition

$\Rightarrow 3.5 \lesssim M_{Z''} \lesssim 7$ TeV (within LHC14 discovery potential)

* before Planck results
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 scalar 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\(^{++} \)

\( \text{for } 0.02 \lesssim |\alpha| \lesssim 0.35 \text{ and } 500 \text{ GeV} \lesssim m_{h''} \lesssim 5 \text{ TeV} \)
\[ M_{Z''} = 4.5 \text{ TeV}; \quad M_s = 10^{14}, 10^{16}, 10^{19} \text{ GeV} \]
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

$M_s \sim 1 \text{ TeV} \Rightarrow$ volume $R^n_\perp = 10^{32} l_s^n$ [33] ($R_\perp \sim .1 - 10^{-13} \text{ mm for } n = 2 - 6$)

- 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 $m_H^2 = \text{a loop factor} \times \Lambda^2$ [10]

But unification has to be probably dropped

New Dark Matter candidates e.g. in the extra dims
Origin of EW symmetry breaking?

possible answer: radiative breaking

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

\( \mu^2 = 0 \) at tree but becomes \(< 0\) at one loop

non-susy vacuum

simplest case: one scalar doublet from the same brane

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

D-terms

\[ \mu^2 = -g^2 \varepsilon^2 M_s^2 \leftrightarrow \text{effective UV cutoff} \]

\[ \varepsilon^2(R) = \frac{R^3}{2\pi^2} \int_0^\infty dl l^{3/2} \cdot \frac{\theta_2^4}{16 l^4 \eta^{12}} \left( il + \frac{1}{2} \right) \sum_n n^2 e^{-2\pi n^2 R^2 l} \]

I.A.-Benakli-Quiros ’00
$R \to 0 : \varepsilon(R) \simeq 0.14 \quad \text{large transverse dim} \quad R_\perp = l_s^2/R \to \infty$

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

Higgs scalar = component of a higher dimensional gauge field

$\Rightarrow \varepsilon_\infty \text{ calculable in the effective field theory}$

$\lambda = g^2/4 \sim 1/8 \quad \Rightarrow \quad M_H \simeq v/2 = 125 \text{ GeV}$

$M_s \text{ or } 1/R \sim \text{ a few or several TeV}$
Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk $\Rightarrow$ missing energy
  
  present LHC bounds: $M_\star \gtrsim 3 - 5$ TeV

- Massive string vibrations $\Rightarrow$ e.g. resonances in dijet distribution
  
  $M_j^2 = M_0^2 + M_s^2 j$ ; maximal spin : $j + 1$

  higher spin excitations of quarks and gluons with strong interactions
  
  present LHC limits: $M_s \gtrsim 5$ TeV

- Large TeV dimensions $\Rightarrow$ KK resonances of SM gauge bosons I.A. ’90
  
  $M_k^2 = M_0^2 + k^2/R^2$ ; $k = \pm 1, \pm 2, \ldots$

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

- extra $U(1)$’s and anomaly induced terms

  masses suppressed by a loop factor from $M_s$ [31]
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)

$$M_{NA} \simeq g_A M_s V_2 \leftarrow (6d \rightarrow 4d) \text{ internal space} \quad \Rightarrow M_{NA} \geq M_A$$

or massless in the absence of such anomalies [21]
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 $\Rightarrow \frac{1}{M_s} LLHH \rightarrow$ 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

$Z' \simeq B$ lighter than 4d anomaly free $Z'' \simeq B - L$ [42]
More general framework: large number of species

$N$ particle species $\Rightarrow$ lower quantum gravity scale: $M_*^2 = M_p^2 / N$

Dvali '07, Dvali, Redi, Brustein, Veneziano, Gomez, Lüst '07-'10

derivation from: black hole evaporation or quantum information storage

$M_* \sim 1$ TeV $\Rightarrow N \sim 10^{32}$ particle species!

2 ways to realize it lowering the string scale

1. Large extra dimensions

   SM on D-branes [26]

   $N = R_n^m l_s^n$: number of KK modes up to energies of order $M_* \sim M_s$

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

   $N = \frac{1}{g_s^2}$ with $g_s \sim 10^{-16}$

   SM on NS5-branes

I.A.-Pioline '99, I.A.-Dimopoulos-Giveon '01
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

Pixel of size \( L \) containing \( N \) species storing information:

localization energy \( E \gtrsim N/L \rightarrow \)

Schwarzschild radius \( R_s = \frac{N}{(LM_p^2)} \)

no collapse to a black hole: \( L \gtrsim R_s \Rightarrow L \gtrsim \sqrt{N}/M_p = 1/M_* \)

\( M_* \sim 1 \text{ TeV} \Rightarrow N \sim 10^{32} \) particle species!
Decouple gravity from NS5-branes

Analogy from D3-branes: decouple gravity $\Rightarrow M_s \to \infty$, $g_s$ fixed

$\to$ (conformal) Field Theory (CFT)

simplest case: 4d $\mathcal{N} = 4$ super Yang Mills $SU(N)$

parameters: number of branes $N$, gauge coupling $g_{YM}$

NS-5 branes: $M_s$ finite, $g_s \to 0 \to$ (little) String Theory without gravity

simplest case: 6d LST (chiral IIA or non-chiral IIB)

massless sector: 6d $SU(N)$ of tensors (IIA) or vectors (IIB)

at a non-trivial fixed point

parameters: number of branes $N$, string scale $M_s$
How to study LST? Using gauge/gravity duality

Gravity background: near horizon geometry (holography) Maldacena ’98

Analogy from D3-branes: $AdS_5 \times S^5$

parameters: $AdS$ radius $r_{AdS} M_s$, $g_s \leftrightarrow N, g_{YM}$

supergravity validity: $r_{AdS} M_s \gg 1, g_s \ll 1 \Rightarrow$ large $N, g_{YM}^2 N$

$\rightarrow$ model independent part: $AdS_5$

NS-5 branes: $(\mathcal{M}_6 \otimes R_+) \times SU(2) \equiv S^3$

linear dilaton background in 7d flat string-frame metric $\Phi = -\alpha |y|$

Aharony-Berkooz-Kutasov-Seiberg ’98

parameters: $M_s$, $\alpha$ (or $S^3$ radius) $\leftrightarrow N$

sugra validity: small $\alpha \Rightarrow$ large $N$

compactify to $d = 4 (\mathcal{M}_6 \rightarrow \mathcal{M}_4) \Rightarrow g_{YM} \sim 2d$ volume

$\rightarrow$ model independent part: linear dilaton
“cut” the space of the extra dimension $\Rightarrow$ gravity on the brane

Toy 5d bulk model

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

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

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [39]
Constant dilaton and AdS metric: Randal Sundrum model

spacetime = slice of AdS$_5$:
\[ ds^2 = e^{-2k|y|} \gamma_{\mu\nu} dx^\mu dx^\nu + dy^2 \]
\[ k^2 \sim \Lambda / M_5^3 \]

- UV-brane: \( y = 0 \)
- Bulk: \( -|\Lambda| \)
- IR-brane: \( y = \pi r_c \)

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

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

\[ m_n = c_n k e^{-2kr_c} \sim \text{TeV} \quad c_n \simeq (n + 1/4) \text{ for large } n \]

\[ \Rightarrow \text{spin-2 TeV resonances in di-lepton or di-jet channels} \]
Linear dilaton background IA-Arvanitaki-Dimopoulos-Giveon '11

dilaton $\Phi = -\alpha |y|$ and flat metric $\Rightarrow$

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

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

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

$\exists$ 4d graviton flat, KK gravitons localized near SM

SM-brane $\quad M_W \quad y = 0$

bulk $\quad -|\Lambda|$

Planck-brane $\quad M_P \quad y = r_c$
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: \( 1/(\alpha r_c)^2 \) suppression \( \sim 1 \text{ GeV} \)

  \[ \Rightarrow \text{narrow resonant peaks in di-lepton or di-jet channels} \]

- extrapolates between RS and flat extra dims \( (n = 1) \)

  \[ \Rightarrow \text{distinct experimental signals} \]
Radion stabilization

Similar to RS using the dilaton as the Goldeberger-Wise scalar

add dilaton boundary potentials $\Rightarrow$

radion stabilization with the desired hierarchy

Radion phenomenology different from RS:

- mass spectrum: similar to the graviton KK modes
  with possible lower parametrically mass gap
- new radion couplings to SM fields besides to the trace of $T_{\mu \nu}$
- larger coupling to the radion 0-mode relative to KK excitations
- Higgs-radion mixing $\Rightarrow$

branching fraction to $\gamma \gamma$ can be significantly enhanced
Conclusions

- Higgs discovery at the LHC:
  - important milestone of the LHC research program
- 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?
  - all options are still open
- LHC enters a new era with possible new discoveries