Mass hierarchy in string theory and experimental predictions

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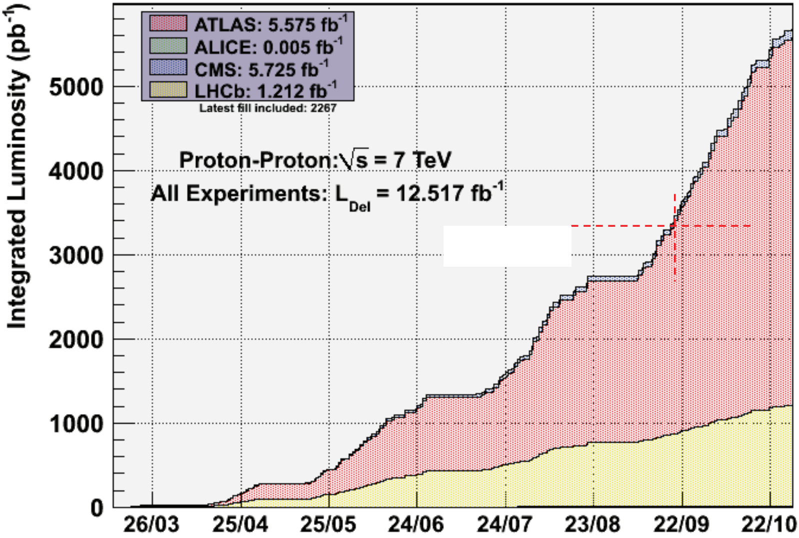
Progress in Quantum Field Theory and String Theory

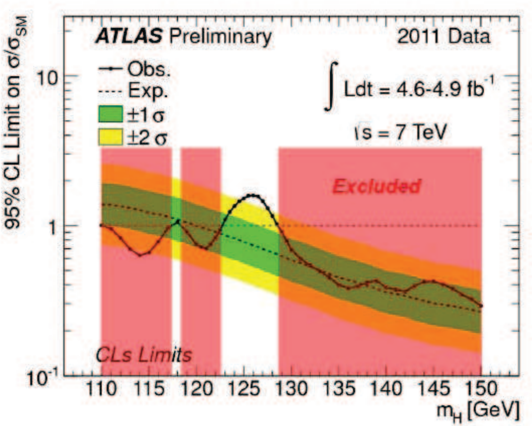
Osaka, Japan, 3-7 April 2012

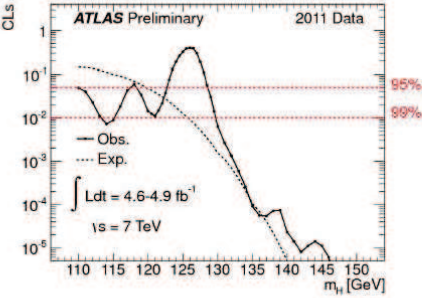
- Motivations and mass hierarchy
- Low scale strings and extra dimensions (flat and warped)
- Infinitesimal string coupling and linear dilaton background
- Main accelerator signatures and nature of the EWSB sector

LHC Luminosity 2011



ATLAS Higgs search : excess 2.5σ



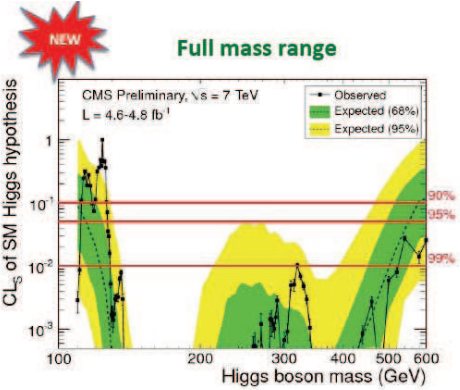


Exclusion at 99% CL: 130-486 GeV

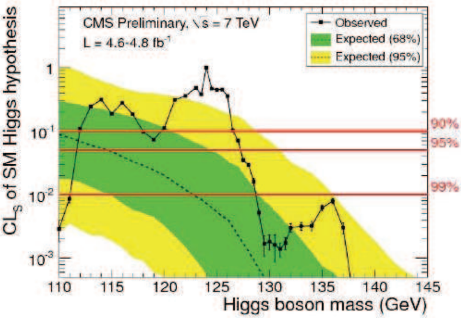
Exclusion at 95% CL: 110-117.5, 118.5-122.5, 129-539 GeV

95% allowed mass range: $117.5 < m_H < 118.5$ or $122.5 < m_H < 129$ GeV

CMS Higgs search : excess 2.1σ



Full mass range



Low mass region

CMS document
HIG-12-008

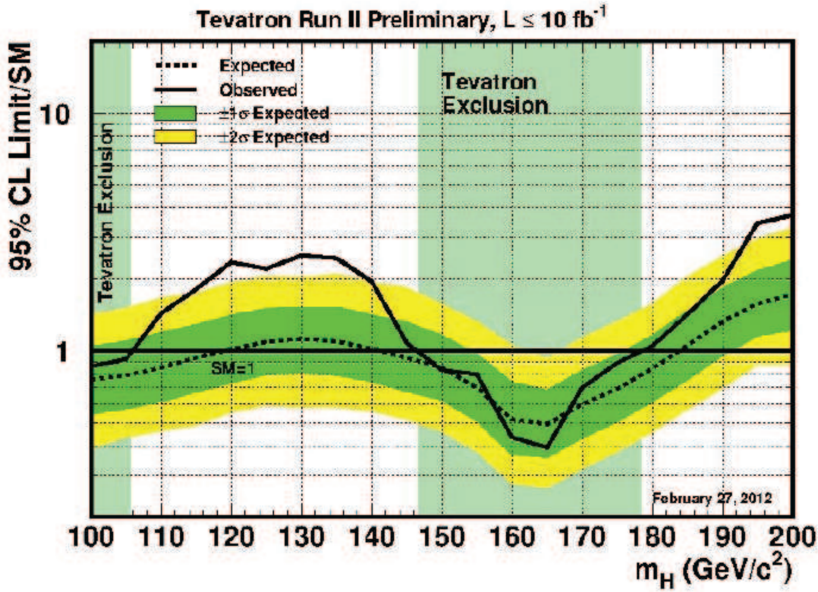
Exclusion at 99% CL: 129-525 GeV

Exclusion at 95% CL: 127.5-600 GeV

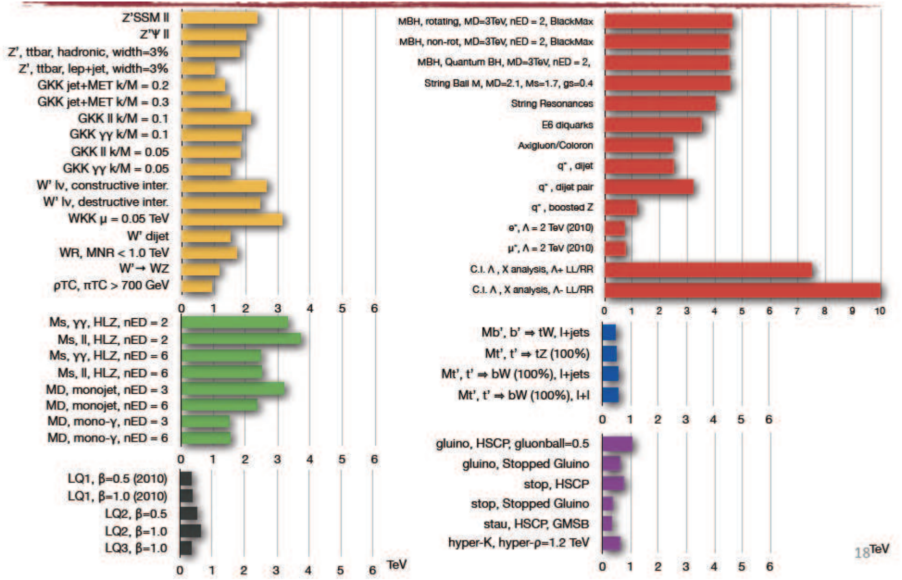
95% allowed mass range: $114.5 < m_H < 127.5$ GeV

ATLAS and CMS excess in good agreement with SM signal

CDF + D0 : broad excess 2.2σ lucky?



The Grand Summary: BSM



SUSY / invisibles: summary

- Analysis of **2011** data still in flow
  - Several analyses with full 5 fb^{-1}, more on the way
- Lower limits* of:
  - **squark ~ 1400 GeV**
  - **gluino ~ 900 GeV**
  - **sbottom ~ 400 GeV**
  - **[stop ~ 300 GeV]****
  - **[gauginos ~ 200-300 GeV]****

* indicative
& for particular scenarios

Direct production
Particular decays

- Also: taus, photons, monojets, disappearing tracks, … + E_T^{miss}
- Preparations for **2012, 8 TeV** in full swing

Beyond the Standard Model of Particle Physics:
driven by the mass hierarchy problem

Standard picture: low energy supersymmetry

Advantages:

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

Problems:

- too many parameters: soft breaking terms
- MSSM : already a % - ‰ fine-tuning 'little' hierarchy problem

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

Alternative answer: Low UV cutoff $\Lambda \sim$ 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

$\Lambda \sim$ a few TeV and $m_H^2 =$ a loop factor $\times \Lambda^2$

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 $\Rightarrow R_{\|} \simeq l_{\rm string}$; $R_{\perp}$ 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}

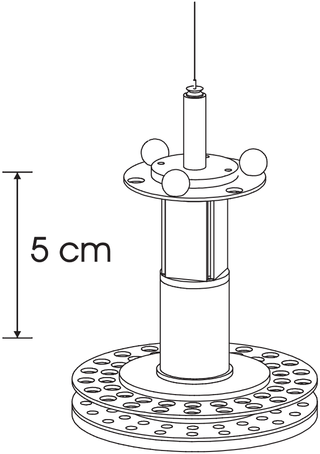
small M_s/M_P : extra-large $R_{\perp}$

$M_s \sim 1$ TeV $\Rightarrow R_{\perp}^n = 10^{32}\, l_s^n$ [23]

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

distances $< R_{\perp}$: gravity $(4+n)$-dim → strong at 10^{-16} cm [12]

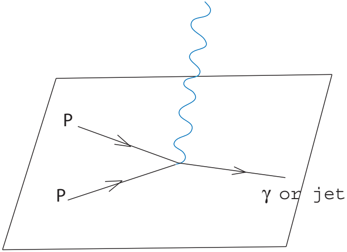
Adelberger et al. '06



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

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

Gravitational radiation in the bulk ⇒ missing energy



Angular distribution ⇒ spin of the graviton

Collider bounds on $R_\perp$ in mm			
	$n = 2$	$n = 4$	$n = 6$
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}

Origin of EW symmetry breaking?

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

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

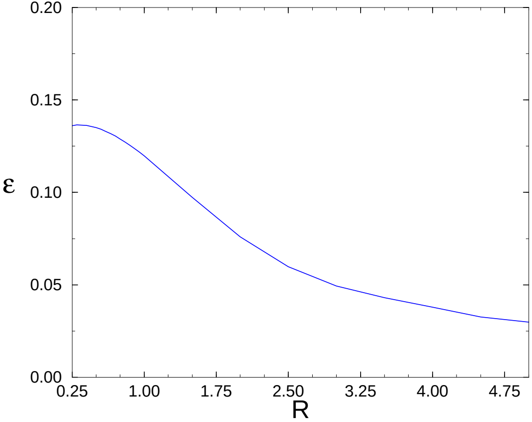
$\mu^2 = 0$ at tree but becomes < 0 at one loop non-susy vacuum

simplest case: one scalar doublet from the same brane

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

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

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



$R \to 0$: $\varepsilon(R) \simeq 0.14$ 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 scalar = component of a higher dimensional gauge field

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

Quartic coupling $\Rrightarrow$ mass prediction:

- tree level : $M_H = M_Z$

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

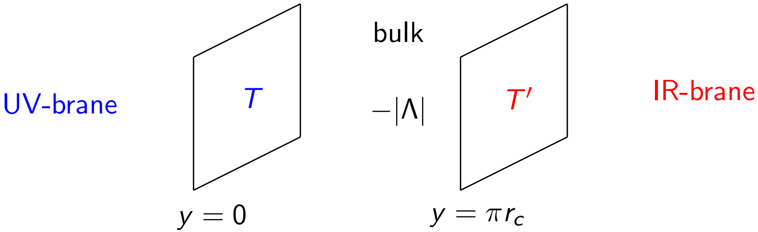
Casas-Espinosa-Quiros-Riotto, Carena-Espinosa-Quiros-Wagner '95

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

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

Randal Sundrum models

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



- 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

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

  $\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels [26] [27]

- weakly coupled for $m_n < M_5 \, e^{-2kr_c}$ $\Rightarrow k < M_5$
- viable models: SM gauge bosons in the bulk

  EWSB sector on the IR-brane
- AdS/CFT duals to strongly coupled 4d field theories

  composite Higgs models, technicolor-type $g_{YM} = M_5/k > 1$

Micro-black hole production?

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

Horowitz-Polchinski '96, Meade-Randall '07

- string size black hole: $r_H \sim l_s = M_s^{-1}$
- black hole mass: $M_{\rm BH} \sim r_H^{d-3}/G_N$ $\qquad G_N \sim l_s^{d-2} g_s^2$

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

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

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 $M_{\rm BH}$

Other accelerator signatures

- string physics and possible strong gravity effects

  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

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

- Large TeV dimensions seen by SM gauge interactions

  ⇒ KK resonances of SM gauge bosons I.A. '90

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

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

  masses suppressed by a loop factor from M_s [20]

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)

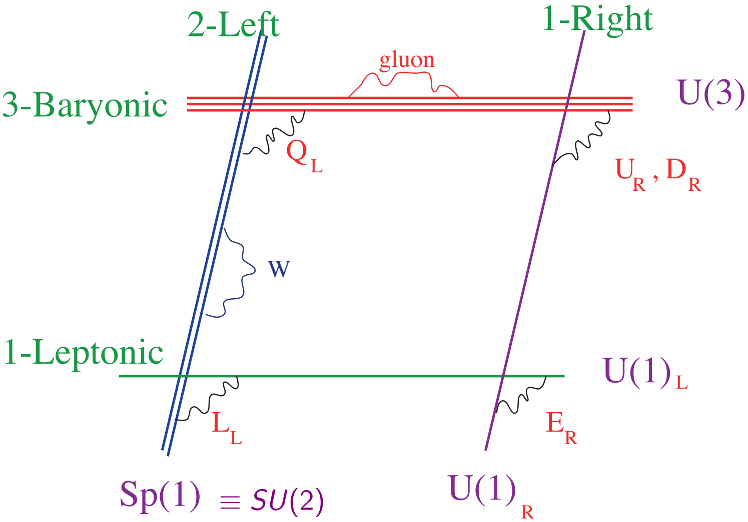
Baryon and Lepton number, or PQ symmetry

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→4d) internal space $\Rightarrow M_{NA} \geq M_A$

Standard Model on D-branes



$U(1)^3$: hypercharge + B, L global

global symmetries

- B and L become massive due to anomalies

  Green-Schwarz terms

- the global symmetries remain in perturbation

  - Baryon number $\Rrightarrow$ proton stability

  - Lepton number $\Rrightarrow$ protect small neutrino masses

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

- $B, L \Rrightarrow$ extra Z's (B lighter than 4d anomaly free $B - L$)

  with possible leptophobic couplings leading to CDF-type Wjj events [10]

  Anchordoqui-I.A.-Goldberg-Huang-Lüst-Taylor '11

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

$M_* \simeq 1$ 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 [10]

   $N = R_\perp^n \, l_s^n$: number of KK modes up to energies of order $M_* \simeq M_s$

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

   $N = \dfrac{1}{g_s^2}$ with $g_s \simeq 10^{-16}$ SM on NS5-branes

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

Decouple gravity from NS5-branes $\Rightarrow$ Little Strings

Analogy from D3-branes : decouple gravity $\Rrightarrow M_s \to \infty$, 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: $r_{AdS} M_s >> 1$, $g_s << 1 \Rightarrow$ large N, $g_{YM}^2 N$

$\longrightarrow$ model independent part : AdS_5

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

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

Aharony-Berkooz-Kutasov-Seiberg '98

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

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

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

$\longrightarrow$ model independent part : linear dilaton

Put gravity back ⇒ toy 5d bulk model

"cut" the space of the extra dimension ⇒ gravity on the brane

but weakly coupled

Analogy from D-branes ⇒ slice of AdS_5

RS, H. Verlinde '99

NS-5 branes : linear dilaton on an interval $y \in [0, r_c]$

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

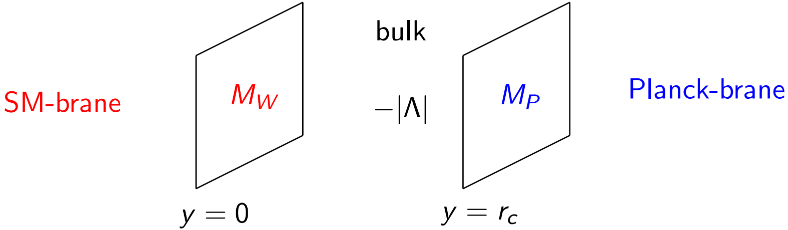
$$S_{vis(hid)} = \int d^4x \sqrt{-g} \left(e^{-\Phi}\right) \left(L_{SM(hid)} - T_{vis(hid)}\right)$$

Tuning conditions: $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$ [16]

Linear dilaton background IA-Arvanitaki-Dimopoulos-Giveon '11

$g_s^2 = e^{-\alpha|y|}$; $ds^2 = e^{\frac{2}{3}\alpha|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right) \leftarrow$ Einstein frame [16]

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



SM-brane

M_W

bulk

$-|\Lambda|$

M_P

Planck-brane

$y = 0$

$y = r_c$

- 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 : $m_n^2 = \left(\frac{n\pi}{r_c}\right)^2 + \frac{\alpha^2}{4}$; $n = 1, 2, \ldots$

  $\Rightarrow$ mass gap + dense KK modes $\alpha \sim 1$ TeV $r_c^{-1} \sim 30$ GeV

- couplings : $\frac{1}{\Lambda_n} \sim \frac{1}{(\alpha r_c) M_5}$

  $\Rightarrow$ extra suppression by a factor $(\alpha r_c) \simeq 30$

- width : $1/(\alpha r_c)^2$ suppression ~ 1 GeV

  $\Rightarrow$ narrow resonant peaks in di-lepton or di-jet channels

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

  $\Rightarrow$ distinct experimental signals

Conclusions

Mass hierarchy ⇒ testing strings at the TeV scale?

- Well motivated theoretical framework

  with many testable experimental predictions

  new resonances, missing energy

- Several realizations with different signatures

  flat large extra dimensions, exp warped metrics,

  tiny string coupling and linear dilaton background

- Stimulus for micro-gravity experiments and accelerator searches