Aspects of string phenomenology in the new LHC era

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STRINGS 2012

Munich, 23-28 July 2012

- High string scale, SUSY and 125 GeV Higgs
- Low scale strings and extra dimensions
- Extra $U(1)$'s

Connect string theory to the real world:

What is the value of the string scale M_s ?

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

- physical motivations $\Rrightarrow$ favored energy regions:

- High : $\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\rm GUT} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$
- Intermediate : around 10^{11} GeV ($M_s^2/M_P \sim$ TeV)

  SUSY breaking, strong CP axion, see-saw scale
- Low : TeV (hierarchy problem)

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

Standard picture: low energy supersymmetry

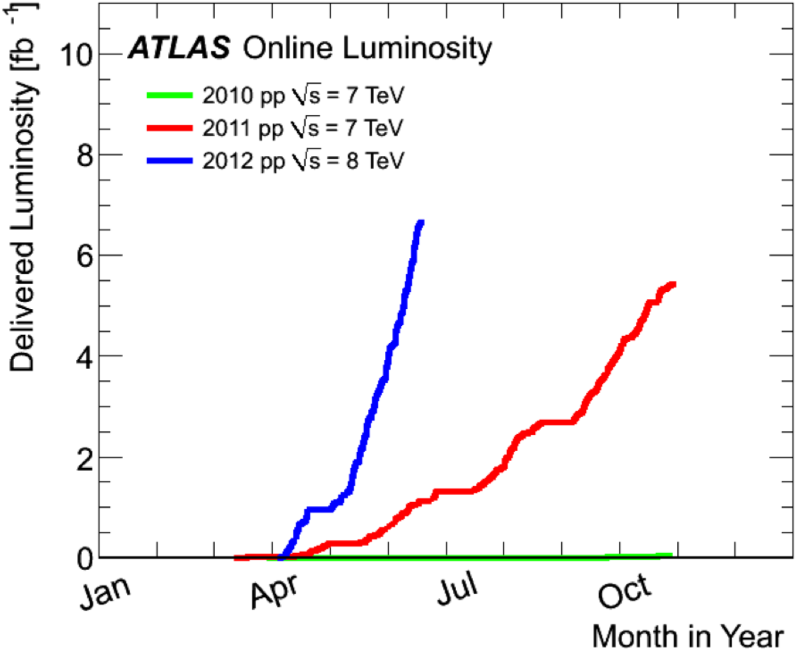
Natural framework: Heterotic string (or high-scale M/F) theory

Advantages:

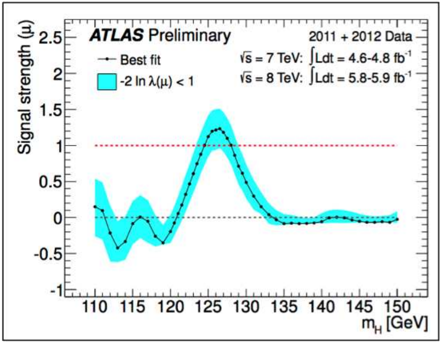
- natural elementary scalars
- gauge coupling unification
- LSP: natural dark matter candidate
- radiative EWSB

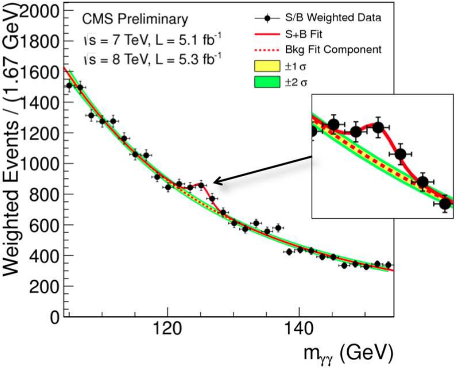
Problems:

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


ATLAS Online Luminosity
2010 pp $\sqrt{s}$ = 7 TeV
2011 pp $\sqrt{s}$ = 7 TeV
2012 pp $\sqrt{s}$ = 8 TeV
Delivered Luminosity [fb^{-1}]
0
2
4
6
8
10
Jan
Apr
Jul
Oct
Month in Year

Higgs search at the LHC





best-fit signal strength at 126.5 GeV

observed: $m_H = 125.3 \pm 0.6$ GeV

at 4.9 σ significance

some remarks

Higgs-like particle discovery around 125 GeV :

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

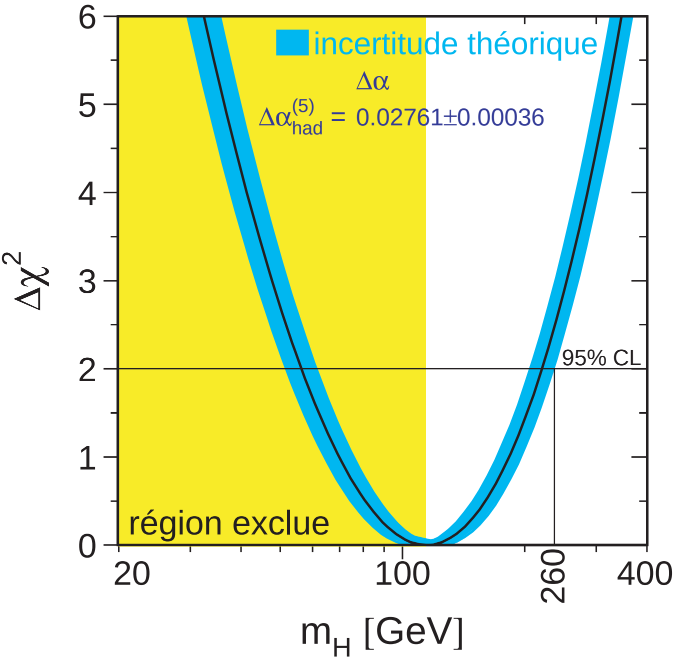
If confirmed :

- supersymmetry becomes 'severely' fine-tuned, in its minimal version
- but still early to draw a general conclusion before LHC13/14

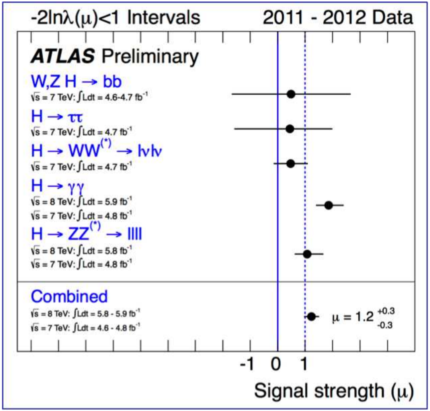
  an extra singlet or split families can remediate the fine tuning to $\lesssim 10$
- very important to measure Higgs couplings [8]

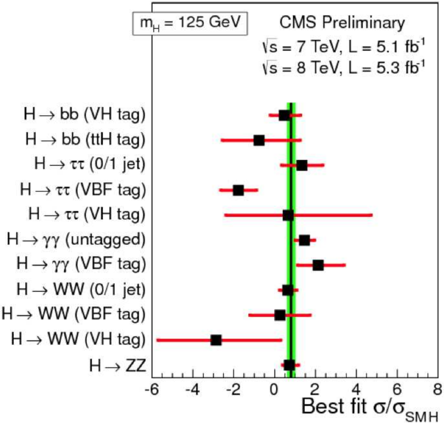
  any deviation of its couplings to top, bottom and EW gauge bosons

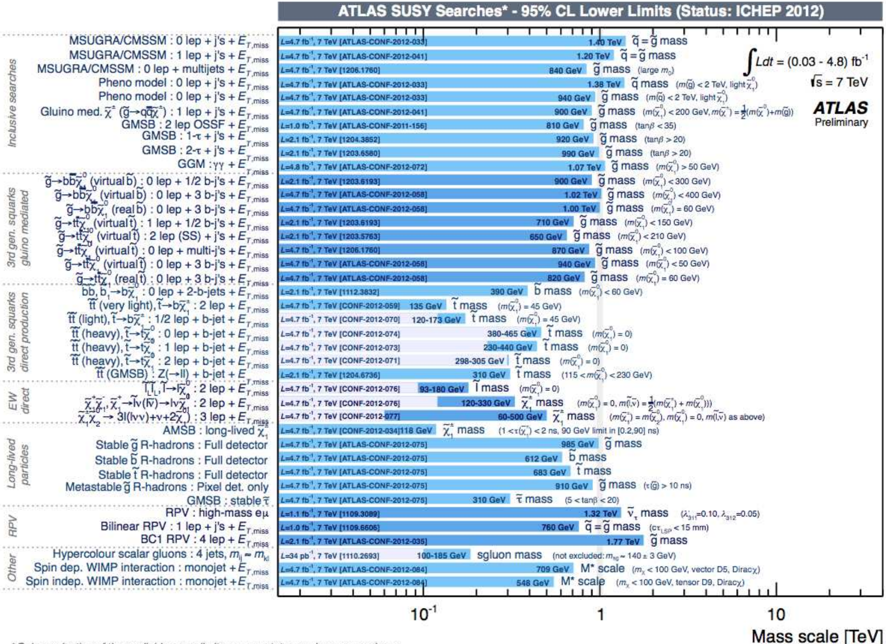
  implies new light states involved in the EWSB altering the fine-tuning


incertitude théorique
Δα
$\Delta\alpha^{(5)}_{had} = 0.02761 \pm 0.00036$
95% CL
région exclue
$\Delta\chi^2$
6
5
4
3
2
1
0
20
100
260
400
m_H [GeV]

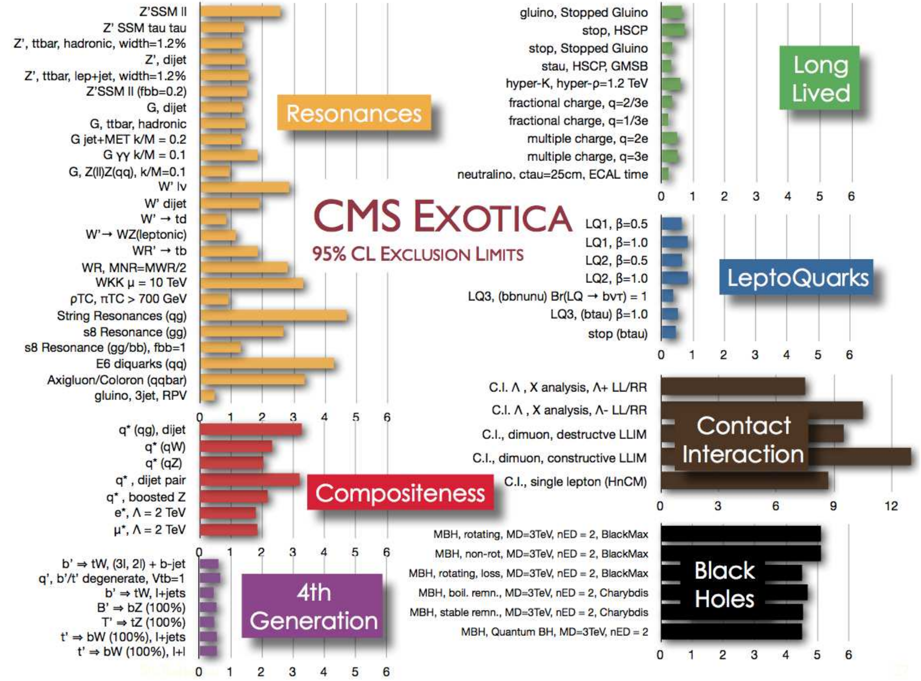
Couplings of the new boson vs SM Higgs





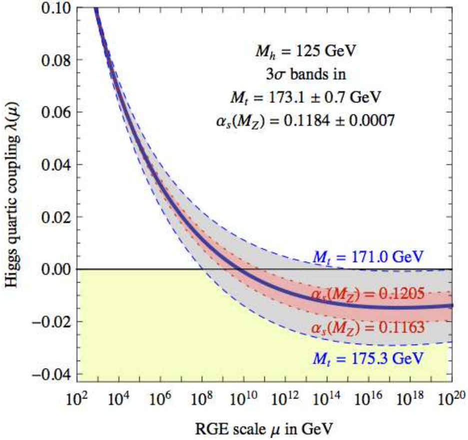


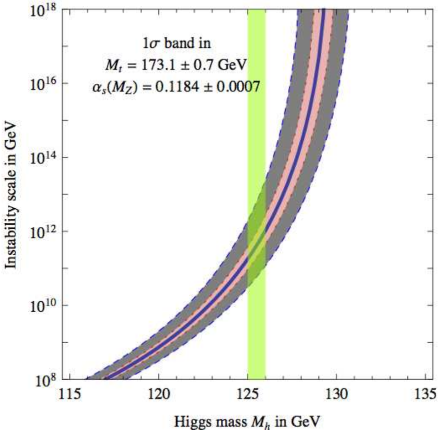
*Only a selection of the available mass limits on new states or phenomena shown


CMS EXOTICA
95% CL EXCLUSION LIMITS
Resonances
Z'SSM ll
Z' SSM tau tau
Z', ttbar, hadronic, width=1.2%
Z', dijet
Z', ttbar, lep+jet, width=1.2%
Z'SSM ll (fbb=0.2)
G, dijet
G, ttbar, hadronic
G jet+MET k/M = 0.2
G γγ k/M = 0.1
G, Z(ll)Z(qq), k/M=0.1
W' lv
W' dijet
W' → td
W'→ WZ(leptonic)
WR' → tb
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
s8 Resonance (gg/bb), fbb=1
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
0
1
2
3
4
5
6
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
0
1
2
3
4
5
6
4th Generation
b' ⇒ tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' ⇒ tW, l+jets
B' ⇒ bZ (100%)
T' ⇒ tZ (100%)
t' ⇒ bW (100%), l+jets
t' ⇒ bW (100%), l+l
0
1
2
3
4
5
6
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
fractional charge, q=2/3e
fractional charge, q=1/3e
multiple charge, q=2e
multiple charge, q=3e
neutralino, ctau=25cm, ECAL time
0
1
2
3
4
5
6
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3, (bbnunu) Br(LQ → bvτ) = 1
LQ3, (btau) β=1.0
stop (btau)
0
1
2
3
4
5
6
Contact Interaction
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., dimuon, destructve LLIM
C.I., dimuon, constructive LLIM
C.I., single lepton (HnCM)
0
3
6
9
12
Black Holes
MBH, rotating, MD=3TeV, nED = 2, BlackMax
MBH, non-rot, MD=3TeV, nED = 2, BlackMax
MBH, rotating, loss, MD=3TeV, nED = 2, BlackMax
MBH, boil. remn., MD=3TeV, nED = 2, Charybdis
MBH, stable remn., MD=3TeV, nED = 2, Charybdis
MBH, Quantum BH, MD=3TeV, nED = 2
0
1
2
3
4
5
6

Can the SM be valid at high energies?

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





Instability of the SM Higgs potential ⇒ metastability of the EW vacuum

Dropping the hierarchy motivation...

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

- Dark Matter ? → could be an axion
- Unification ? → perhaps different realization
- What could be the physics at M_I ? → susy, string scale, ...

If the weak scale is tuned ⇒ 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 ⇒ 'moderate' split

  $m_S \sim$ few - thousands TeV

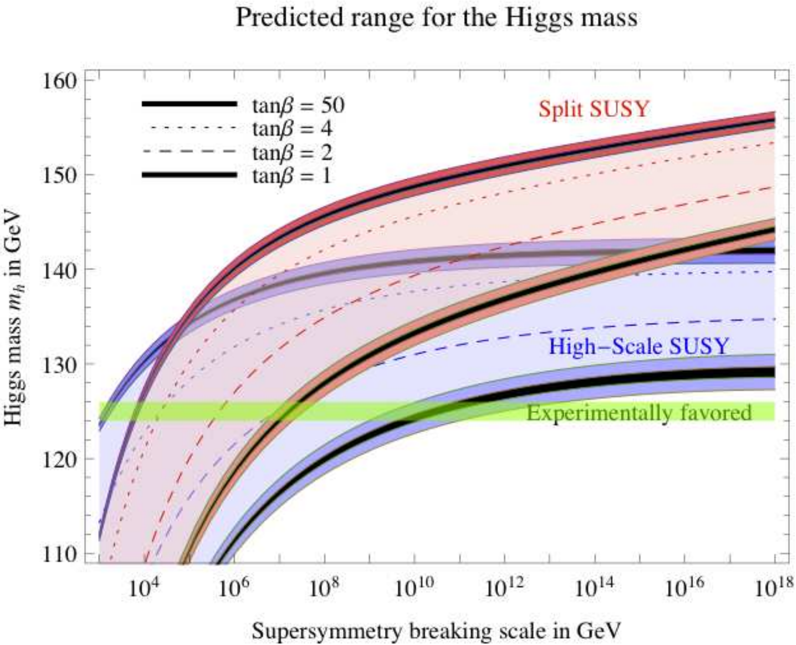
  gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)
- natural string framework: intersecting (or magnetized) branes

  IA-Dimopoulos '04

  D-brane stacks are supersymmetric with massless gauginos

  intersections have chiral fermions with broken SUSY & massive scalars

Giudice-Strumia '11



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 $\times \Lambda^2$ [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 $\Rightarrow R_{\parallel} \simeq l_{\rm string}$; $R_{\perp}$ 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 $\Rightarrow R_{\perp}^n = 10^{32}\ l_s^n$

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

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

Origin of EW symmetry breaking?

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

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

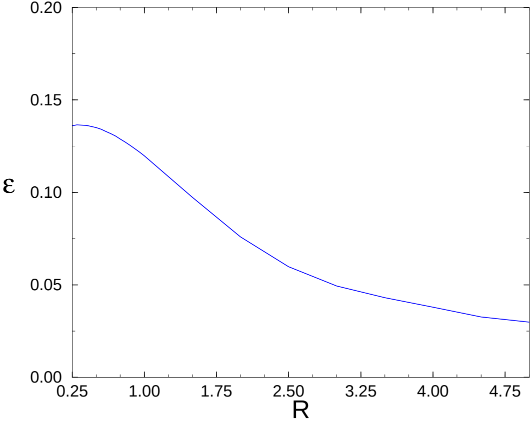
$\mu^2 = 0$ at tree but becomes < 0 at one loop non-susy vacuum

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

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



$R \to 0 \;:\; \varepsilon(R) \simeq 0.14$ 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 $\Rightarrow$ mass prediction:

- tree level : $M_H = M_Z$

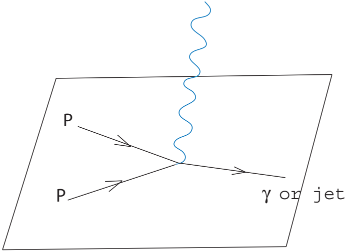
- low-energy SM radiative corrections (from top quark) : $M_H \sim 120$ GeV

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

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

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

Gravitational radiation in the bulk ⇒ missing energy



Angular distribution ⇒ spin of the graviton

present LHC bounds:

$M_* \gtrsim 2.5 - 4$ TeV

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}

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

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

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

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: 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 [24]

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

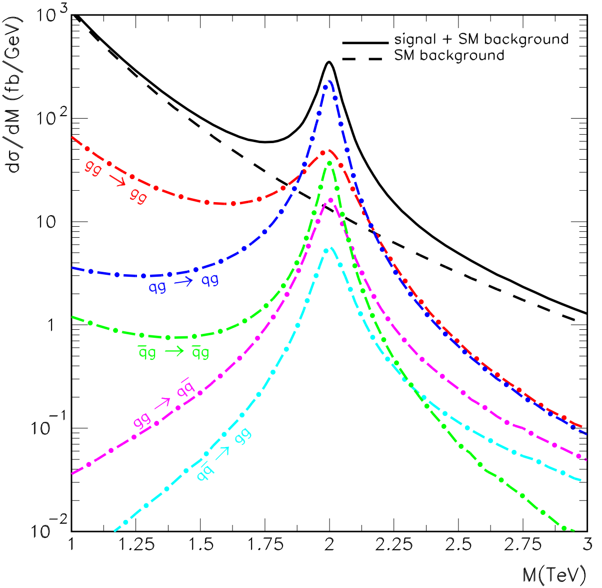
  $$M_k^2 = M_0^2 + \frac{k^2}{R^2} \ ; \ k = \pm 1, \pm 2, \ldots \quad R = V_\parallel^{1/d_\parallel} \quad ; \quad g^2 = 1/(V_\parallel M_s^{d_\parallel})$$

  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 [25]

Universal deviation
from Standard Model
in dijet distribution



$M_s = 2$ TeV

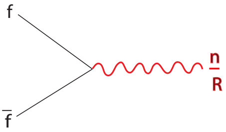
Width = 15-150 GeV

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

present LHC limits: $M_s \gtrsim 4.5$ TeV

Localized fermions (on 3-brane intersections) [22]

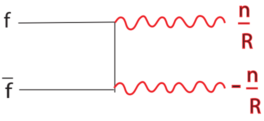
⇒ single production of KK modes I.A.-Benakli '94



- strong bounds indirect effects
- new resonances but at most $n = 1$

Otherwise KK momentum conservation

⇒ pair production of KK modes (universal dims)



- weak bounds
- no resonances
- lightest KK stable : dark matter candidate

Servant-Tait '02

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

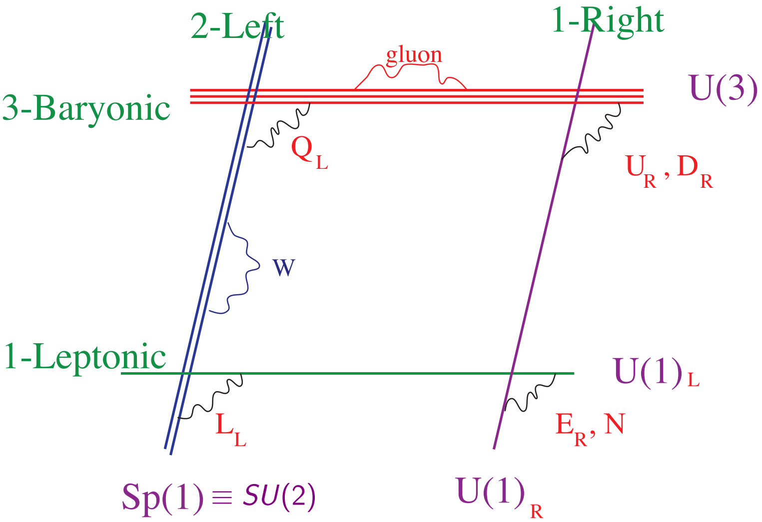
Two kinds of massive $U(1)$'s: I.A.-Kiritsis-Rizos '02

- 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 $\Rightarrow M_{NA} \geq M_A$

or massless in the absence of such anomalies

Standard Model on D-branes : SM^{++}



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

TeV string scale

Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor '11

- 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: $\frac{\langle H \rangle^2}{M_s} LL$

  $\sim$ GeV

- $B, L \Rrightarrow$ extra Z's

  with possible leptophobic couplings leading to CDF-type Wjj events

  $Z' \simeq B$ lighter than 4d anomaly free $Z'' \simeq B - L$

High string scale

AAGHLT+Vlcek '12

- $Z' \simeq B$ 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 and B global symmetry $\Rightarrow$ Z''-gauge coupling fixed
- present LHC limits: $m_{Z''} \gtrsim 2.5$ TeV scale
- 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 $U(1)_R$ (mostly)
- LHC14 discovery potential: $M_{Z''}$ up to ~ 5 TeV (in dijets)

Recent cosmological observations indicate an extra relativistic component

dark radiation parametrized by an effective neutrino number close to 4

→ use the 3 ν_R's interacting with SM fermions via Z''

data: their decoupling during the quark-hadron transition

- absence of chemical potential $\Rightarrow 3.6 < M_{Z''} < 4.8$ TeV
- thermal equlibrium $\Rightarrow 5.4 < M_{Z''} < 6$ TeV

Stability analysis in (non-susy) SM^{++} AAGHLTV to appear

Scalar potential:

$$V\left(H,H''\right)=\mu^2\left|H\right|^2+\mu'^2\left|H''\right|^2+\lambda_1\left|H\right|^4+\lambda_2\left|H''\right|^4+\lambda_3\left|H\right|^2\left|H''\right|^2$$

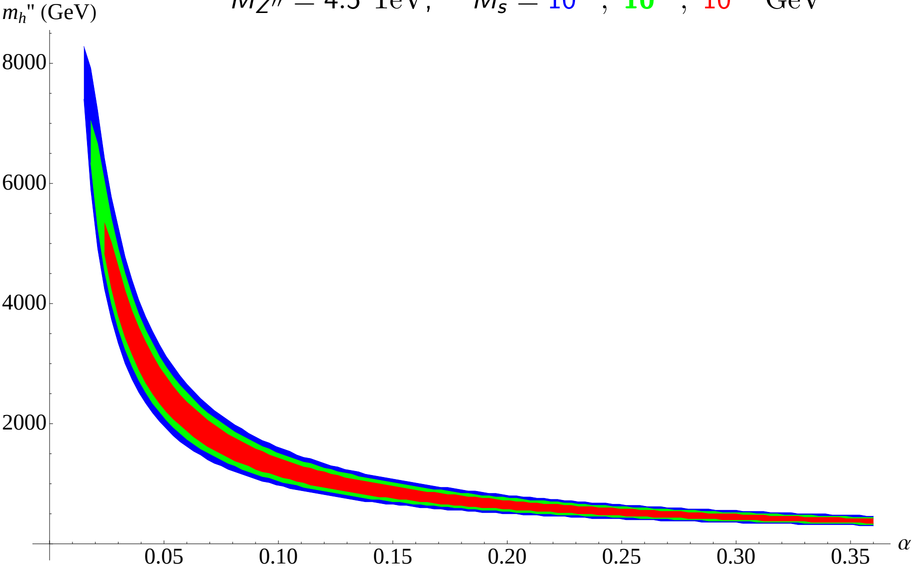
5 parameters $\Rightarrow v, m_h, v'', m_{h''}$ + a Higgs mixing angle α

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

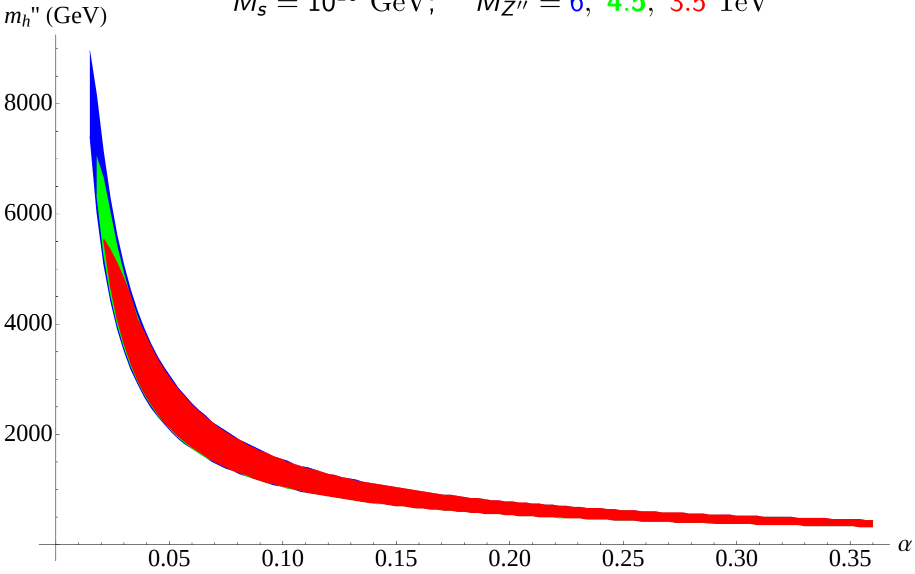
Stability conditions: $\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_1\lambda_2 > \frac{1}{4}\lambda_3^2$

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

$M_{Z''} = 4.5$ TeV; $M_s = 10^{14}, 10^{16}, 10^{19}$ GeV



$M_s = 10^{16}$ GeV; $M_{Z''} = 6,\ 4.5,\ 3.5$ TeV



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