

# Aspects of string phenomenology in the LHC era

I. Antoniadis



Pre-SUSY 2014, Manchester, 15-18 July 2014



- 1 LHC: where do we stand? where do we go?
- 2 Supersymmetry: is it alive?
- 3 String phenomenology: what for? main issues
- 4 High string scale - heterotic string
- 5 High string scale - type IIA/B and intersecting/magnetized branes
- 6 Low string scale and large extra dimensions
- 7 Experimental predictions
- 8 Warped spaces and holography

- *Topics on String Phenomenology*  
I. Antoniadis  
e-Print: arXiv:0710.4267 [hep-th]
- *An Introduction to perturbative and nonperturbative string theory*  
Ignatios Antoniadis, Guillaume Ovarlez  
e-Print: hep-th/9906108
- *String theory and particle physics: An introduction to string phenomenology*  
Luis E. Ibanez, Angel M. Uranga  
Published in Cambridge, UK: Univ. Pr. (2012) 673 p

## $H^0$ (Higgs Boson)

particle  
listing

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

### $H^0$ MASS

<u>VALUE (GeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>125.9±0.4 OUR AVERAGE</b>			
125.8±0.4±0.4	<sup>1</sup> CHATRCHYAN 13J	CMS	<i>pp</i> , 7 and 8 TeV
126.0±0.4±0.4	<sup>2</sup> AAD 12AI	ATLS	<i>pp</i> , 7 and 8 TeV
● ● ● We do not use the following	data for averages, fits, limits, etc. ● ● ●		
126.2±0.6±0.2	<sup>3</sup> CHATRCHYAN 13J	CMS	<i>pp</i> , 7 and 8 TeV
125.3±0.4±0.5	<sup>4</sup> CHATRCHYAN 12N	CMS	<i>pp</i> , 7 and 8 TeV

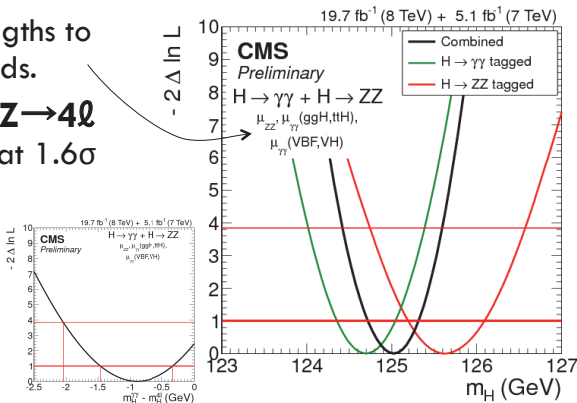
[HTTP://PDG.LBL.GOV](http://pdg.lbl.gov)

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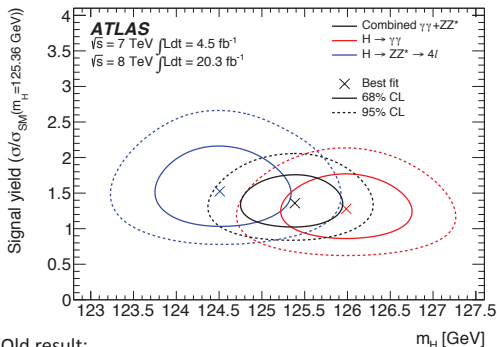
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$$m_H = 125.03 \pm 0.30 \left[ \begin{array}{l} +0.26 \\ -0.27 \end{array} (\text{stat.}) \begin{array}{l} +0.13 \\ -0.15 \end{array} (\text{syst.}) \right] \text{ GeV}$$

- Float 3 signal strengths to not depend on yields.
- $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4\ell$  results compatible at 1.6 $\sigma$  level.



# Measurement of the Higgs boson mass (and signal strengths)



Note measure channels  
signal strength

$$\mu_{(m_H=125.98 \text{ GeV})}^{\gamma\gamma} = 1.29 \pm 0.30$$

$$\mu_{(m_H=124.51 \text{ GeV})}^{ZZ} = 1.66^{+0.45}_{-0.38}$$

ZZ and  $\gamma\gamma$  compatibility

$$\text{Old} \left\{ \begin{array}{l} \Delta m = 2.3 \pm 0.9 \\ \text{Compatibility } 2.4\sigma \end{array} \right.$$

$$\Delta m = 1.47 \pm 0.72$$

$$\text{Compatibility } 1.97\sigma_{18}$$

Old result:

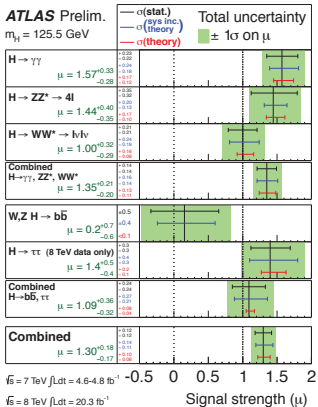
$$125.5 \pm 0.2 \text{ (stat)}^{+0.5}_{-0.6} \text{ (syst)} \text{ GeV}$$

New:

$$125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)} \text{ GeV}$$

0.3% Precision measurement (statistical uncertainty dominant)

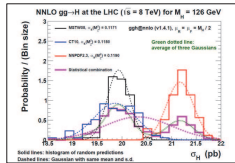
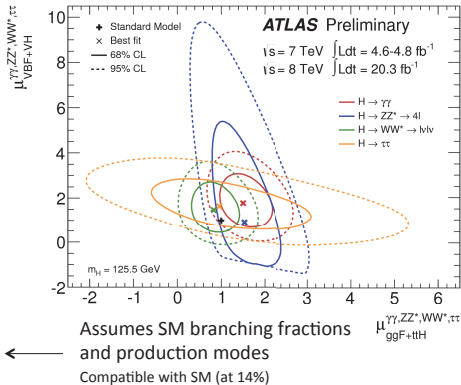
# Main Decay and Production Modes



$$\mu = 1.30 \pm 0.12 \text{ (stat)} \pm 0.10 \text{ (th)} \pm 0.09 \text{ (syst)}$$

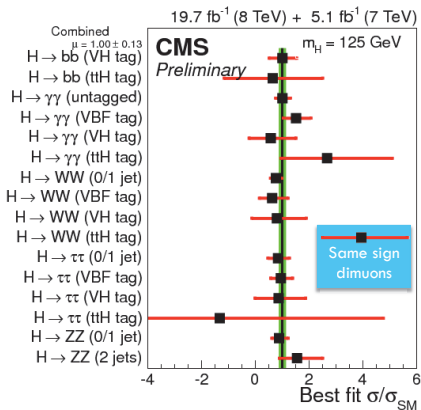
All channels couplings updated soon

Stay tuned !



$$\sigma/\sigma_{\text{SM}} = 1.00 \pm 0.13 \left[ \pm 0.09(\text{stat.})_{-0.07}^{+0.08}(\text{theo.}) \pm 0.07(\text{syst.}) \right]$$

- Grouped by production tag and dominant decay:
  - ▣  $\chi^2/\text{dof} = 10.5/16$
  - ▣ p-value = 0.84 (asymptotic)
- ttH-tagged  $2.0\sigma$  above SM.
  - ▣ Driven by one channel.





François Englert



Peter Higgs



Nobel Prize of Physics 2013



# The value of its mass $\sim 125$ GeV

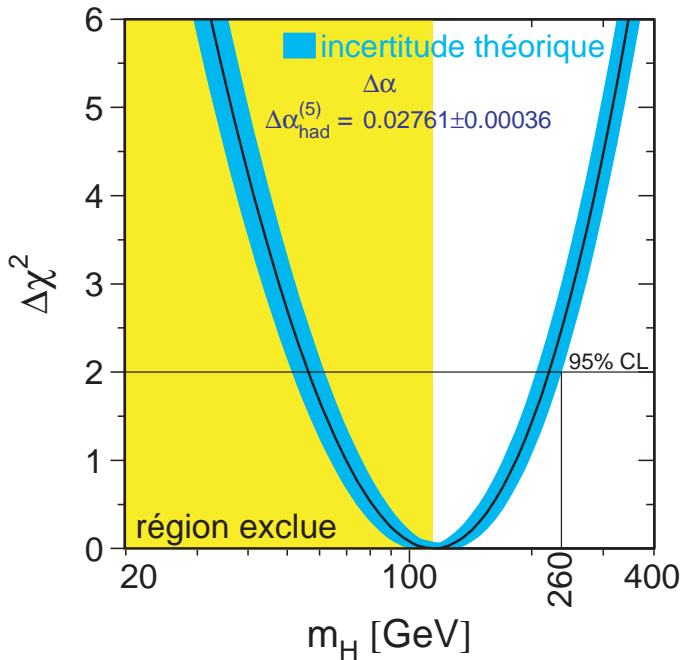
- consistent with expectation from precision tests of the SM
- favors perturbative physics     quartic coupling  $\lambda = m_H^2/v^2 \simeq 1/8$
- 1st elementary scalar in nature signaling perhaps more to come
- triumph of QFT and renormalized perturbation theory!

Standard Theory has been tested with radiative corrections

## Window to new physics ?

- very important to measure precisely its properties and couplings
- several new and old questions wait for answers

Dark matter, neutrino masses, baryon asymmetry, flavor physics, axions, electroweak scale hierarchy, early cosmology, ...



# Beyond the Standard Theory 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 % - %<sub>00</sub> fine-tuning     'little' hierarchy problem

Inclusive searches

3rd gen. gluino mediated

3rd gen. squarks direct production

EW direct

Long-lived particles

RPV

- MSUGRA/CMSSM : 0 lep +  $j's + E_{T,miss}$
- MSUGRA/CMSSM : 1 lep +  $j's + E_{T,miss}$
- Pheno model : 0 lep +  $j's + E_{T,miss}$
- Pheno model : 0 lep +  $j's + E_{T,miss}$
- Glauino med.  $\tilde{\chi}^0(\tilde{g} \rightarrow q\tilde{\chi}^0)$  : 1 lep +  $j's + E_{T,miss}$
- GMSB (NLSP) : 2 lep (OS) +  $j's + E_{T,miss}$
- GMSB (NLSP) : 1-2  $\tau + j's + E_{T,miss}$
- GGM (bino NLSP) :  $\gamma\gamma + E_{T,miss}$
- GGM (wino NLSP) :  $\gamma + lep + E_{T,miss}$
- GGM (higgsino-bino NLSP) :  $\gamma + b + E_{T,miss}$
- GGM (higgsino NLSP) :  $Z + jets + E_{T,miss}$
- Gravitino LSP : 'monojet' +  $E_{T,miss}$
- $\tilde{g} \rightarrow b\tilde{b}^*$  : 0 lep + 3 b-jets +  $E_{T,miss}$
- $\tilde{g} \rightarrow t\tilde{t}^*$  : 2 SS-lep + (0-3b- $j's + E_{T,miss}$
- $\tilde{g} \rightarrow t\tilde{t}^*$  : 0 lep + multi- $j's + E_{T,miss}$
- $\tilde{g} \rightarrow t\tilde{t}^*$  : 0 lep + 3 b-jets +  $E_{T,miss}$
- $\tilde{b}_1, \tilde{b}_2 \rightarrow b\tilde{b}^*$  : 0 lep + 2-b-jets +  $E_{T,miss}$
- $\tilde{b}_1, \tilde{b}_2 \rightarrow t\tilde{t}^*$  : 2 SS-lep + (0-3b- $j's + E_{T,miss}$
- $\tilde{t}_1$  (light),  $\tilde{t}_2 \rightarrow b\tilde{b}^*$  : 1/2 lep + (b-jet) +  $E_{T,miss}$
- $\tilde{t}_1$  (medium),  $\tilde{t}_2 \rightarrow b\tilde{b}^*$  : 1 lep + b-jet +  $E_{T,miss}$
- $\tilde{t}_1$  (heavy),  $\tilde{t}_2 \rightarrow b\tilde{b}^*$  : 2 lep +  $E_{T,miss}$
- $\tilde{t}_1$  (heavy),  $\tilde{t}_2 \rightarrow t\tilde{t}^*$  : 1 lep + b-jet +  $E_{T,miss}$
- $\tilde{t}_1$  (heavy),  $\tilde{t}_2 \rightarrow t\tilde{t}^*$  : 0 lep + 6(2b)-jets +  $E_{T,miss}$
- $\tilde{t}_1$  (natural GMSB) :  $Z(\rightarrow ll) + b\text{-jet} + E_{T,miss}$
- $\tilde{t}_1, \tilde{t}_2 \rightarrow l\tilde{l} + Z$  :  $Z(\rightarrow ll) + 1 \text{lep} + b\text{-jet} + E_{T,miss}$
- $\tilde{t}_1, \tilde{t}_2 \rightarrow l\tilde{l} + \tilde{g}$  : 2 lep +  $E_{T,miss}$
- $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{l} \tilde{l}^* + \nu(\tilde{\nu})$  : 2 lep +  $E_{T,miss}$
- $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\nu} \tilde{\nu}^* + \nu(\tilde{\nu})$  : 2  $\tau + E_{T,miss}$
- $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{l} \tilde{l}^* + \nu(\tilde{\nu})$ ,  $\tilde{l} \tilde{l}^* + \nu(\tilde{\nu})$  : 3 lep +  $E_{T,miss}$
- $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W^+ \tilde{\chi}_1^{\pm} Z^0 \tilde{\chi}_2^0$  : 3 lep +  $E_{T,miss}$
- Direct  $\tilde{\chi}_1^0$  pair prod. (AMSB) : long-lived  $\tilde{\chi}_1^0$
- Stable  $\tilde{g}$ , R-hadrons : low  $\beta$ , low GMSB, stable  $\tilde{t}$ , low  $\beta$
- GMSB,  $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$  : non-pointing photons
- $\tilde{\chi}_1^0 \rightarrow q\tilde{q}$  (RPV) :  $\mu +$  heavy displaced vertex
- LFV :  $pp \rightarrow \tilde{\nu} + X, \tilde{\nu} \rightarrow e + \mu$  resonance
- LFV :  $pp \rightarrow \tilde{\nu} + X, \tilde{\nu} \rightarrow e(\mu) + \tau$  resonance
- Bilinear RPV CMSSM : 1 lep + 7  $j's + E_{T,miss}$
- $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W_{\tau}^0 \tilde{\chi}_1^{\pm} \rightarrow e\tilde{\nu}_\tau e\nu_\tau$  : 4 lep +  $E_{T,miss}$
- $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\nu}_\tau + \tau\nu_\tau, e\nu_\tau$  : 3 lep + 1  $\tau + E_{T,miss}$
- $\tilde{g} \rightarrow q\tilde{q}$  : 3-jet resonance pair
- $\tilde{g} \rightarrow t\tilde{t}$ ,  $\tilde{t} \rightarrow bs$  : 2 SS-lep + (0-3b- $j's + E_{T,miss}$
- Scalar gluon : 2-jet resonance pair
- WIMP interaction (D5, Dirac  $\chi$ ) : 'monojet' +  $E_{T,miss}$

Search	Lower Limit [TeV]	Upper Limit [TeV]	Notes
$\tilde{g}$ mass	1.80 TeV	$\tilde{g} = \tilde{g}$ mass	
$\tilde{g}$ mass	1.24 TeV	$\tilde{g} = \tilde{g}$ mass	
$\tilde{g}$ mass	1.18 TeV	$\tilde{g}$ mass ( $m(\tilde{g}) < 2 \text{ TeV}, \text{light } \tilde{\chi}_2^0$ )	
$\tilde{g}$ mass	1.28 TeV	$\tilde{g}$ mass ( $m(\tilde{g}) < 2 \text{ TeV}, \text{light } \tilde{\chi}_1^0$ )	
$\tilde{g}$ mass	900 GeV	$\tilde{g}$ mass ( $m(\tilde{\chi}_2^0) < 200 \text{ GeV}, m(\tilde{\chi}_1^0) = \frac{1}{2}m(\tilde{\chi}_2^0) + m(\tilde{g})$ )	
$\tilde{g}$ mass	1.24 TeV	$\tilde{g}$ mass ( $\tan\beta < 15$ )	
$\tilde{g}$ mass	1.40 TeV	$\tilde{g}$ mass ( $ \tan\beta  > 18$ )	
$\tilde{g}$ mass	1.07 TeV	$\tilde{g}$ mass ( $m(\tilde{\chi}_2^0) > 50 \text{ GeV}$ )	
$\tilde{g}$ mass	619 GeV	$\tilde{g}$ mass	
$\tilde{g}$ mass	900 GeV	$\tilde{g}$ mass ( $m(\tilde{\chi}_2^0) < 220 \text{ GeV}$ )	
$\tilde{g}$ mass	880 GeV	$\tilde{g}$ mass ( $m(\tilde{H}^0) > 200 \text{ GeV}$ )	
$F$ scale	845 GeV	$F$ scale ( $m(\tilde{G}) > 10^4 eV$ )	
$\tilde{g}$ mass	1.24 TeV	$\tilde{g}$ mass ( $m(\tilde{\chi}_2^0) < 200 \text{ GeV}$ )	
$\tilde{g}$ mass	900 GeV	$\tilde{g}$ mass (any $m(\tilde{\chi}_2^0)$ )	
$\tilde{g}$ mass	1.00 TeV	$\tilde{g}$ mass ( $m(\tilde{\chi}_2^0) < 300 \text{ GeV}$ )	
$\tilde{g}$ mass	1.18 TeV	$\tilde{g}$ mass ( $m(\tilde{\chi}_2^0) < 200 \text{ GeV}$ )	
$\tilde{b}$ mass	620 GeV	$\tilde{b}$ mass ( $m(\tilde{\chi}_2^0) < 120 \text{ GeV}$ )	
$\tilde{b}$ mass	430 GeV	$\tilde{b}$ mass ( $m(\tilde{\chi}_2^0) = 2m(\tilde{\chi}_1^0)$ )	
$\tilde{t}$ mass	167 GeV	$\tilde{t}$ mass ( $m(\tilde{\chi}_2^0) = 55 \text{ GeV}$ )	
$\tilde{t}$ mass	160-410 GeV	$\tilde{t}$ mass ( $m(\tilde{\chi}_2^0) = 0 \text{ GeV}, m(\tilde{\chi}_1^0) = 150 \text{ GeV}$ )	
$\tilde{t}$ mass	160-640 GeV	$\tilde{t}$ mass ( $m(\tilde{\chi}_2^0) = 0 \text{ GeV}, m(\tilde{\chi}_1^0) = 10 \text{ GeV}$ )	
$\tilde{t}$ mass	200-610 GeV	$\tilde{t}$ mass ( $m(\tilde{\chi}_2^0) > 0$ )	
$\tilde{t}$ mass	200-660 GeV	$\tilde{t}$ mass ( $m(\tilde{\chi}_2^0) = 0$ )	
$\tilde{t}$ mass	500 GeV	$\tilde{t}$ mass ( $m(\tilde{\chi}_2^0) > 150 \text{ GeV}$ )	
$\tilde{t}$ mass	520 GeV	$\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0) + 180 \text{ GeV}$ )	
$\tilde{t}$ mass	85-195 GeV	$\tilde{t}$ mass ( $m(\tilde{\chi}_2^0) = 0$ )	
$\tilde{\chi}_2^0$ mass	116-340 GeV	$\tilde{\chi}_2^0$ mass ( $m(\tilde{\chi}_2^0) < 10 \text{ GeV}, m(\tilde{\nu}_\tau) = \frac{1}{2}m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)$ )	
$\tilde{\chi}_2^0$ mass	180-330 GeV	$\tilde{\chi}_2^0$ mass ( $m(\tilde{\chi}_2^0) < 10 \text{ GeV}, m(\tilde{\nu}_\tau) = \frac{1}{2}m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)$ )	
$\tilde{\chi}_2^0$ mass	600 GeV	$\tilde{\chi}_2^0$ mass ( $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\nu}_\tau) \text{ as above}$ )	
$\tilde{\chi}_2^0$ mass	315 GeV	$\tilde{\chi}_2^0$ mass ( $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 0$ , sleptons decoupled)	
$\tilde{\chi}_1^0$ mass	220 GeV	$\tilde{\chi}_1^0$ mass ( $1 < \tau(\tilde{\chi}_1^0) < 10 \text{ ns}$ )	
$\tilde{g}$ mass	985 GeV	$\tilde{g}$ mass	
$\tilde{t}$ mass	300 GeV	$\tilde{t}$ mass ( $ \delta < \tan\beta < 20$ )	
$\tilde{\chi}_1^0$ mass	230 GeV	$\tilde{\chi}_1^0$ mass ( $0.4 < \tau(\tilde{\chi}_1^0) < 2 \text{ ns}$ )	
$\tilde{q}$ mass	790 GeV	$\tilde{q}$ mass (1 mm $< c\tau < 1 \text{ m}, \tilde{g}$ decoupled)	
$\tilde{\nu}_\tau$ mass	1.61 TeV	$\tilde{\nu}_\tau$ mass ( $\lambda_{311} = 0.10, \lambda_{323} = 0.05$ )	
$\tilde{\nu}_\tau$ mass	1.10 TeV	$\tilde{\nu}_\tau$ mass ( $\lambda_{311} = 0.10, \lambda_{323} = 0.05$ )	
$\tilde{g}$ mass	1.2 TeV	$\tilde{g} = \tilde{g}$ mass ( $c\tau_{311} < 1 \text{ mm}$ )	
$\tilde{\chi}_1^0$ mass	760 GeV	$\tilde{\chi}_1^0$ mass ( $m(\tilde{\chi}_2^0) > 300 \text{ GeV}, \lambda_{311} > 0$ )	
$\tilde{\chi}_1^0$ mass	350 GeV	$\tilde{\chi}_1^0$ mass ( $m(\tilde{\chi}_2^0) > 80 \text{ GeV}, \lambda_{311} > 0$ )	
$\tilde{g}$ mass	666 GeV	$\tilde{g}$ mass	
$\tilde{g}$ mass	880 GeV	$\tilde{g}$ mass (any $m(\tilde{\chi}_2^0)$ )	
sgluon mass	100-287 GeV	sgluon mass (incl. limit from 1110.2693)	
$M^*$ scale	704 GeV	$M^*$ scale ( $m_* < 80 \text{ GeV}$ , limit of $< 687 \text{ GeV}$ for D8)	

$$\int L dt = (4.4 - 20.7) \text{ fb}^{-1}$$

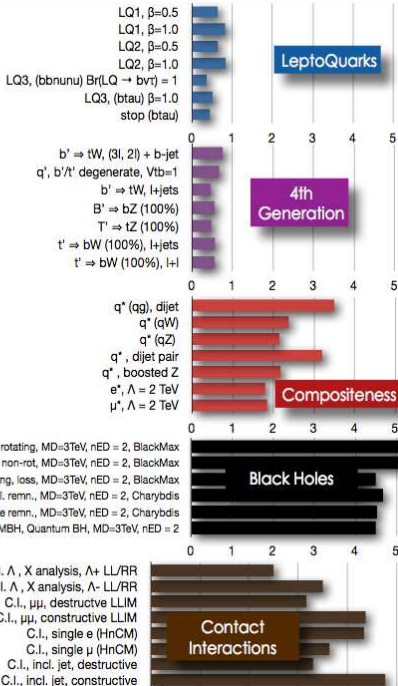
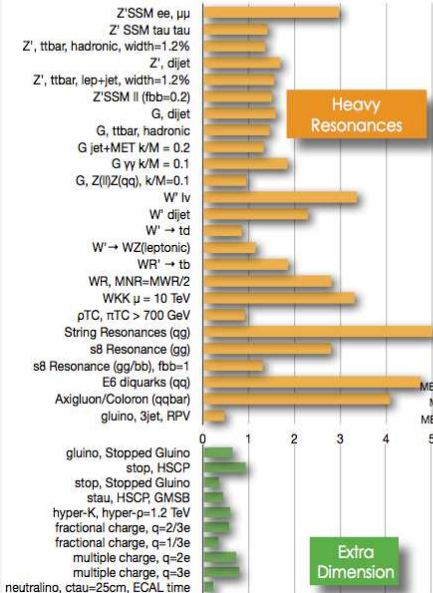
$$\sqrt{s} = 7, 8 \text{ TeV}$$

- 8 TeV, all 2012 data
- 8 TeV, partial 2012 data
- 7 TeV, all 2011 data

\*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty

# CMS EXOTICA

95% CL EXCLUSION LIMITS (TeV)



# What is next?

# What is next?

Physics is an experimental science

- Exploit the full potential of LHC
- Go on and explore the multi TeV energy range





# The LHC timeline

## LS1 Machine Consolidation

## LS2 Machine upgrades for high Luminosity

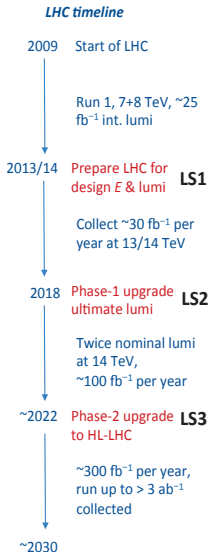
- Collimation
- Cryogenics
- Injector upgrade for high intensity (lower emittance)
- Phase I for ATLAS : Pixel upgrade, FTK, and new small wheel

## LS3 Machine upgrades for high Luminosity

- Upgrade interaction region
- Crab cavities?
- Phase II: full replacement of tracker, new trigger scheme (add L0), readout electronics.

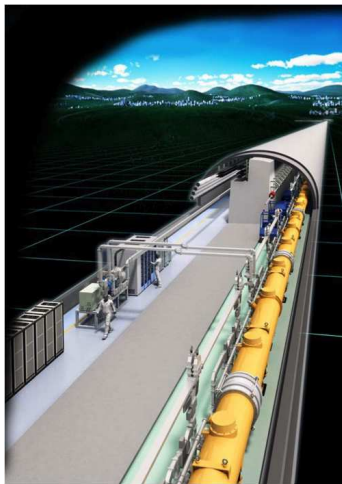


*Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.*

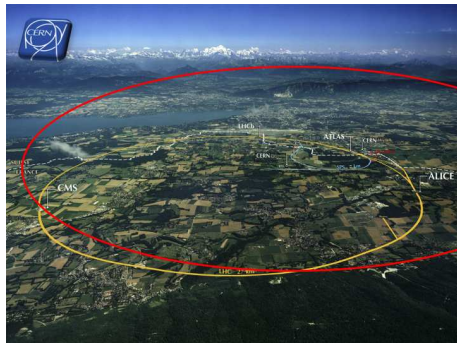


# We must **fully** explore the 10-100 TeV energy range

## ILC project



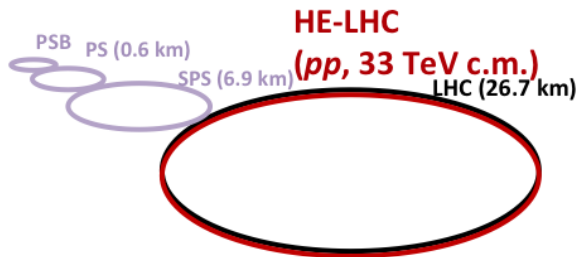
## The future of LHC



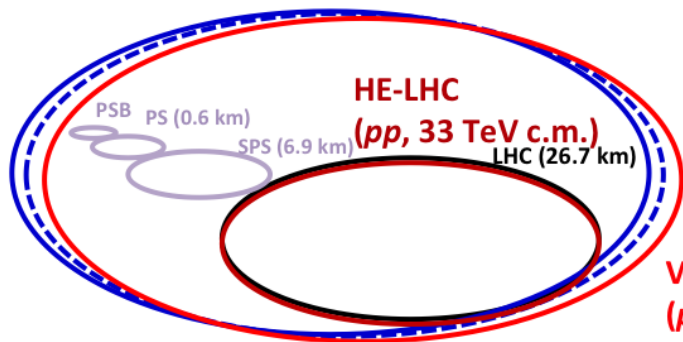
# *possible long-term strategy*



# *possible long-term strategy*

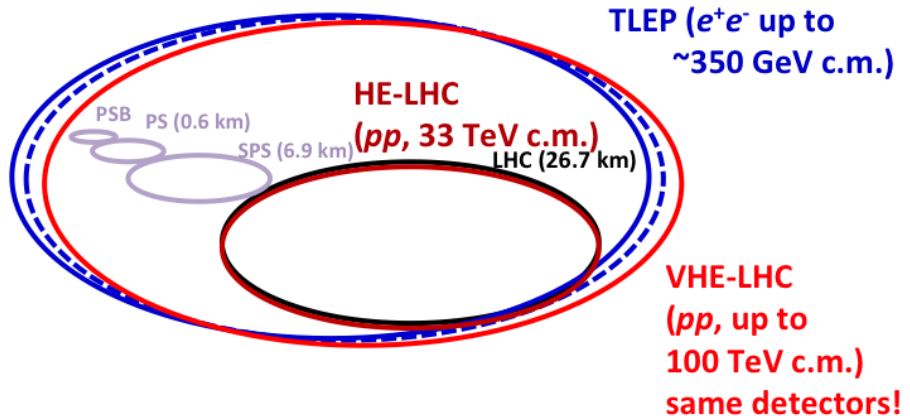


# *possible long-term strategy*



**VHE-LHC**  
**(pp, up to**  
**100 TeV c.m.)**  
**same detectors!**

# possible long-term strategy



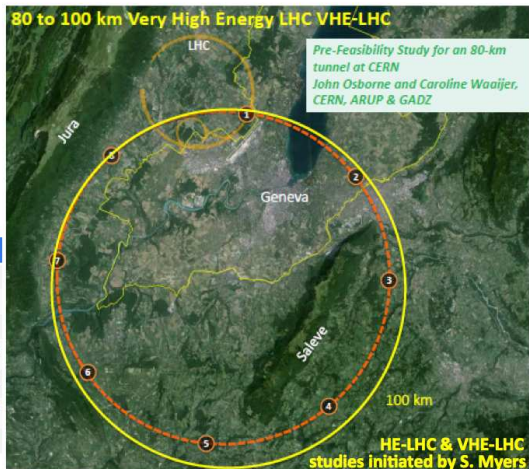
also:  $e^\pm$  (120 GeV) –  $p$  (7 & 50 TeV) collisions

$\geq 50$  years of  $e^+e^-$ ,  $pp$ ,  $ep/A$  physics at highest energies

# VHE-LHC: location and size

- 100 TeV p-p collider
- CDR and cost review to be ready for next European Strategy Update
- The tunnel could also house a  $e^+e^-$  Higgs factory (TLEP)

	TLEP
circumference	80 km
Beam energy up to	370 GeV c.m.
max no. of IPs	4
Luminosity/IP at 350 GeV c.m.	$1.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Luminosity/IP at 240 GeV c.m.	$4.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Luminosity/IP at 160 GeV c.m.	$1.6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
Luminosity/IP at 90 GeV c.m.	$5.6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$



A circumference of 100 km is being considered for cost-benefit reasons  
20T magnet in 80 km / 16T magnet in 100 km → 100 TeV

## Future Circular Collider Study - FCC

### Mandate

#### Context

A conceptual design study of options for a future high-energy frontier circular collider at CERN for the post-LHC era shall be carried out, implementing the request in the 2013 update of the European Strategy for Particle Physics (CERN-Council-S/106), which states, inter alia, that:

*“... Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.” and that “CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.”*

<http://cds.cern.ch/record/1567258/files/esc-e-106.pdf>

This design study shall be organised on a world-wide international collaboration basis under the auspices of the European Committee for Future Accelerators (ECFA) and shall be available in time for the next update of the European Strategy for Particle Physics, foreseen by 2018.





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## Future Circular Colliders Study Kickoff Meeting

12-15 February 2014  
University of Geneva - UNI

MAIL

Europe/Zurich timezone

Webcast: Please note that this event will be available live via the Webcast Service.

### Future Circular Collider Kickoff Meeting

#### Overview

#### Organizing Committees

#### Important dates

#### Timetable

#### Contribution List

#### Registration

#### [Registration Form](#)

This meeting is the starting point of a five-year international design study called "Future Circular Colliders" (FCC) with emphasis on a hadron collider with a centre-of-mass energy of the order of 100 TeV in a new 80-100 km tunnel as a long-term goal. The design study includes a 90-400 GeV lepton collider, seen as a potential intermediate step. It also examines a lepton-hadron collider option. The international kick-off meeting for the FCC design study will be held at the University of Geneva, Unimail site, on 12-15 February 2014. The scope of this meeting will be to discuss the main study topics and to prepare the groundwork for the establishment of international collaborations and future studies. The formal part of the meeting will start at noon on Wednesday 12 February and last until noon on Friday 14 February. It will be followed by break-out sessions on the various parts of the project on the Friday afternoon, with summary sessions until noon on Saturday 15 February.

# 126 GeV Higgs compatible with supersymmetry

Upper bound on the lightest scalar mass:

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

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

$\Rightarrow$  % to a few ‰ fine-tuning

$$\text{minimum of the potential: } m_Z^2 = 2 \frac{m_1^1 - m_2^2 \tan^2 \beta}{\tan^2 \beta - 1} \sim -2m_2^2 + \dots$$

$$\begin{aligned} \text{RG evolution: } m_2^2 &= m_2^2(M_{\text{GUT}}) - \frac{3\lambda_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln \frac{M_{\text{GUT}}}{m_{\tilde{t}}} + \dots \quad [31] \\ &\sim m_2^2(M_{\text{GUT}}) - \mathcal{O}(1)m_{\tilde{t}}^2 + \dots \end{aligned}$$

# Reduce the fine-tuning

- minimize radiative corrections

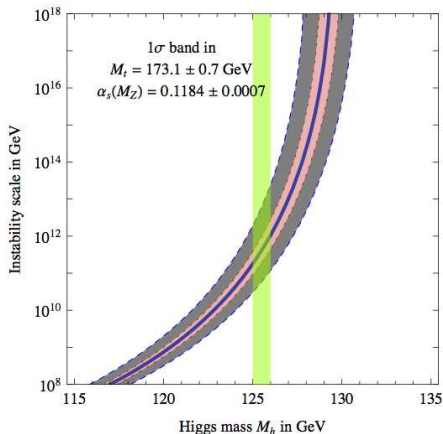
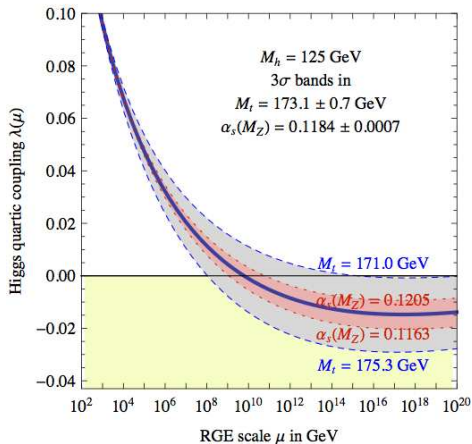
$M_{\text{GUT}} \rightarrow \Lambda$  : low messenger scale (gauge mediation)

$$\delta m_{\tilde{t}}^2 = \frac{8\alpha_s}{3\pi} M_3^2 \ln \frac{\Lambda}{M_3} + \dots$$

- increase the tree-level upper bound  $\Rightarrow$  extend the MSSM  
extra fields beyond LHC reach  $\rightarrow$  effective field theory approach
- Low scale SUSY breaking  $\Rightarrow$  extend MSSM with the goldstino  
 $\rightarrow$  Non linear MSSM
- ...

# 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

If the weak scale is tuned  $\Rightarrow$  split supersymmetry is a possibility

Arkani Hamed-Dimopoulos '04, Giudice-Romanino '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  $\Rightarrow$  'mini' split

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

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

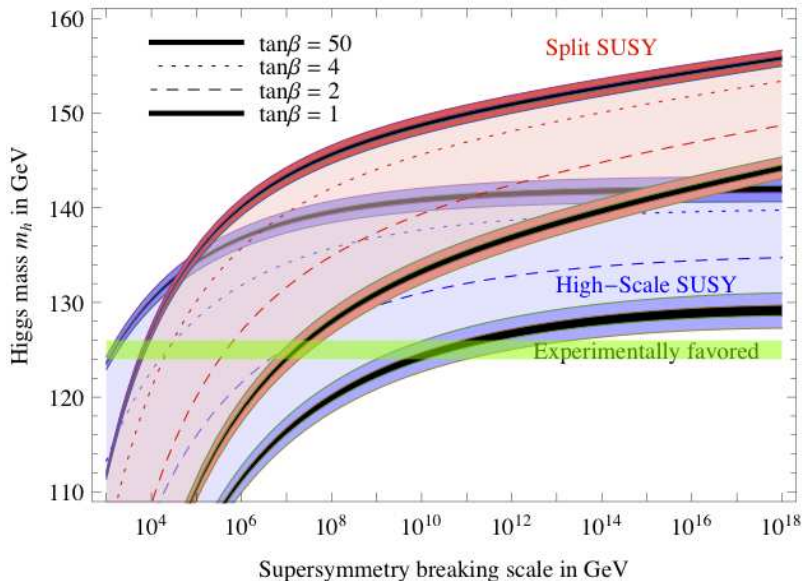
- natural string framework: intersecting (or magnetized) branes

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



## 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  $R_{\perp}^n = 10^{32} l_s^n$  ( $R_{\perp} \sim .1 - 10^{-13} \text{ mm}$  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 [26]

$\Lambda \sim$  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

# Connect string theory to the real world

- Is it a tool for strong coupling dynamics or a theory of fundamental forces?
- Can string theory describe both particle physics and cosmology?
- What can we hope to learn from LHC and cosmological observations on string phenomenology?





# At what energies strings may be observed?

Very different answers depending mainly on the value of the string scale  $M_s$

Before 1994:  $M_s \simeq M_{\text{Planck}} \sim 10^{18}$  GeV     $l_s \simeq 10^{-32}$  cm    After 1994:

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

- physical motivations  $\Rightarrow$  favored energy regions:

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

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

SUSY breaking, strong CP axion, see-saw scale

• Low : TeV (hierarchy problem)

# High string scale

perturbative heterotic string : the most natural for SUSY and unification

gravity and gauge interactions have same origin

massless excitations of the closed string

But mismatch between string and GUT scales:

$$M_s = g_H M_P \simeq 50 M_{\text{GUT}} \quad g_H^2 \simeq \alpha_{\text{GUT}} \simeq 1/25 \quad [51]$$

in GUTs only one prediction from 3 gauge couplings unification:  $\sin^2 \theta_W$

introduce large threshold corrections or strong coupling  $\rightarrow M_s \simeq M_{\text{GUT}}$

but loose predictivity

# Heterotic string

gravity + gauge kinetic terms [52]

$$\int [d^{10}x] \frac{1}{g_H^2} M_H^8 \mathcal{R}^{(10)} + \int [d^{10}x] \frac{1}{g_H^2} M_H^6 \mathcal{F}_{MN}^2 \quad \text{simplified units: } 2 = \pi = 1$$

Compactification in 4 dims on a 6-dim manifold of volume  $V_6 \Rightarrow$

$$\int [d^4x] \frac{V_6}{g_H^2} M_H^8 \mathcal{R}^{(4)} + \int [d^4x] \frac{V_6}{g_H^2} M_H^6 \mathcal{F}_{\mu\nu}^2$$

$$\begin{array}{ccc} \parallel & \parallel & \Rightarrow \\ M_P^2 & 1/g^2 & \end{array}$$

$$M_P^2 = \frac{1}{g^2} M_H^2 \quad \frac{1}{g^2} = \frac{1}{g_H^2} V_6 M_H^6 \quad \Rightarrow \quad M_H = g M_P \quad g_H = g \sqrt{V_6} M_H^3$$

$$g_H \lesssim 1 \Rightarrow V_6 \sim \text{string size}$$

# Heterotic string: Spectrum

Gauge group  $G \leftrightarrow$  affine current algebra in the R-movers (bosonic) CFT

$$\left[ J_n^a, J_m^b \right] = f^{abc} J_{n+m}^c + k_G \delta^{ab} \delta_{n+m} \quad k_G : \text{integer level of central extension}$$

- $g_G^2 = g_H^2 / k_G$
  - dims of allowed matter reps constrained by  $k_G$
- }  $\Rightarrow k_G = 1 :$
- simplest constructions (CY's, orbifolds, lattices, free fermions)
  - maximum rank: 22
  - guarantee gauge coupling unification at  $M_H$
  - allowed reps: fundamentals & 2-index antisym of unitary groups, spinors of orthogonal groups

However: - no adjoints to break GUT groups

- in SM  $\sin^2 \theta_W = 3/8 \Rightarrow$  fractional electric charges

Schellekens '90

# (Hyper)charge quantization

All color singlet states have integer charges

fractional electric charged states: nice prediction or problematic?

lightest is stable  $\Rightarrow$  problematic?

ways out: - superheavy + inflate away

- be confined to integrally charged by extra gauge group

live without adjoints  $\Rightarrow$  non conventional 'semi'-GUTs

e.g. break fictitious  $SO(10)$  by discrete Wilson lines or projection to

flipped  $SU(5) \times U(1)$ , Pati-Salam type  $SU(4) \times SU(2)_L \times SU(2)_R$ , or direct SM

Heterotic models revived: Orbifold GUTs

groups in Munich, Bonn, Hamburg, Ohio, U Penn

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

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

- Yukawa couplings: hierarchies à la Froggatt-Nielsen

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

$$\lambda_n \sim \Phi^n \quad \langle \Phi \rangle \sim 0.1 M_s \rightarrow \text{hierarchies}$$

A single anomalous  $U(1) \Rightarrow \langle \Phi \rangle \neq 0$  to cancel the FI D-term

$$\text{D-term is shifted to } D + \frac{\text{Tr} Q}{192\pi^2} g_H^2 \quad [74]$$

- R-neutrinos: natural framework for see-saw mechanism

$$\langle h \rangle \nu_L \nu_R + M \nu_R \nu_R \quad \langle h \rangle = v \ll M \Rightarrow m_R \sim M; m_L \sim v^2/M$$

- proton decay: problematic dim-5 operators

in general need suppression higher than  $M_s$  or small couplings

- SUSY in a hidden sector from the other  $E_8 \rightarrow$  gravity mediation

# Open strings and D-branes

string propagation in space-time  $\Rightarrow$  2-dim world-sheet  $(\tau, \sigma)$   $X^\mu(\tau, \sigma)$

$\tau$ : time,  $\sigma \in [0, \pi]$ : spatial extension of the string

closed strings  $\Rightarrow \sigma$ : periodic  $X^\mu(\tau, 0) = X^\mu(\tau, \pi)$

open string  $\Rightarrow$  endpoints:  $\sigma = 0, \pi$  world-sheet boundaries  
they also carry gauge charges

D-branes = hypersurfaces where open strings can end

$D_p$ -brane: parallel dimensions:  $X^1, \dots, X^p$  (also time  $X^0$ )

$\partial_\sigma X^\mu = 0$  at  $\sigma = 0$  normal derivative vanishes

Newmann boundary conditions  $\Rightarrow$  free propagation along the boundary

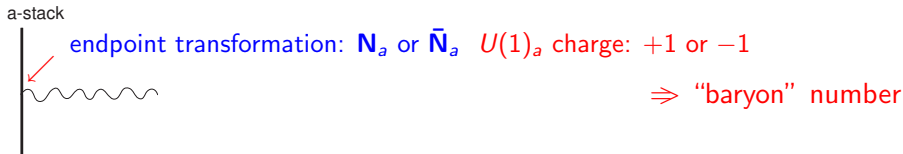
transverse dimensions:  $X^{p+1}, \dots, X^9$

$X^\mu = X_0^\mu$  at  $\sigma = 0$  ( $\partial_\tau X^\mu = 0$  at  $\sigma = 0$ )

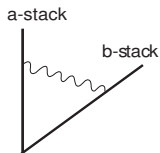
Dirichlet conditions: endpoint fixed at the boundary

# D-brane spectrum

Generic spectrum:  $N$  coincident branes  $\Rightarrow U(N)$



- open strings from the same stack  $\Rightarrow$  adjoint gauge multiplets of  $U(N_a)$
- stretched between two stacks  $\Rightarrow$  bifundamentals of  $U(N_a) \times U(N_b)$



non-oriented strings  $\Rightarrow$  also:

- orthogonal and symplectic groups  $SO(N)$ ,  $Sp(N)$
- matter in antisymmetric + symmetric reps

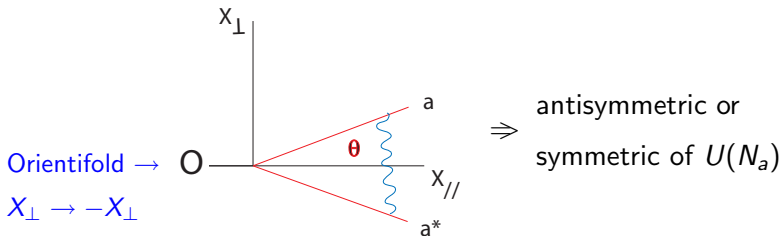


# Non oriented strings $\Rightarrow$ orientifold planes

where closed strings change orientation

$\Rightarrow$  mirror branes identified with branes under orientifold action

- strings stretched between two mirror stacks



# Minimal Standard Model embedding

General analysis using 3 brane stacks [56]

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

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

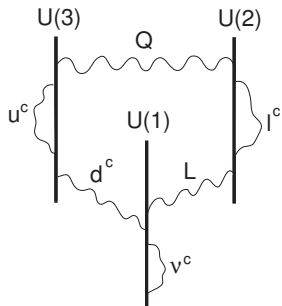
$N_i$  stack of D-branes:  $U(N_i) = SU(N_i) \times U(1)_i$

gauge couplings:  $\alpha_{N_i} = \frac{g_{N_i}^2}{4\pi}$  and  $\alpha_i$

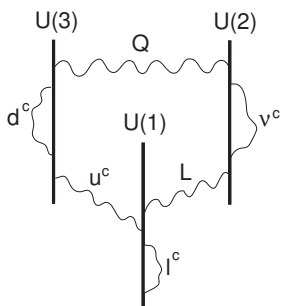
normalization:  $\text{Tr } T^a T^b = \frac{1}{2} \delta^{ab} \Rightarrow \alpha_i = \frac{\alpha_{N_i}}{2N_i}$

$$Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow \frac{1}{g_Y^2} = \frac{2c_1^2}{g_1^2} + \frac{4c_2^2}{g_2^2} + \frac{6c_3^2}{g_3^2}$$

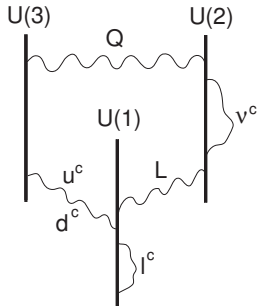
$$\sin^2 \theta_W = \frac{g_Y^2}{g_2^2 + g_Y^2} = \frac{1}{g_2^2/g_Y^2 + 1} = \frac{1}{1 + 4c_2^2 + 2c_1^2 g_2^2/g_1^2 + 6c_3^2 g_2^2/g_3^2}$$



**Model A**



**Model B**

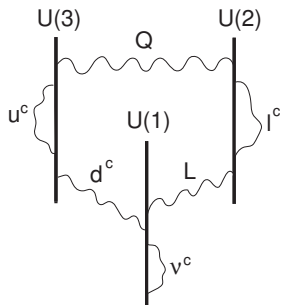


**Model C**

$Q$	$(\mathbf{3}, \mathbf{2}; 1, 1, 0)_{1/6}$
$u^c$	$(\bar{\mathbf{3}}, \mathbf{1}; 2, 0, 0)_{-2/3}$
$d^c$	$(\bar{\mathbf{3}}, \mathbf{1}; -1, 0, \varepsilon_d)_{1/3}$
$L$	$(\mathbf{1}, \mathbf{2}; 0, -1, \varepsilon_L)_{-1/2}$
$l^c$	$(\mathbf{1}, \mathbf{1}; 0, 2, 0)_1$
$\nu^c$	$(\mathbf{1}, \mathbf{1}; 0, 0, 2\varepsilon_\nu)_0$

$Q$	$(\mathbf{3}, \mathbf{2}; 1, \varepsilon_Q, 0)_{1/6}$
$u^c$	$(\bar{\mathbf{3}}, \mathbf{1}; -1, 0, 1)_{-2/3}$
$d^c$	$(\bar{\mathbf{3}}, \mathbf{1}; 2, 0, 0)_{1/3}$
$L$	$(\mathbf{1}, \mathbf{2}; 0, \varepsilon_L, 1)_{-1/2}$
$l^c$	$(\mathbf{1}, \mathbf{1}; 0, 0, -2)_1$
$\nu^c$	$(\mathbf{1}, \mathbf{1}; 0, 2\varepsilon_\nu, 0)_0$

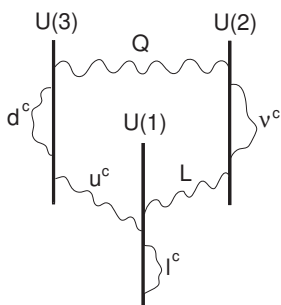
$Q$	$(\mathbf{3}, \mathbf{2}; 1, \varepsilon_Q, 0)_{1/6}$
$u^c$	$(\bar{\mathbf{3}}, \mathbf{1}; -1, 0, 1)_{-2/3}$
$d^c$	$(\bar{\mathbf{3}}, \mathbf{1}; -1, 0, -1)_{1/3}$
$L$	$(\mathbf{1}, \mathbf{2}; 0, \varepsilon_L, 1)_{-1/2}$
$l^c$	$(\mathbf{1}, \mathbf{1}; 0, 0, -2)_1$
$\nu^c$	$(\mathbf{1}, \mathbf{1}; 0, 2\varepsilon_\nu, 0)_0$



**Model A**

$$Y_A = -\frac{1}{3}Q_3 + \frac{1}{2}Q_2$$

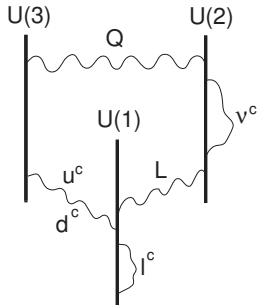
$$\sin^2 \theta_W = \frac{1}{2 + 2\alpha_2/3\alpha_3} \Big|_{\alpha_2=\alpha_3} = \frac{3}{8}$$



**Model B**

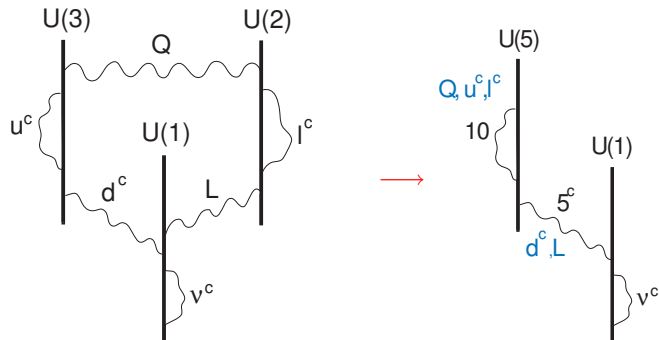
$$Y_{B,C} = \frac{1}{6}Q_3 - \frac{1}{2}Q_1$$

$$\frac{1}{1 + \alpha_2/2\alpha_1 + \alpha_2/6\alpha_3} \Big|_{\alpha_2=\alpha_3} = \frac{6}{7 + 3\alpha_2/\alpha_1}$$



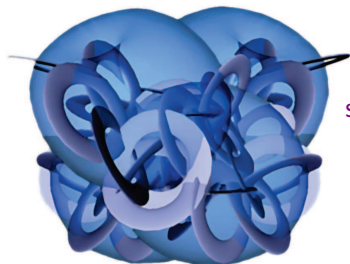
**Model C**

# $SU(5)$ GUT



# String moduli

String compactifications from 10/11 to 4 dims  $\rightarrow$  scalar moduli  
arbitrary VEVs: parametrize the compactification manifold



size of cycles, shapes,  $\dots$ , string coupling

- $N = 1$  SUSY  $\Rightarrow$  complexification: scalar +  $i$  pseudoscalar  $\equiv \phi_i$
- Low energy couplings: functions of moduli

e.g. gauge couplings:  $\frac{1}{g_a^2} F_a^2$       $a$ : gauge group

$N = 1$  SUSY  $\Rightarrow$  holomorphicity:  $\frac{1}{g_a^2} = \text{Re } f_a(\phi_i)$

SUSY transformation  $\Rightarrow$  moduli-dependent  $\theta$ -angles:

$$\theta_a F_a \tilde{F}_a \quad \text{with} \quad \theta_a = \text{Im } f_a(\phi_i)$$

In superspace:  $\int d^2\theta f(\phi_i) W_a^2$   $\leftarrow$  gauge field-strength chiral superfield



# Moduli stabilization

If moduli massless  $\rightarrow$  inconsistent

long range forces, cosmological production, accelerators

Outstanding problem: moduli stabilization

- avoid experimental conflict
- fix their VEVs  $\Rightarrow$  compute low energy couplings

Generate moduli potential: - preserving SUSY via  
- after SUSY breaking

- non-perturbative effects or by
- turn-on fluxes: constant field-strengths of generalized gauge potentials

gauge fields: internal magnetic fields

generalization: higher rank antisymmetric tensors

# Intersecting branes: 'perfect' for SM embedding

product of unitary gauge groups (brane stacks) and bi-fundamental reps  
but no unification: no prediction for  $M_s$ , independent gauge couplings

however GUTs: problematic:

- no perturbative  $SO(10)$  spinors
- no top-quark Yukawa coupling in  $SU(5)$ :  $10 10 5_H$   
 $SU(5)$  is part of  $U(5) \Rightarrow U(1)$  charges :  $10$  charge 2 ;  $5_H$  charge  $\pm 1$   
 $\Rightarrow$  cannot balance charges with  $SU(5)$  singlets  
can be generated by D-brane instantons but ...

→ Non-perturbative M/F-theory models:

combine good properties of heterotic and intersecting branes

but lack exact description for systematic studies

# 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 [54]

calculability  $\Rightarrow R_{\parallel} \simeq l_{\text{string}}$  ;  $R_{\perp}$  arbitrary

$$M_P^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_{\perp}^n \quad g_s = \alpha : \text{weak string coupling [34]}$$

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

$$M_s \sim 1 \text{ TeV} \Rightarrow R_{\perp}^n = 10^{32} l_s^n \text{ [83]} \quad \text{small } M_s/M_P : \text{extra-large } R_{\perp}$$

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

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

Type I/II strings: gravity and gauge interactions have different origin

gravity + gauge kinetic terms

$$\int [d^{10}x] \frac{1}{g_s^2} M_s^8 \mathcal{R}^{(10)} + \int [d^{p+1}x] \frac{1}{g_s} M_s^{p-3} \mathcal{F}_{MN}^2 \quad [35]$$

Compactification in 4 dims  $\Rightarrow$

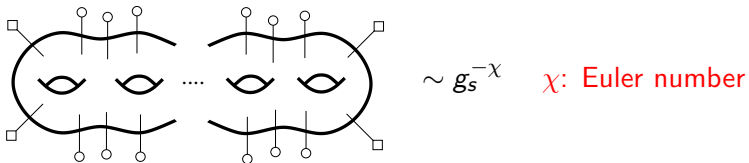
$$\int [d^4x] \frac{V_{\perp}}{g_s^2} M_s^8 \mathcal{R}^{(4)} + \int [d^4x] \frac{V_{\parallel}}{g_s} M_s^{p-3} \mathcal{F}_{\mu\nu}^2 \quad V_{\perp} = V_{\parallel} V_{\perp}$$

$$\begin{array}{ccc} \parallel & \parallel & \Rightarrow \\ M_P^2 & 1/g^2 & \\ \Rightarrow & & \\ g_s = g^2 V_{\parallel} M_s^{p-3} \lesssim 1 & \Rightarrow & V_{\parallel} \sim \text{string size} \end{array}$$

$$\Rightarrow M_P^2 = \frac{V_{\perp}}{g_s^2} M_s^{2+n} \quad g_s \simeq g^2$$

string propagation in space-time  $\Rightarrow$  2-dim world-sheet

string perturbation theory : world-sheet topological expansion



general characterization of 2-dim Riemann surfaces:

$$\chi = 2 - 2h - b - c$$

genus=nb of handles  $\nearrow$  boundaries  $\uparrow$  crosscaps  $\nwarrow$

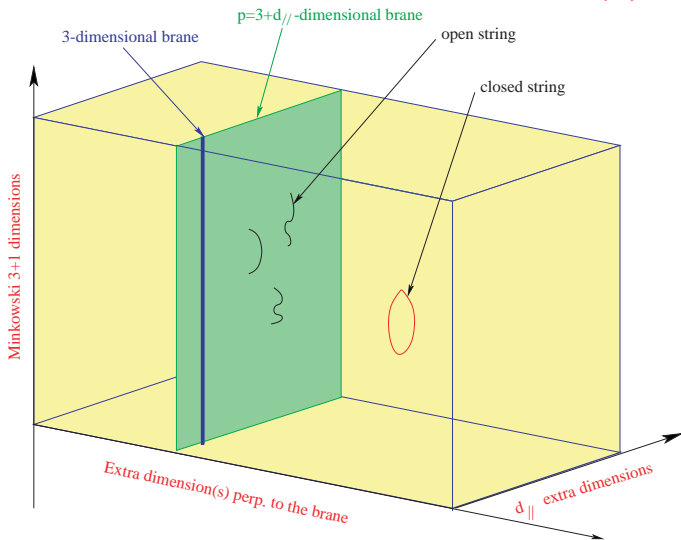
tree-level:  $h = b = c = 0 \Rightarrow 1/g_s^2$

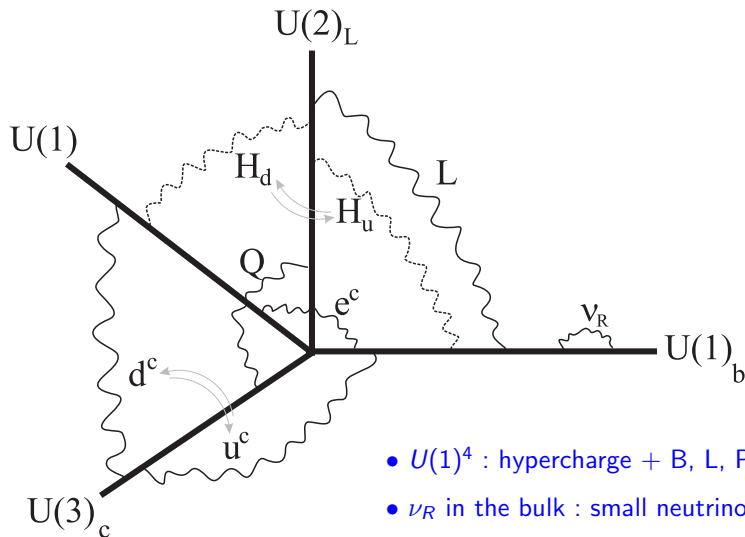
“tree-level” open strings:  $h = c = 0, b = 1 \Rightarrow 1/g_s$

# Braneworld

2 types of compact extra dimensions:

- parallel ( $d_{\parallel}$ ):  $\lesssim 10^{-16}$  cm (TeV) [51]
- transverse ( $\perp$ ):  $\lesssim 0.1$  mm (meV)





- $U(1)^4$  : hypercharge + B, L, PQ global
- $\nu_R$  in the bulk : small neutrino masses

fermion generation  $U(3) \times U(2) \times U(1)$  [42]

$$\begin{array}{ll}
 Q & (\mathbf{3}, \mathbf{2}; 1, w, 0)_{1/6} \quad w = \pm 1 \\
 u^c & (\bar{\mathbf{3}}, \mathbf{1}; -1, 0, x)_{-2/3} \quad x = \pm 1, 0 \\
 d^c & (\bar{\mathbf{3}}, \mathbf{1}; -1, 0, y)_{1/3} \quad y = \pm 1, 0 \\
 L & (\mathbf{1}, \mathbf{2}; 0, 1, z)_{-1/2} \quad z = \pm 1, 0 \\
 l^c & (\mathbf{1}, \mathbf{1}; 0, 0, 1)_1
 \end{array}$$

hypercharge  $Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow 2$  possibilities:

$$c_3 = -1/3 \quad c_2 = \pm 1/2 \quad x = -1 \quad y = 0 \quad w = \pm 1 \quad z = -1/0$$

$$c_3 = 2/3 \quad c_2 = \pm 1/2 \quad x = 0 \quad y = 1 \quad w = \mp 1 \quad z = -1/0$$



# R-neutrinos: in the bulk

Arkani Hamed-Dimopoulos-Dvali-March Russell '98

Dienes-Dudas-Gherghetta '98 Dvali-Smirnov '98

R-neutrino:  $\nu_R(x, y)$   $y$ : bulk coordinates

$$S_{int} = g_s \int d^4x H(x) L(x) \nu_R(x, y = 0)$$

$\langle H \rangle = v \Rightarrow$  mass-term:  $\frac{g_s v}{R_\perp^{n/2}} \nu_L \nu_R^0 \leftarrow$  4d zero-mode

Dirac neutrino masses:  $m_\nu \simeq \frac{g_s v}{R_\perp^{n/2}} \simeq v \frac{M_*}{M_p}$

$\simeq 10^{-3} - 10^{-2}$  eV for  $M_* \simeq 1 - 10$  TeV

$m_\nu \ll 1/R_\perp \Rightarrow$  KK modes unaffected

# 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 Higgs from the same brane

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

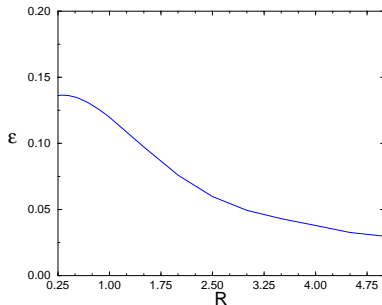
D-terms

$\mu^2 = -g^2 \epsilon^2 M_5^2 \leftarrow$  effective UV cutoff

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

Diagrammatic annotations for the integral:

- UV  $\swarrow$  (points to the upper limit  $\infty$ )
- IR  $\nearrow$  (points to the lower limit  $0$ )
- $e^{-\pi l}$   $\nearrow$  (points to the exponential term)
- $1$   $\swarrow$  (points to the constant term  $\frac{1}{2}$  in the parentheses)



$R \rightarrow 0 : \varepsilon(R) \simeq 0.14$     large transverse dim     $R_{\perp} = l_s^2/R \rightarrow \infty$

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

Higgs scalar = component of a higher dimensional gauge field

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

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

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

# Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk  $\Rightarrow$  missing energy [62]

present LHC bounds:  $M_* \gtrsim 3 - 5$  TeV

- Massive string vibrations  $\Rightarrow$  e.g. resonances in dijet distribution [64]

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

higher spin excitations of quarks and gluons with strong interactions

present LHC limits:  $M_s \gtrsim 5$  TeV

- Large TeV dimensions  $\Rightarrow$  KK resonances of SM gauge bosons I.A. '90

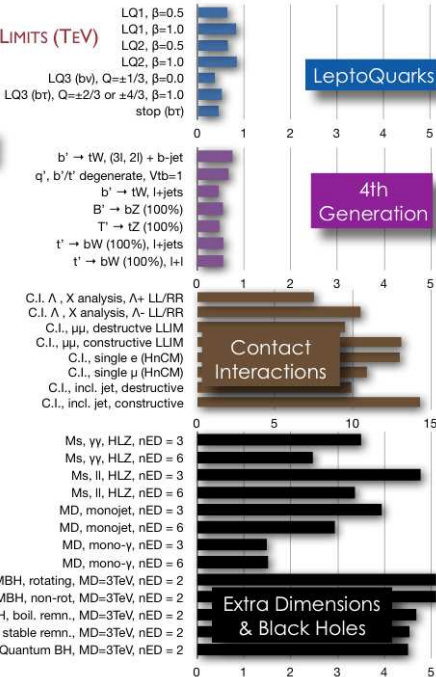
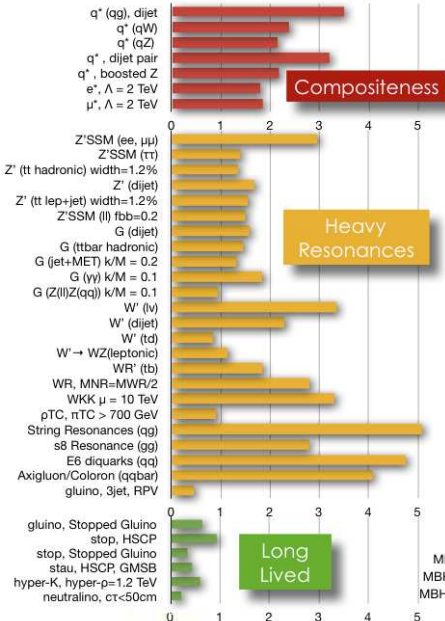
$$M_k^2 = M_0^2 + k^2/R^2 \quad ; \quad k = \pm 1, \pm 2, \dots$$

experimental limits:  $R^{-1} \gtrsim 0.5 - 4$  TeV (UED - localized fermions) [68]

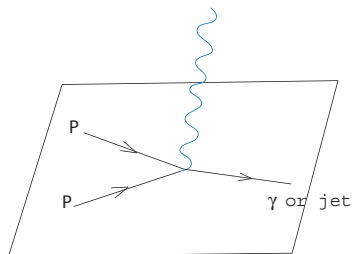
- extra  $U(1)$ 's and anomaly induced terms

masses suppressed by a loop factor from  $M_s$  [73]

# CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)



# Gravitational radiation in the bulk $\Rightarrow$ missing energy



Angular distribution  $\Rightarrow$  spin of the graviton

present LHC bounds:

$M_* \gtrsim 3 - 5 \text{ TeV}$

Collider bounds on  $R_\perp$  in mm

	$n = 2$	$n = 4$	$n = 6$
LEP 2	$4.8 \times 10^{-1}$	$1.9 \times 10^{-8}$	$6.8 \times 10^{-11}$
Tevatron	$5.5 \times 10^{-1}$	$1.4 \times 10^{-8}$	$4.1 \times 10^{-11}$
LHC	$4.5 \times 10^{-3}$	$5.6 \times 10^{-10}$	$2.7 \times 10^{-12}$

# Black hole production

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

Horowitz-Polchinski '96, Meade-Randall '07

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

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

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

Comparison with Regge excitations :  $M_n = M_s \sqrt{n} \Rightarrow$

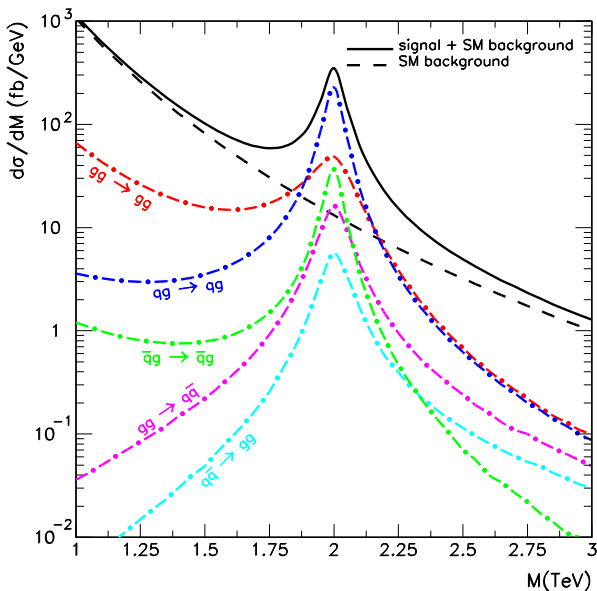
production of  $n \sim 1/g_s^4 \sim 10^4$  string states before reach  $M_{\text{BH}}$  [60]

**Universal** deviation  
from Standard Model  
in dijet distribution

$M_s = 2$  TeV

Width = 15-150 GeV

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



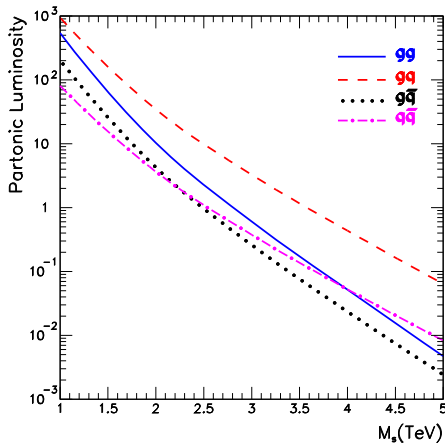


Tree level superstring amplitudes involving at most 2 fermions and gluons:  
 model independent for any compactification, # of susy's, even none  
 no intermediate exchange of KK, windings or graviton emission  
 Universal sum over infinite exchange of string (Regge) excitations

Parton luminosities in pp above TeV  
 are dominated by  $gq$ ,  $gg$

⇒ model independent

$gq \rightarrow gq$ ,  $gg \rightarrow gg$ ,  $gg \rightarrow q\bar{q}$



# Cross sections

$$\left. \begin{array}{l} |\mathcal{M}(gg \rightarrow gg)|^2, \quad |\mathcal{M}(gg \rightarrow q\bar{q})|^2 \\ |\mathcal{M}(q\bar{q} \rightarrow gg)|^2, \quad |\mathcal{M}(qg \rightarrow qg)|^2 \end{array} \right\} \begin{array}{l} \text{model independent} \\ \text{for any compactification} \end{array}$$

$$|\mathcal{M}(gg \rightarrow gg)|^2 = g_{YM}^4 \left( \frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2} \right) \times \left[ \frac{9}{4} (s^2 V_s^2 + t^2 V_t^2 + u^2 V_u^2) - \frac{1}{3} (sV_s + tV_t + uV_u)^2 \right]$$

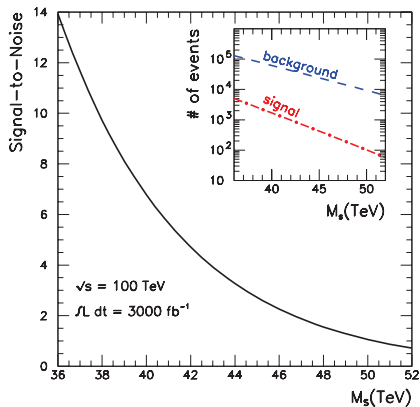
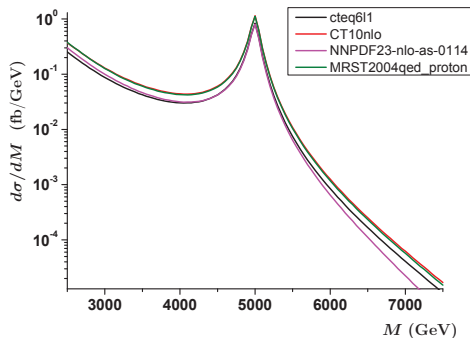
$$|\mathcal{M}(gg \rightarrow q\bar{q})|^2 = g_{YM}^4 \frac{t^2 + u^2}{s^2} \left[ \frac{1}{6} \frac{1}{tu} (tV_t + uV_u)^2 - \frac{3}{8} V_t V_u \right] \quad M_s = 1$$

$$V_s = -\frac{tu}{s} B(t, u) = 1 - \frac{2}{3}\pi^2 tu + \dots \quad V_t : s \leftrightarrow t \quad V_u : s \leftrightarrow u$$

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

# String Resonances production at Hadron Colliders

I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor in prep

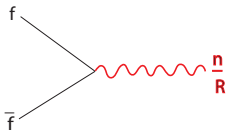


[60]

## Localized fermions (on 3-brane intersections)

⇒ single production of KK modes

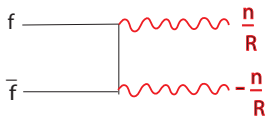
I.A.-Benakli '94



- strong bounds indirect effects:  $R^{-1} \gtrsim 3 \text{ TeV}$
- new resonances but at most  $n = 1$

## Otherwise KK momentum conservation [70]

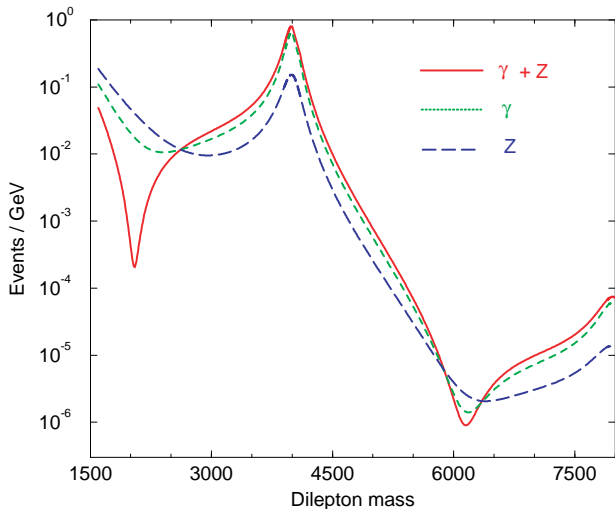
⇒ pair production of KK modes (universal dims)



- weak bounds  $R^{-1} \gtrsim 500 \text{ GeV}$
- no resonances
- lightest KK stable : dark matter candidate

Servant-Tait '02

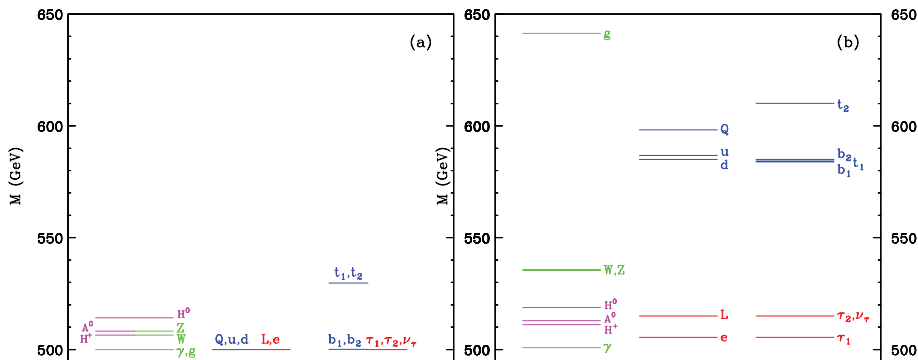
$$R^{-1} = 4 \text{ TeV}$$



- no observation in dijets  $\Rightarrow R^{-1} \gtrsim 20 \text{ TeV}$  ; 95% CL
- more than one dimension  $\Rightarrow$  stronger limits

# Universal extra dimensions (UED) : Mass spectrum

Radiative corrections  $\Rightarrow$  mass shifts that lift degeneracy at lowest KK level  
 divergent sum over KK modes in the loop  $\Rightarrow$  cutoff scale  $\Lambda \simeq 10/R$



# UED hadron collider phenomenology

- large rates for KK-quark and KK-gluon production
- cascade decays via KK- $W$  bosons and KK-leptons  
determine particle properties from different distributions
- missing energy from LKP: weakly interacting escaping detection
- phenomenology similar to supersymmetry

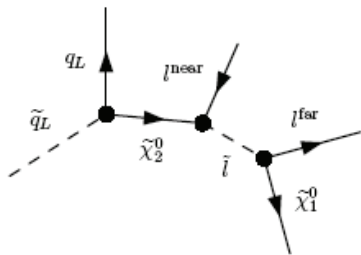
spin determination important for distinguishing SUSY and UED [60]

gluino	1/2	KK-gluon	1
squark	0	KK-quark	1/2
chargino	1/2	KK- $W$ boson	1
slepton	0	KK-lepton	1/2
neutralino	1/2	KK- $Z$ boson	1

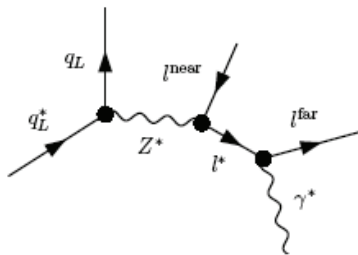
# SUSY vs UED signals at LHC

Example: jet dilepton final state

SUSY



UED





# 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

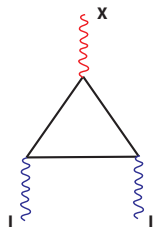
- 4d anomalous  $U(1)$ 's:  $M_A \simeq g_A M_s$

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

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

or massless in the absence of such anomalies

# Green-Schwarz anomaly cancellation



$$= k_I^A \sim \text{Tr} Q_A Q_I^2 \rightarrow \text{axion } \theta : \delta A = d\Lambda \quad \delta\theta = -m_A \Lambda$$

$$-\frac{1}{4g_I^2} F_I^2 - \frac{1}{2} (d\theta + m_A A)^2 + \frac{\theta}{m_A} k_I^A \text{Tr} F_I \wedge F_I$$

cancel the anomaly

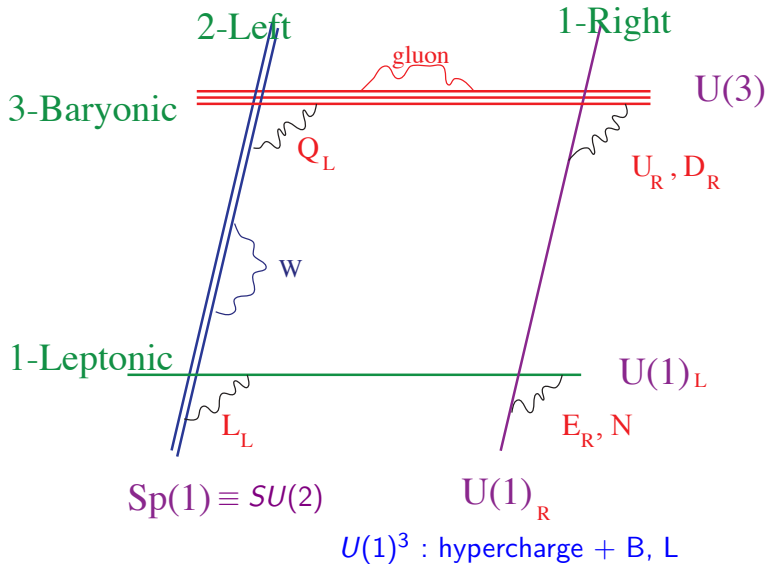
string theory:  $\theta = \text{Poincaré dual of a 2-form}$   $d\theta = *dB_2$

Heterotic: single universal axion [38]

D-brane models:  $U(1)_A$  gauge boson acquires a mass

but global symmetry remains in perturbation theory

# Standard Model on D-branes : SM<sup>++</sup>




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


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

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

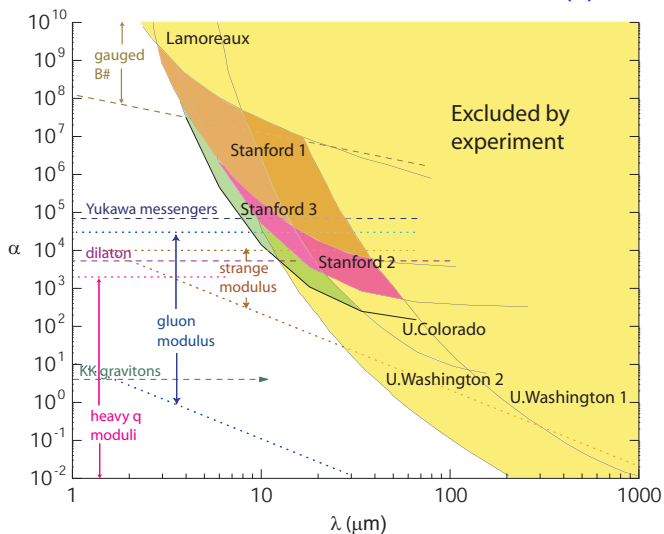
$Z' \simeq B$  lighter than 4d anomaly free  $Z'' \simeq B - L$

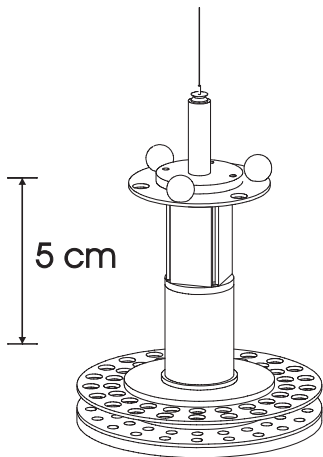
# microgravity experiments

- change of Newton's law at short distances
  - detectable only in the case of two large extra dimensions
- new short range forces
  - light scalars and gauge fields if SUSY in the bulk
    - or broken by the compactification on the brane
  - I.A.-Dimopoulos-Dvali '98, I.A.-Benakli-Maillard-Laugier '02
  - such as radion and lepton number
  - volume suppressed mass:  $(\text{TeV})^2/M_P \sim 10^{-4} \text{ eV} \rightarrow \text{mm range}$
  - can be experimentally tested for any number of extra dimensions
  - Light  $U(1)$  gauge bosons: no derivative couplings
    - $\Rightarrow$  for the same mass much stronger than gravity:  $\gtrsim 10^6$

# Experimental limits on short distance forces

$$V(r) = -G \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$



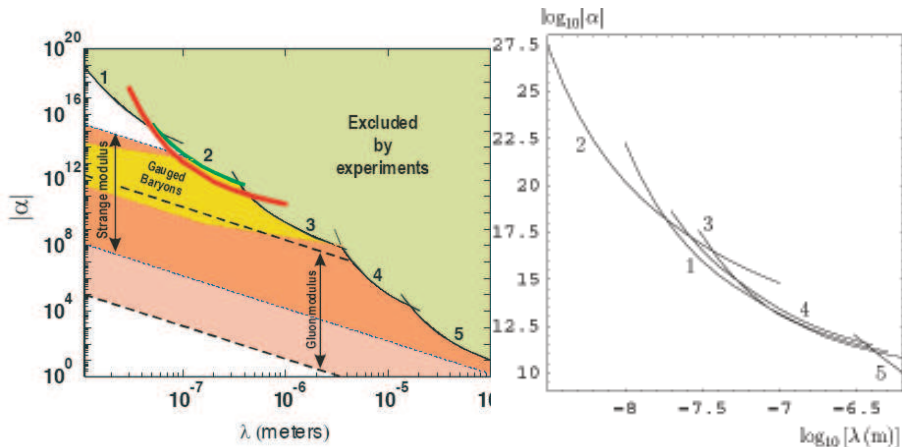


$$\alpha = 1 \Rightarrow \lambda \lesssim 55 \mu\text{m}$$

- dark-energy length scale  $\approx 85 \mu\text{m}$

## improved bounds from Casimir effect in the nm range

Decca-Fischbach et al '07, '08



5: Colorado

4: Stanford

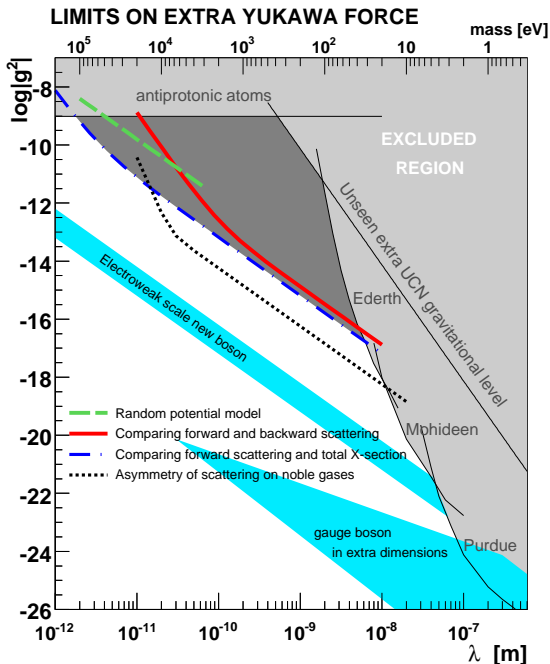
3: Lamoureux

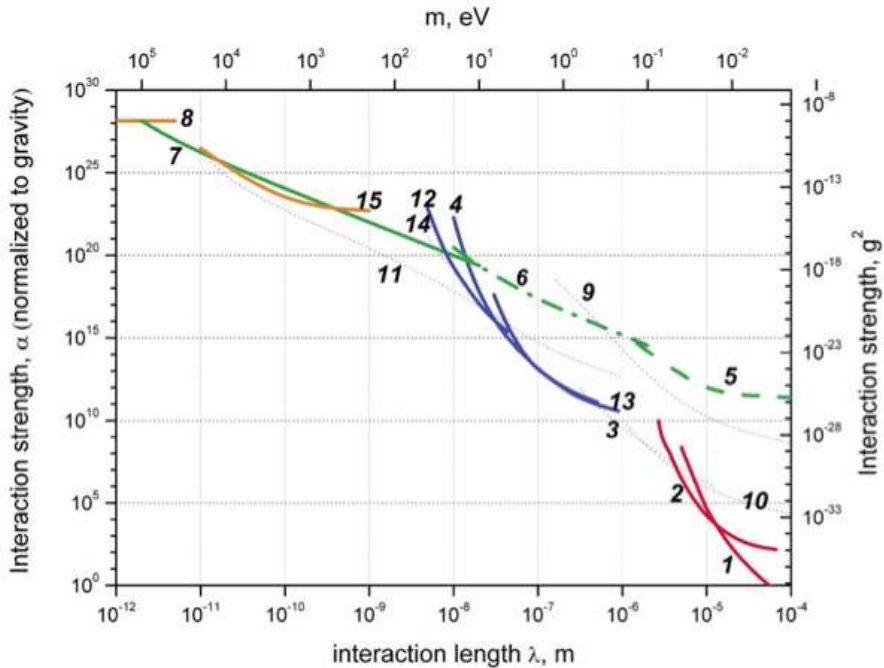
1: Mohideen et al.



Neutron scattering:  
 bounds in the range  
 $\sim 1\text{pm} - 1\text{nm}$

Nesvizhevsky-Pignol-  
 Protasov '07





# 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

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

2 ways to realize it lowering the string scale

① Large extra dimensions SM on D-branes [51]

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

② Effective number of string modes contributing to the BH bound

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

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

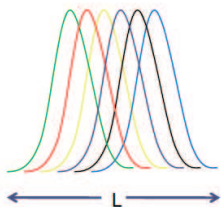
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derivation from: black hole evaporation or quantum information storage

Pixel of size  $L$  containing  $N$  species storing information:



localization energy  $E \gtrsim N/L \rightarrow$

Schwarzschild radius  $R_s = N/(LM_p^2)$

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

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

# What is LST ? Decouple gravity from NS5-branes

Analogy from D3-branes : decouple gravity  $\Rightarrow M_s \rightarrow \infty$ ,  $g_s$  fixed  
 $\rightarrow$  (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,  $g_s \rightarrow 0 \rightarrow$  (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 :  $(\mathcal{M}_6 \otimes R_+) \times SU(2) \equiv S^3$

$\uparrow$   
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

# Put gravity back **but weakly coupled**

“cut” the space of the extra dimension  $\Rightarrow$  gravity on the brane

Toy 5d bulk model

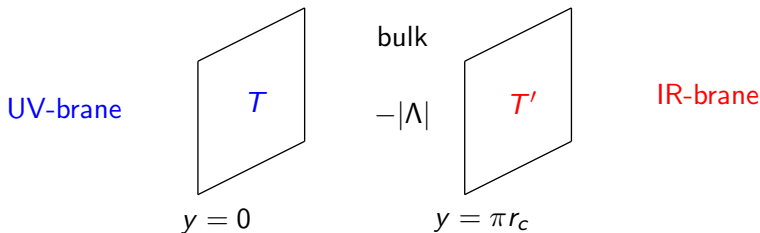
$$S_{bulk} = \int d^4x \int_0^{r_c} dy \sqrt{-g} e^{-\Phi} (M_5^3 R + M_5^3 (\nabla\Phi)^2 - \Lambda)$$

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

Tuning conditions:  $T_{vis} = -T_{hid} \leftrightarrow \Lambda < 0$  [89]

# Constant dilaton and AdS metric : Randal Sundrum model

spacetime = slice of AdS<sub>5</sub> :  $ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$   $k^2 \sim \Lambda/M_5^3$



- 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

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

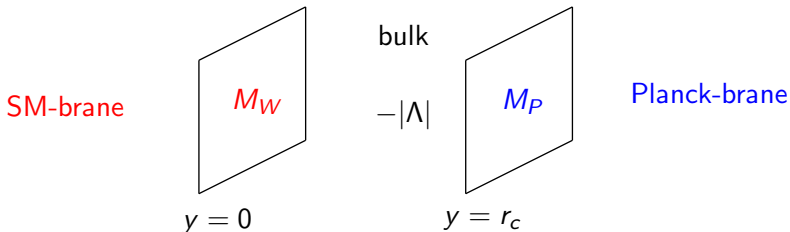
$\Rightarrow$  spin-2 TeV resonances in di-lepton or di-jet channels



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

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

$z \sim e^{\alpha y/3} \Rightarrow$  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 :  $m_n^2 = \left(\frac{n\pi}{r_c}\right)^2 + \frac{\alpha^2}{4}$  ;  $n = 1, 2, \dots$

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

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

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

- width :  $1/(\alpha r_c)^2$  suppression  $\sim 1 \text{ GeV}$

⇒ narrow resonant peaks in di-lepton or di-jet channels

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

⇒ distinct experimental signals

# Conclusions

- Discovery of a Higgs scalar 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
- Future plans to explore the 10-100 TeV energy frontier