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KIT, 6-10 February '12

Beyond the Standard Model

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Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  The most ambitious and widely accepted
  Simplest versions now marginal
  Plenty of viable alternatives

- Strong EWSB: Technicolor

  Strongly disfavoured by LEP. Coming back in new forms

  Composite Higgs

  Higgs as PG Boson, Little Higgs models……

- Extra spacetime dim's that somehow "bring" M_{Pl} down to o(1TeV) [large ED, warped ED, ……]. Holographic composite H

  Exciting. Many facets. Rich potentiality. No baseline model emerged so far

- Ignore the problem: invoke the anthropic principle

  Extreme, but not excluded by the data

The anthropic route

The scale of the cosmological constant is a big mystery.

$\Omega_\Lambda \sim 0.75 \longrightarrow \rho_\Lambda \sim (2\ 10^{-3}\ \text{eV})^4 \sim (0.1\text{mm})^{-4}$ → Similar to m_ν!?

In Quantum Field Theory: $\rho_\Lambda \sim (\Lambda_{cutoff})^4$

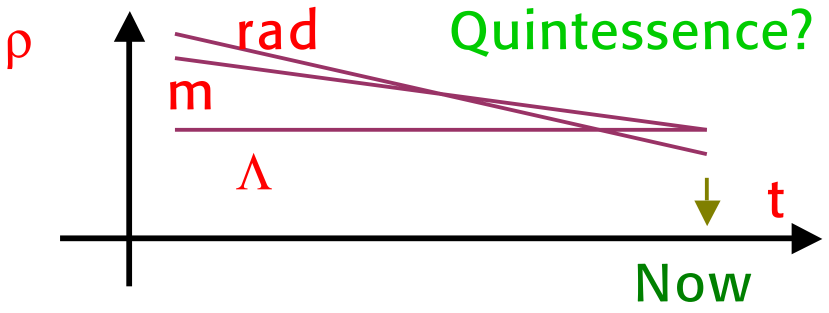
If $\Lambda_{cutoff} \sim M_{Pl} \longrightarrow \rho_\Lambda \sim 10^{123}\,\rho_{obs}$

Exact SUSY would solve the problem: $\rho_\Lambda = 0$

But SUSY is broken: $\rho_\Lambda \sim (\Lambda_{SUSY})^4 \sim 10^{60}\,\rho_{obs}$

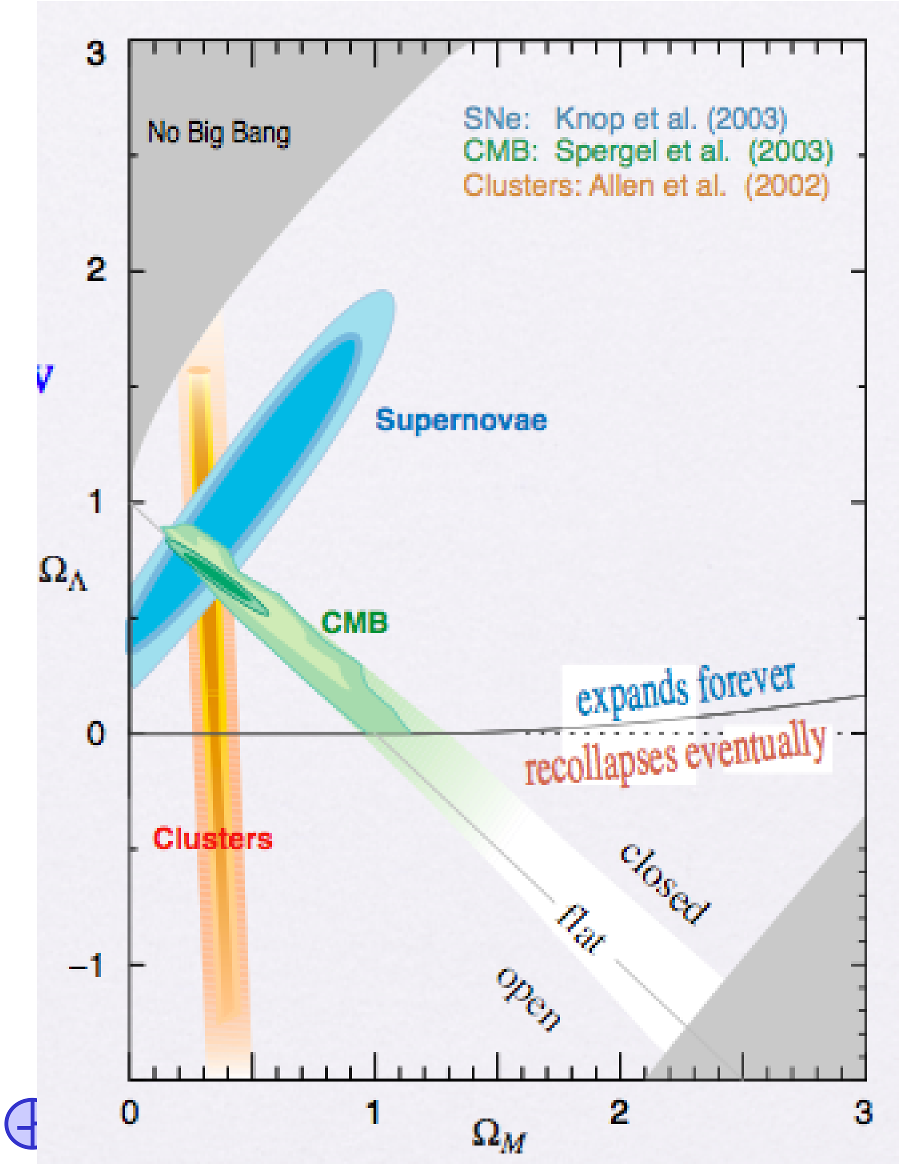
It is interesting that the correct order is $(\rho_\Lambda)^{1/4} \sim (\Lambda_{EW})^2/M_{Pl}$

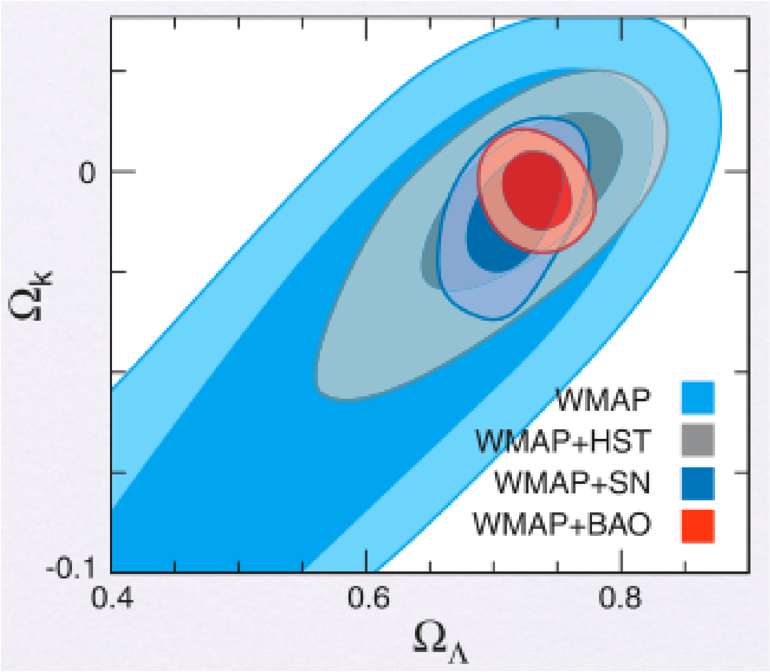
Other problem:
"Why now"?



"Quintessence"
Λ as a vev of a field ϕ?

Coupled to gauge singlet matter, eg ν_R, to solve magnitude and why now?


No Big Bang
SNe: Knop et al. (2003)
CMB: Spergel et al. (2003)
Clusters: Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
−1
0
1
2
3


Ω_k
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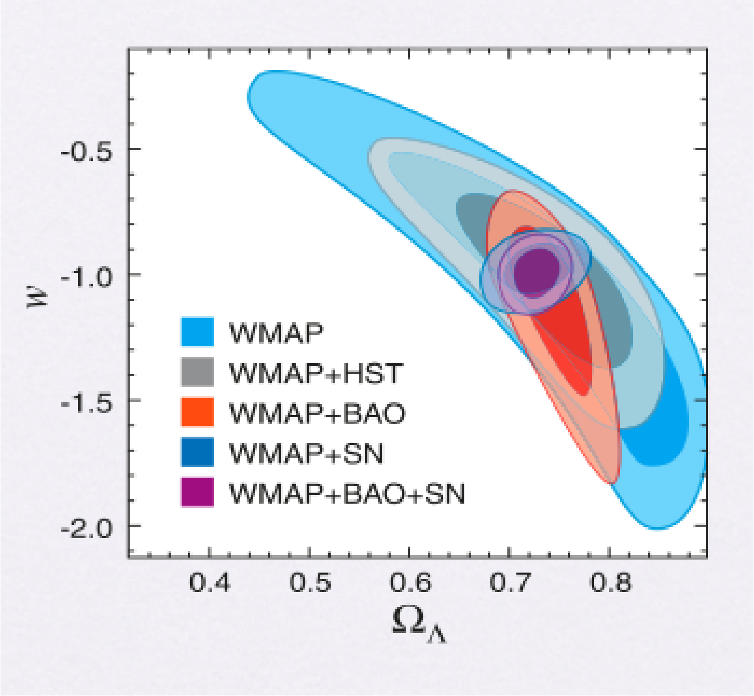
WMAP
WMAP+HST
WMAP+SN
WMAP+BAO


w
Ω_Λ
-0.5
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0.7
0.8
WMAP
WMAP+HST
WMAP+BAO
WMAP+SN
WMAP+BAO+SN

Is naturalness relevant?

Speculative physics reasons to doubt:

- The empirical value of the cosmological constant Λ poses a tremendous, unsolved naturalness problem

  yet the value of Λ is close to the Weinberg upper bound for galaxy formation
- Possibly our Universe is just one of infinitely many continuously created from the vacuum by quantum fluctuations
- Different physics in different Universes according to the multitude of string theory solutions ($\sim 10^{500}$)

Perhaps we live in a very unlikely Universe but one that allows our existence

If naturalness does not apply to the cosmological constant why should guide us for the SM?

I find applying the anthropic principle to the SM hierarchy problem not appropriate

After all we can find plenty of models that reduce the fine tuning from 10^{14} to 10^{2}:
so why make our Universe so terribly unlikely?

The case of the cosmological constant is a lot different:
the context is not as fully specified as the for the SM
(quantum gravity, string cosmology, branes in extra dims., wormholes thru different Universes....)

An enlarged SM (to include RH ν's and no new physics) remains an (enormously fine tuned) option

A light Higgs

SO(10) non SUSY GUT

SO(10) breaking down to $SU(4)xSU(2)_LxSU(2)_R$ at an intermediate scale (10^{11-12})

Majorana neutrinos and see-saw (-> $0\nu\beta\beta$)

Axions as dark matter

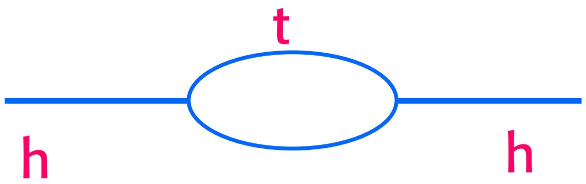
Baryogenesis thru leptogenesis

(but: $(g-2)_\mu$ and other present deviations from SM should be disposed of)

The “little hierarchy” problem

e.g. the top loop (the most pressing):

$m_h^2 = m^2_{bare} + \delta m_h^2$



$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

This hierarchy problem demands new physics near the weak scale

$\Lambda \sim$ o(1TeV)

Λ: scale of new physics beyond the SM

- $\Lambda \gg m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim$ o(1TeV) for a natural explanation of m_h or m_W

Barbieri, Strumia

The LEP Paradox: m_h light, new physics must be close but its effects were not visible at LEP2

The B-factory Paradox: and not visible in flavour physics

A crucial question for the LHC

What damps the top loop Λ^2 dependence?

- the s-top (SUSY)
- some new fermion
  t′ (Little Higgs)
  KK recurrences of the top (Extra dim.)
  ......

- nothing dumps it and we accept the ever increasing fine tuning

Principles tried to ensure a light Higgs:

H is a (pseudo) Goldstone; (almost) no mass, derivative couplings

Little Higgs

H is the 5th comp of a gauge boson in 5 dimensions

H is replaced by boundary conditions or orbifolding
in extra-dim. models

The hierarchy problem is solved by exponential warping

Extra dimensions

Little Higgs Models

Georgi (moose)/Arkani-Hamed et al/Low, Skiba, Smith/Kaplan, Schmaltz/Chang,Wacker/Gregoire et al

$$\underset{\substack{\uparrow \\ \text{global}}}{G} \supset [SU(2) \underset{\substack{\uparrow \\ \text{gauged}}}{\otimes} U(1)]^2 \supset SU(2) \underset{\substack{\uparrow \\ \text{SM}}}{\otimes} U(1)$$

H is (pseudo)-Goldstone boson of G: takes mass only at 2-loops (needs breaking of 2 subgroups or 2 couplings)

recall: $\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$ $G_F \sim g^2 \to \overset{\searrow}{g^4}$

cutoff Λ ~10 TeV

Λ^2 divergences canceled by:

$$\left.\begin{array}{ll} \delta m^2_{H|top} & \text{new coloured fermion } \chi \text{ with } Q=2/3 \\ \delta m^2_{H|gauge} & W', Z', \gamma' \\ \delta m^2_{H|Higgs} & \text{new scalars} \end{array}\right\} \sim 1 \text{ TeV}$$

2 Higgs doublets ~0.2 TeV

Little Higgs: Big Problems with Precision Tests

Hewett, Petriello, Rizzo/ Csaki et al/Casalbuoni, De Andrea, Oertel/
Kilian, Reuter/

Even with vectorlike new fermions large corrections arise mainly from W_i', Z' exchange.
[lack of custodial SU(2) symmetry]

A combination of LEP and Tevatron limits gives:

$$f > 4 \text{ TeV at } 95\% \ (\Lambda = 4\pi f)$$

Fine tuning > 100 needed to get m_h ~ 200 GeV
better if m_H heavier

Can be fixed by complicating the model: T-parity, mirror fermions.... Cheng, Low

T parity interchanges the two SU(2)xU(1) groups

Cheng, Low

Standard gauge bosons are T even, heavy ones are T odd

Lightest T-odd particle stable --> Dark Matter

With some tension Little Higgs models can work.

Technically sophisticated. But the main drawback is:
Little Higgs provides just a postponement:
UV completion beyond ~10 TeV? GUT's?

Still important as it offers well specified signals and signatures for searching at the LHC:
a light Higgs, a new top-like fermion χ to damp the top loop, new W', Z' for the W, Z loops,.....

Extra Dimensions (ED)

String Theory ---> ED at M_{Pl}

Perhaps ED have a direct impact on physics below M_{Pl}

Exciting possibilities (a large domain of contemporary BSM)

- Large ED or (exponentially) warped ED

applied to

- GUT's in ED (M_{GUT})
- ED as (part of the) solution of the hierarchy probem (M_{EW})
- EW symmetry breaking from ED (M_{EW})

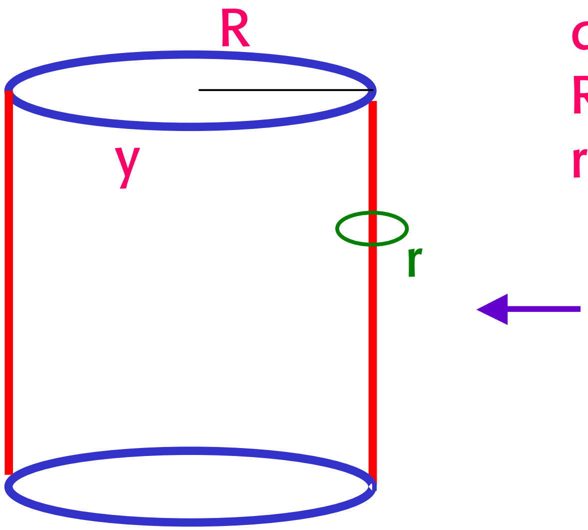
Early formulation

Solve the hierachy problem by bringing gravity down from M_{Pl} to o(1TeV)

Arkani-Hamed, Dimopoulos/ Dvali+Antoniadis

- Large compactified extra dimensions
- SM fields are on a brane
- Gravity propagates in the whole bulk

$R >>> 10^{-33}$ cm



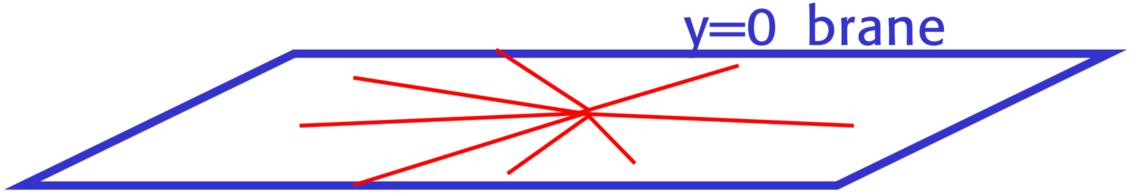
y: extra dimension
R: compact'n radius

y=0 "our" brane (possibly with thickness r)

$G_N \sim 1/M^2_{Pl}$: Newton const.
M_{Pl} large as G_N weak

The idea is that gravity appears weak as a lot of lines of force escape in extra dimensions r >> R: ordinary Newton law

$$F \sim \frac{G_N}{r^2} \sim \frac{1}{M_{Pl}^2 r^2}$$

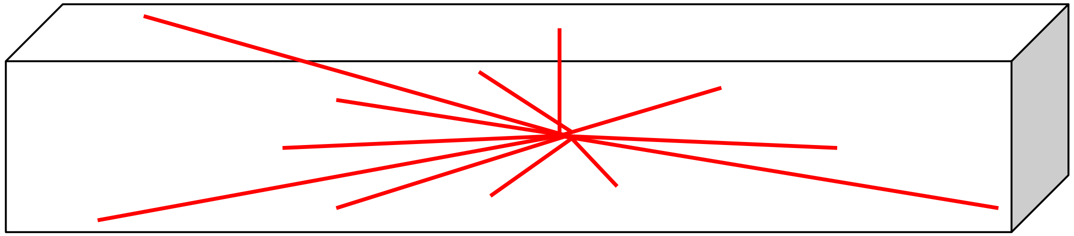


r << R: lines in all dimensions

Gauss in d dim:

r^{d-2} F ~ constant

$$F \sim \frac{1}{m^2 (mr)^{d-4} \cdot r^2}$$



By matching at r=R

$$\left(\frac{M_{Pl}}{m}\right)^2 = (Rm)^{d-4}$$

For m ~ 1 TeV, (d-4 = n)

n = 1 R~ 10^{15} cm (excluded)
n = 2 R~ 1 mm (close to limits)
n = 4 R~ 10^{-9} cm
...

Limits on deviations from Newton law

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

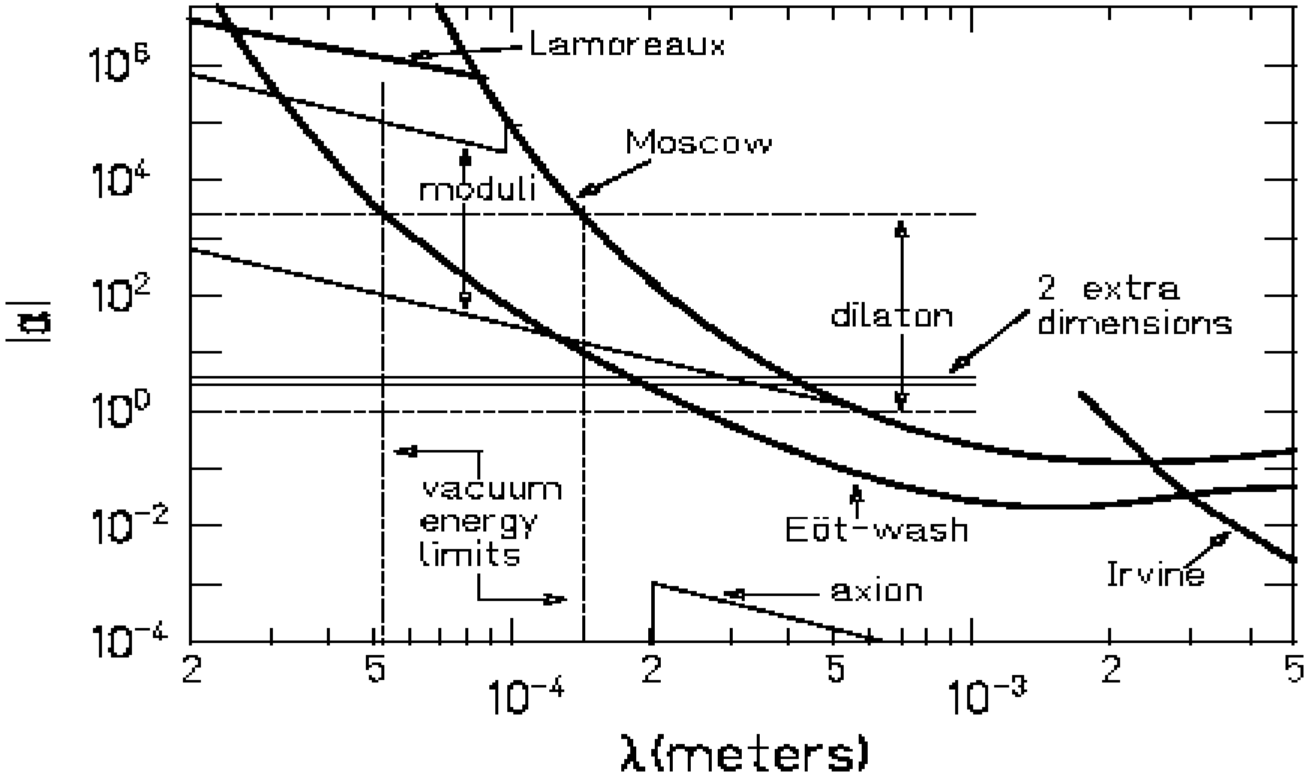


FIG. 4. 95% confidence upper limits on $1/r^2$-law violating interactions of the form given by Eq. (2). The region excluded by previous work [2,3,20] lies above the heavy lines labeled Irvine, Moscow and Lamoreaux, respectively. The data in Fig. 3 imply the constraint shown by the heavy line labeled Eöt-wash. Constraints from previous experiments and the theoretical predictions are adapted from Ref. [8], except for the dilaton prediction which is from Ref. [14].

Hoyle et al,

PRL 86,1418,2001

- Large Extra Dimensions is an exciting scenario.

- However, by itself it is difficult to see how it can solve the main problems (hierarchy, the LEP Paradox)

    * Why (Rm) not 0(1)?

      needs d-4 large

$$\boxed{\left(\frac{M_{Pl}}{m}\right)^{2} = (Rm)^{d-4}}$$

    * $\Lambda \sim 1/R$ must be small (m_H light)

    * But precision tests put very strong lower limits on Λ (several TeV)

In fact in simplest models of this class there is no mechanism to sufficiently quench the corrections

- Randall-Sundrum: warped versions with non factorizable metric emerged as more promising

Generic feature of extra dim. models:

compact dim. → Kaluza-Klein (KK) modes

$p=n/R$ $m^2=n^2/R^2$ (quantization in a box)

Many possibilities:

- SM fields on a brane or in bulk

cfr: • Gravity always on bulk

- Factorized metric:

$$ds^2 = \eta_{\mu\nu}dx^\mu dx^\nu + h_{ij}(y)dy^i dy^j$$

- Warped metric: Randall-Sundrum (R-S)

$$ds^2 = e^{-2mR|\varphi|}\eta_{\mu\nu}dx^\mu dx^\nu - R^2\varphi^2$$

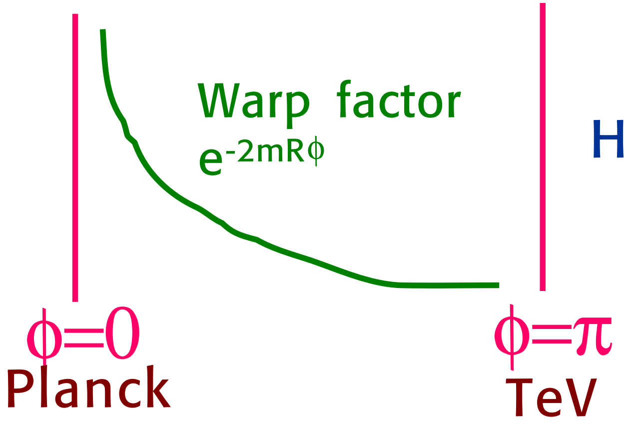
$m_{weak}=M_{Pl}\exp(-mR\pi)$ → $Rm \sim 12$

emerges as the most promising formulation

A more promising scheme (warped ED)

$$ds^2 = e^{-2mR|\varphi|}\eta_{\mu\nu}dx^\mu dx^\nu - R^2\varphi^2$$

Randall-Sundrum:



H is here

This non-fact.ble metric is solution of Einstein eq.s with 2 branes at $\phi=0,\pi$ and specified 5-dim cosmological term

All SM particles in bulk except the H

$m \sim M_{Pl}$ for all mR: $m^2 \sim M_{Pl}^2(1-e^{-2mR\phi})$

All 4-dim masses m_4 are scaled down with respect to 5-dim masses $m_5 \sim M_{Pl}$ by the warp factor: $m_4 = M_{Pl}e^{-mR\pi}$

The hierarchy problem demands that $mR \sim 12$: not too large!!

R not large in this case!

Stabilization of mR at a compatible value can be assured by a scalar field in the bulk with a suitable potential

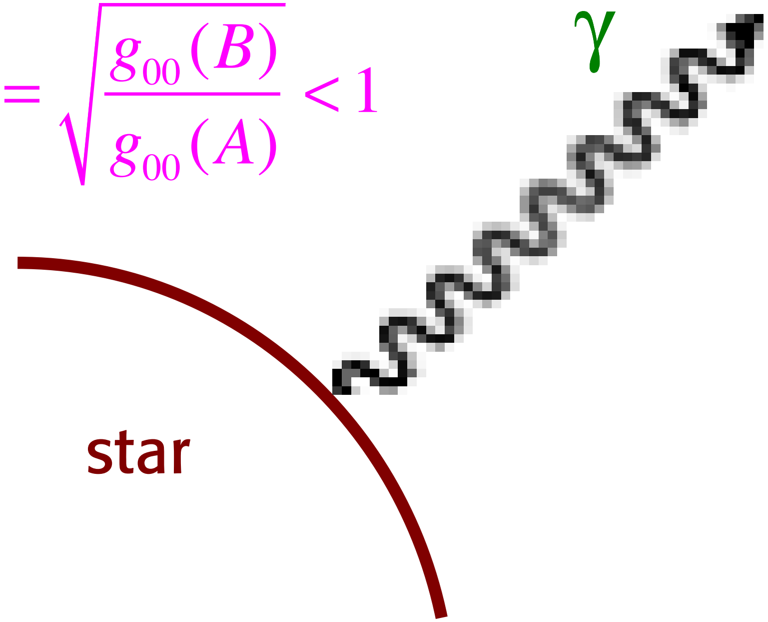
"radion"

Goldberger, Wise

2 identical atoms in
A and B emit light
with frequencies
ν_A and ν_B

$h\nu$ here is smaller:
kinetic energy lost
by climbing out of
grav. field

$$\frac{\nu_B}{\nu_A} = \sqrt{\frac{g_{00}(B)}{g_{00}(A)}} < 1$$



Similarly mc^2 is smaller
by the same factor
$g_{00}{}^{1/2}$--> $m_4=M_{Pl}e^{-mR\pi}$

Good tutorials:
R. Sundrum '04
TASI lectures
R. Rattazzi '05
Cargese Lectures

The RS original formulation is very elegant but
when going to a realistic formulation it has problems

- Electroweak precision tests

too large corrections (e.g. at tree level)

- In a description of physics from m_W to M_{Pl} there should be place for GUT's.

But, If all SM particles are on the TeV brane the effective theory cut-off is low and no way to M_{GUT} is open

Pomarol; Agashe, Delgado, Sundrum

Inspired by RS different realizations of warped geometry tried:

- gauge fields in the bulk
- all SM fields (except the Higgs) on the bulk

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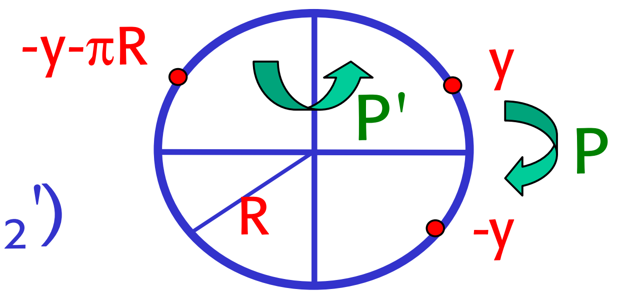
Model building based on RS explored in many directions

We consider now some ideas on electroweak symmetry breaking in extra dimensional models

Symmetry breaking by orbifolding



$S/(Z_2 x Z_2')$

P and P' break the symmetries of 5-dim theory

Z_2-> P: y ⟺ -y

On the branes at the fixed points y=0 and y= -πR/2 symmetry is reduced

Z_2'-> P': y' ⟺ -y'

y'=y + πR/2

or y ⟺ -y- πR

$$\phi_{++}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{++}^{(2n)}(x_\mu) \cos\frac{2ny}{R}$$

$$\phi_{+-}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{+-}^{(2n+1)}(x_\mu) \cos\frac{2n+1}{R}y$$

$m^2 \sim n^2/R^2$

$$\phi_{-+}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{-+}^{(2n+1)}(x_\mu) \sin\frac{2n+1}{R}y$$

$$\phi_{--}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{--}^{(2n+2)}(x_\mu) \sin\frac{2n+2}{R}y$$

Symmetry breaking at the weak scale

$1/R \sim o(\mathrm{TeV})$

- **SUSY Breaking**

Barbieri, Hall, Nomura.....Papucci, Marandella.

5D SUSY-SM compactified on $S/(Z_2 x Z_2')$

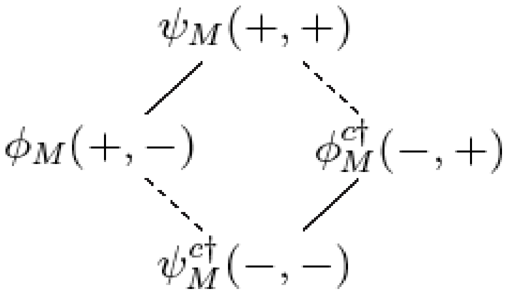
P breaks N=2 SUSY, P' N=1 SUSY (Scherk-Schwarz)

effective theory non-SUSY (SUSY recovered at d < R)

- Higgs boson mass in principle computable

no invariant Higgs mass operator in 5-dim

rather insensitive to UV $m_H \sim$ 110 - 125 GeV

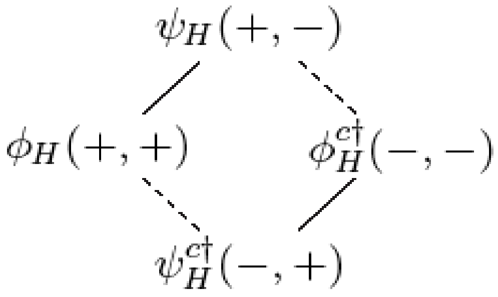


$\psi_M(+,+)$

$\phi_M(+,-)$ $\phi_M^{c\dagger}(-,+)$

$\psi_M^{c\dagger}(-,-)$

matter

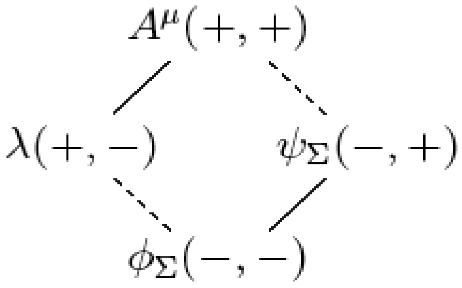


$\psi_H(+,-)$

$\phi_H(+,+)$ $\phi_H^{c\dagger}(-,-)$

$\psi_H^{c\dagger}(-,+)$

Higgs (only 1!)



$A^\mu(+,+)$

$\lambda(+,-)$ $\psi_\Sigma(-,+)$

$\phi_\Sigma(-,-)$

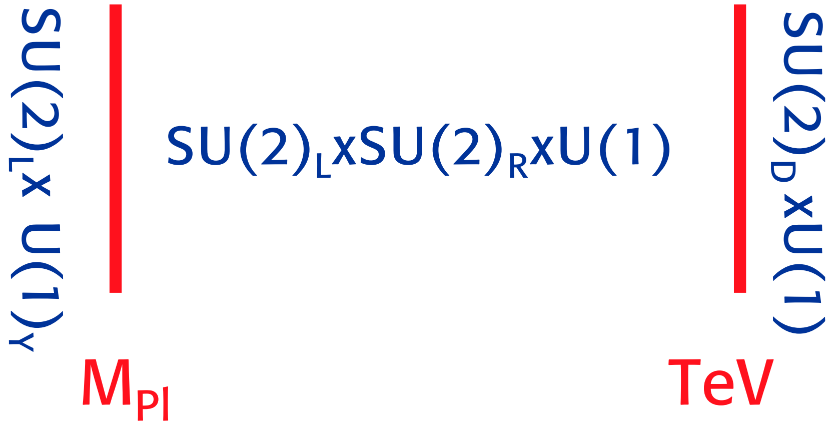
gauge

all are in the bulk

- **Gauge Symmetry Breaking (Higgsless theories)**

Csaki et al/Nomura/Davoudiasl et al/Barbieri, Pomarol, Rattazzi;....

The only ED models were no Higgs would be found at LHC.
But signals of new physics would be observed



Warped R-S background

Symmetries broken by Boundary Conditions (BC) on the branes

Altogether only $U(1)_Q$ unbroken

- Unitarity breaking (no Higgs) delayed by KK recurrences
- Dirac fermions on the bulk (L and R doublets). Only one chirality has a zero mode on the interval

y-Boundary Conditions

A scalar example

Action: $S = \int dx \int dy \left[\frac{1}{2}(\partial_M \phi)^2 - V(\phi)\right] + \int_{y=0,\pi R} dx \left[\frac{1}{2} M^2 \phi^2\right]$

Varying the action: $\delta S = \int dx \int dy \left[\Box \phi + \frac{\partial V}{\partial \phi}\right] \delta\phi + \int dx [(\partial_y \phi - M^2 \phi)\delta\phi]_0^{\pi R}$

Thus, at y=0,πR $[\delta\phi]_{0,\pi R} = 0$ or $[\partial_y \phi - M^2 \phi]_{0,\,\pi R} = 0$

Note: $M^2 \to 0$ $[\partial_y \phi]_{0,\,\pi R} = 0$ Neumann $\phi \sim \cos\frac{ny}{R}$

$M^2 \to$ infinity $\phi_{0,\,\pi R} = 0$ Dirichlet $\phi \sim \sin\frac{ny}{R}$

Gauge theory: $[\delta A^a{}_\mu]_{0,\pi R} = 0$ or $[\partial_y A^a_\mu - V^{ab} A^b_\mu]_{0,\,\pi R} = 0$

$V^{ab} = v t^a t^b v$ can arise from a Higgs H localised on the brane:

$D_M H D^M H$, $D_M = \ldots + t^a A_M^a$, $\langle H \rangle = v$

Suppose we want, at y=πR: $\partial_y A = VA$

We set: $A = A_0 \cos My$

Note. At y=0: $\partial_y A = 0$

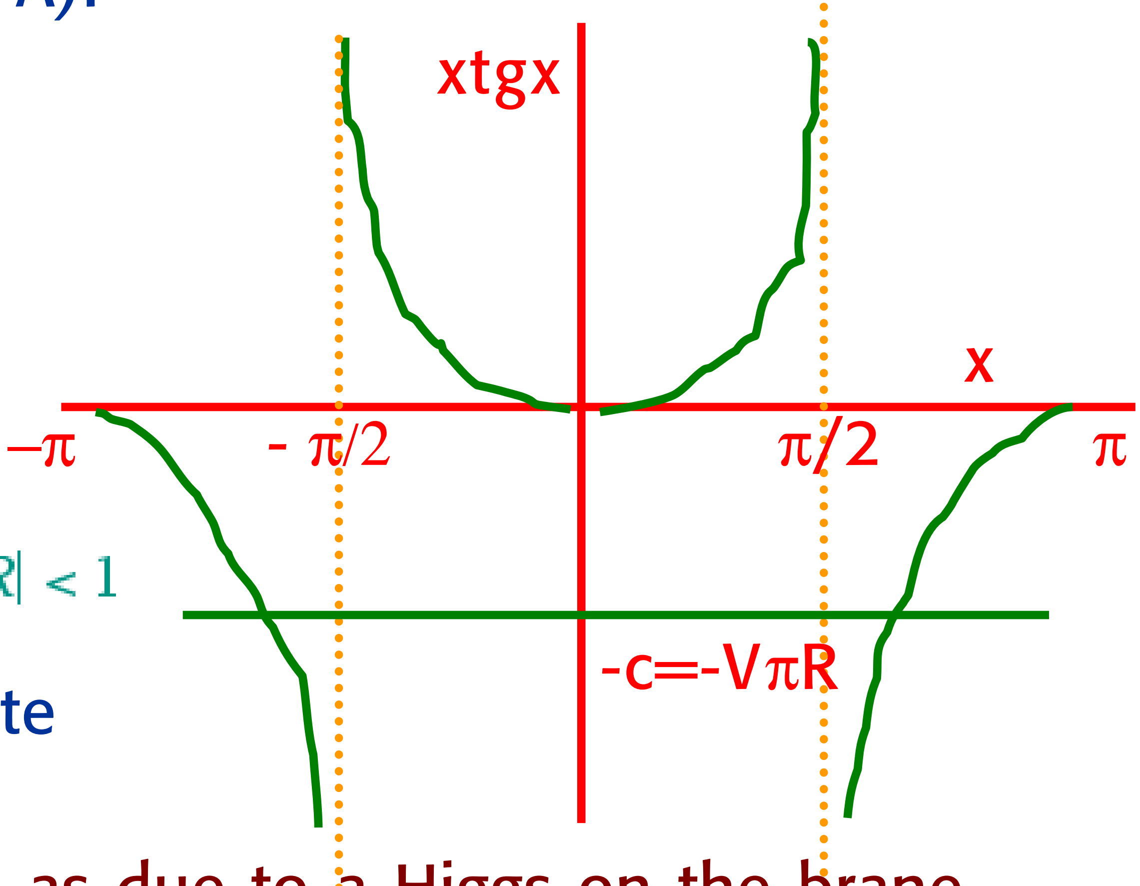
We find M (mass of boson A):

$$-M \sin M\pi R = V \cos M\pi R$$

$$-M\pi R \sin M\pi R = V\pi R \cos M\pi R$$

$$x\,tg\,x = -c$$

$$\frac{\pi}{2} < |x| < \pi \longrightarrow \frac{1}{2} < |MR| < 1$$



Note that MR remains finite for V-> infinity

The breaking can be seen as due to a Higgs on the brane which can be made to disappear by V -> infinity

With no Higgs unitarity violations, eg:

$$A\left(W_L^+W_L^- \to Z_LZ_L\right) = \frac{G_F E^2}{8\sqrt{2}\pi}$$

At E ~ 1.2 TeV unitarity is violated

In Higgsless models unitarity breaking is delayed by the exchange of KK recurrences

$Z_k = k_{th}$ KK

Cancellation guaranteed
by sum rules implied
by 5-dim symmetry

$$g^2_{WWWW} - e^2 - \sum_k g^2_{WWZ_k} = 0\,;$$

$$4M_W^2\, g^2_{WWWW} - 3\sum_k g^2_{WWZ_k} M_{Z_k^2} = 0\,.$$

The small W, Z mass implies a small KK gap --> W’, Z’ at the LHC

Higgsless models can also be formulated in 4 dimensions (pioneered by Casalbuoni, De Curtis, Dominici, Gatto ‘85)

Boundary conditions allow a general breaking pattern
(for example, can lower the rank of the group)

equivalent to have generic Higgses on the brane
(with vev -> infinity)

Breaking by orbifolding is more rigid
(the rank remains fixed)

corresponds to Higgs in the adjoint (A_5 the 5th A_M)

No convincing, realistic Higgsless model for EW symmetry breaking emerged so far:

Serious problems with EW precision tests

e.g. Barbieri, Pomarol, Rattazzi '03 ; Chivukula et al

also with Z->bb

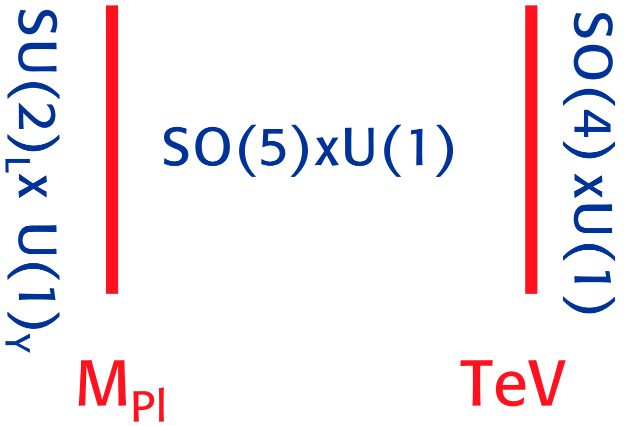
Substantial fine tuning required

Best try: Cacciapaglia et al '06

However be alerted of possible signals at the LHC: no Higgs but KK recurrences of W, Z and additional gauge bosons

- Composite Higgs in a 5-dim holographic theory

Agashe, Contino, Pomarol......


$SU(2)_L x U(1)_Y$

SO(5)xU(1)

SO(4)xU(1)

M_{Pl}

TeV

A new way to look at walking technicolor using AdS/CFT corresp.

All SM fields in the bulk (but the Higgs is localised on the TeV brane)

Warped R-S background

As in Little Higgs models

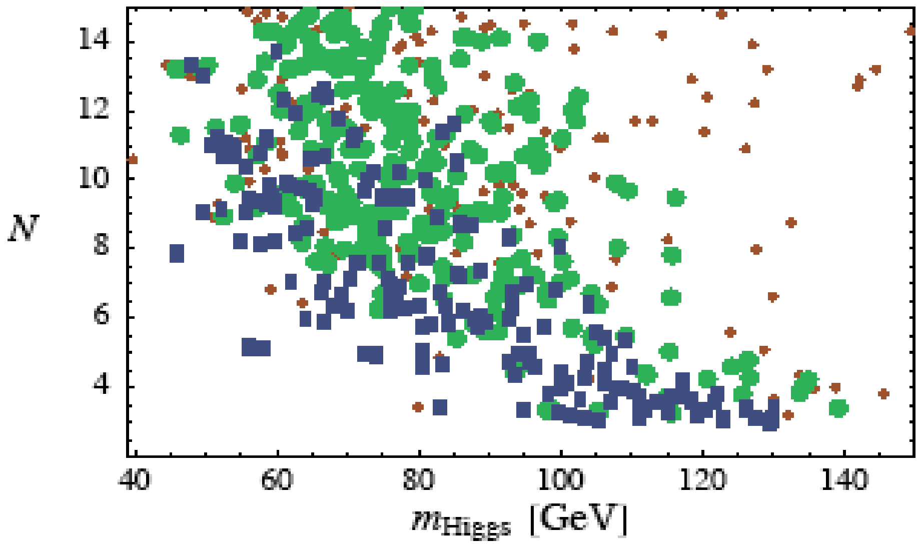
The Higgs is a PGB and EW symmetry breaking is triggered by bulk effects (in 4-dim the bulk appears as a strong sector).

The 5-dim theory is weakly coupled so that the Higgs potential and EW observables can be computed

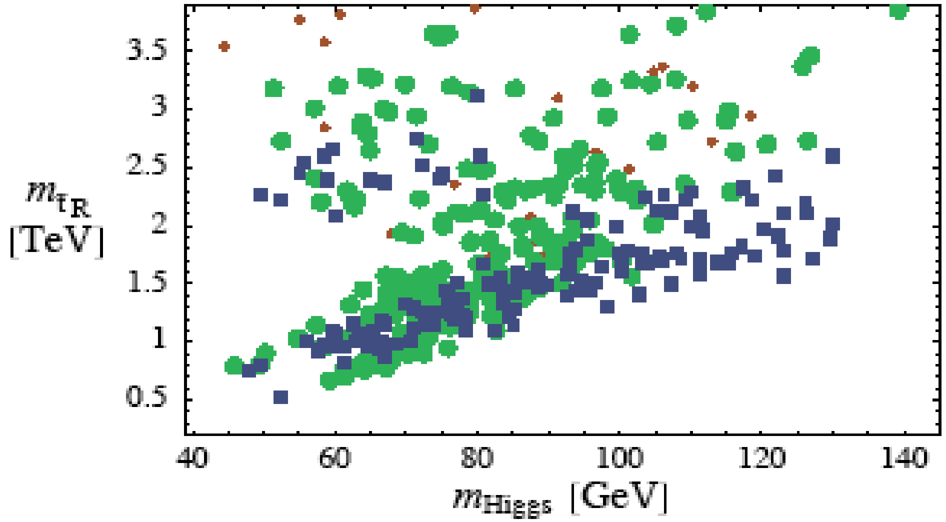
The Higgs is rather light: $m_H < 140$ GeV

Also in these models a sizable fine-tuning is required

The Higgs is (too?) light
in this model

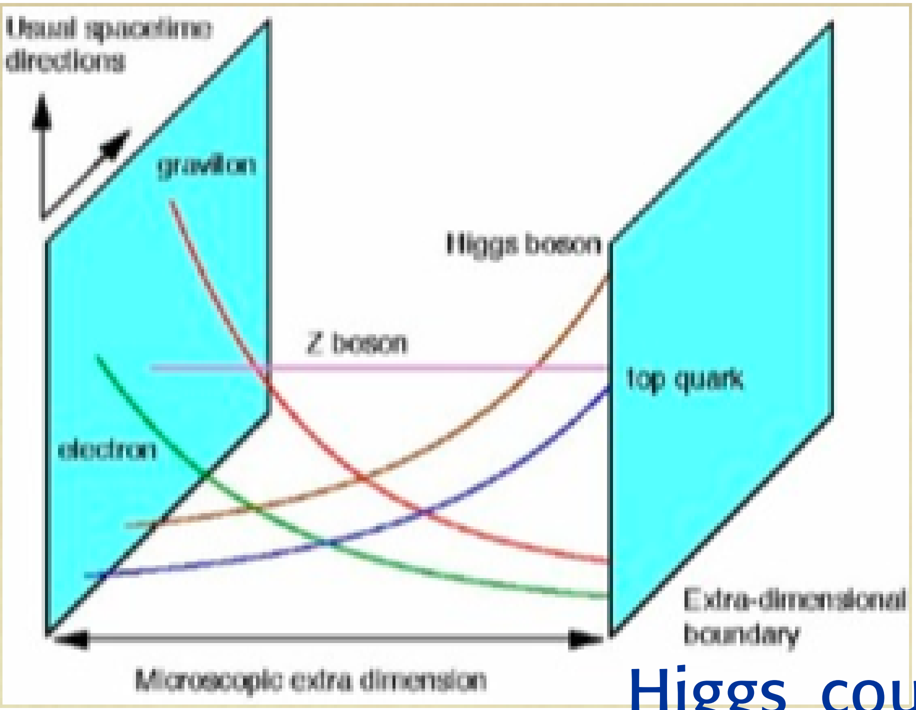


Problems with EW precision
tests and Zbb (can be fixed)



Signals at the LHC:
a light Higgs and
new resonances at ~ 2 TeV

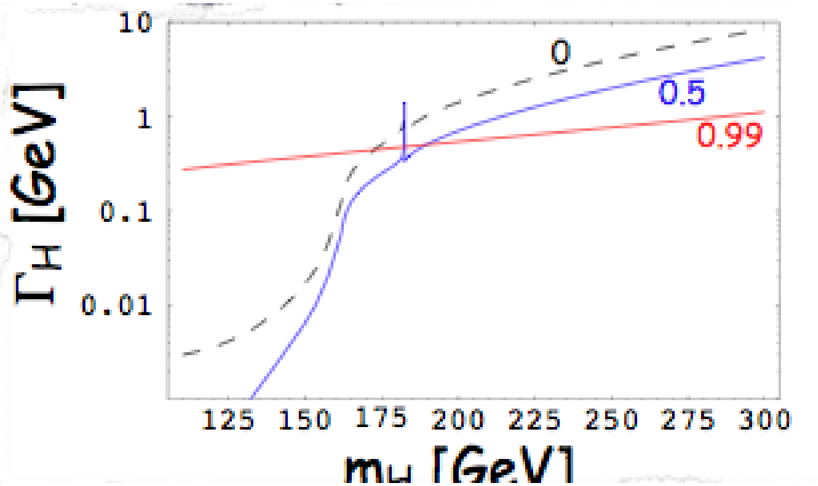
Apart from Higgsless models (if any?) all theories discussed here have a Higgs in LHC range (most of them light)

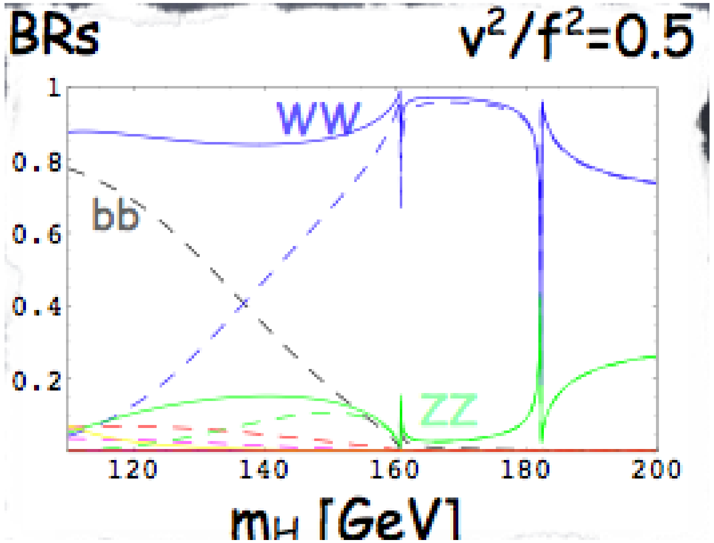


Also: a promising description of flavour

The fermion mass hierarchies explained by exp warp factors with o(1) exponents

Higgs couplings modified



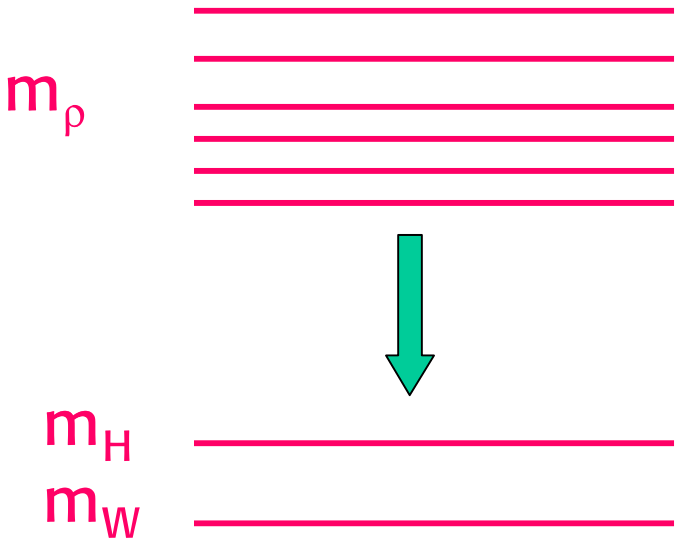


• Composite Higgs: a more model indep. approach

Georgi, Kaplan ‘84

The light Higgs is a bound state of a strongly interacting sector.
Pseudo-Goldstone boson of an enlarged symmetry.
eg. SO(5)/SO(4)

Agashe/ Contino/Pomarol/Sundrum/ Grojean/Rattazzi....



v ~ EW scale f ~ SI scale

$\sim f < m_\rho <\sim 4\pi f$

$\xi = (v/f)^2$

ξ interpolates between SM [$\xi \sim 0$]
and some degree of
compositeness
$\xi \sim 1$ similar to Technicolor
[$\xi \sim o(1)$ limited by precision EW tests]

a=b=1 is the SM Higgs

$$\Sigma = e^{i\sigma^a\pi^a/v}$$

$$\mathcal{L}_{\mathrm{EWSB}} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda\bar{\psi}_L\Sigma\psi_R\left(1 + c\frac{h}{v}\right)$$

In a given model, defined by the enlarged symmetry, e.g. SO(5)/SO(4), the SM couplings are deformed

Agashe, Contino, Pomarol'04

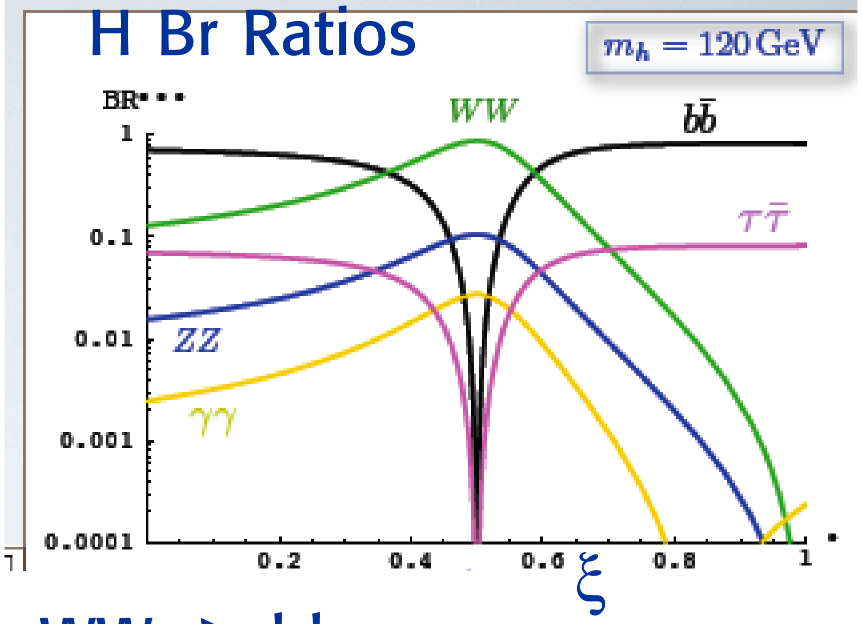
$$\xi = v^2/f^2$$

$$a = 1-\xi/2 \qquad b = 1-2\xi \qquad c = 1-\xi/2$$

Detectable ξ effects at the LHC

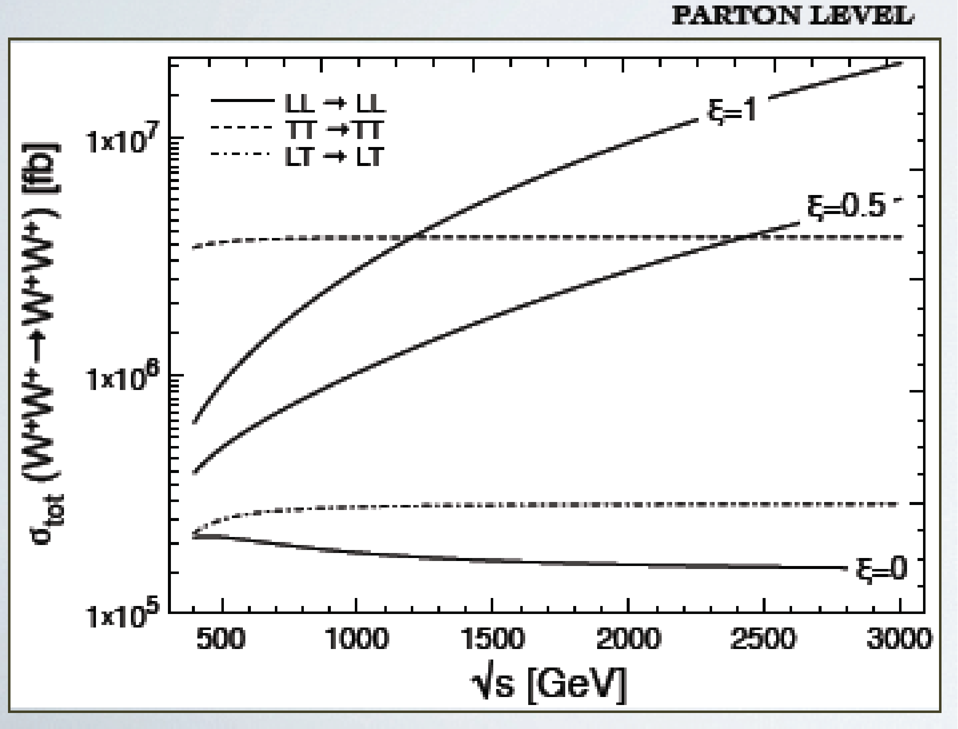
- Higgs couplings
- WW scattering
- 2-Higgs Production

H Br Ratios

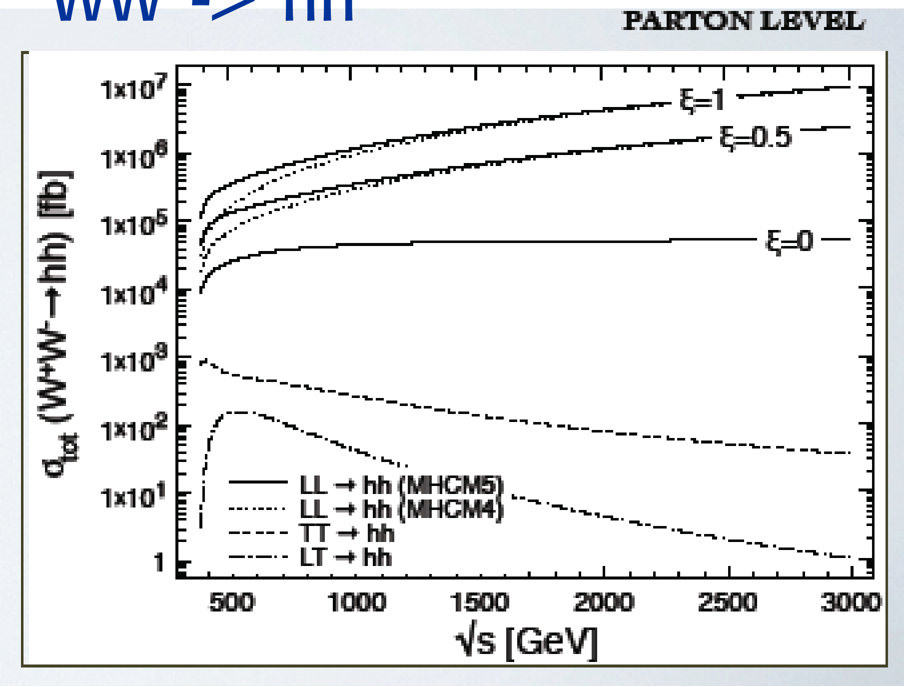


WW -> WW

Contino et al



WW -> hh



Lessons from model building

In all the new physics models we mentioned

there is a light Higgs ($<$ 200 GeV)

[except in Higgsless models (if any) but new light new vector bosons exist in this case]

there is at least a % fine tuning

Fine tuning appears to be imposed on us by the data

Outlook

Is it possible that the LHC does not find the Higgs particle?

Yes, it is possible, but then something else must be found

Is it possible that the LHC finds the Higgs particle but no other new physics (pure and simple SM)?

Yes, it is technically possible but it is not natural

Is it possible that the LHC finds neither the Higgs nor new physics?

No, it is “approximately impossible”

Conclusion

The Higgs comes closer

2012 will be the year of the Higgs:
yes or no to the SM Higgs

New Physics is pushed further away

But the LHC experiments are just at the start and
larger masses can be reached in 2012
and even more in the 14 TeV phase

Supersymmetry? Compositeness? Extra dimensions?
Anthropic? We shall see!