Split - 4 October '10

LHC Physics in the SM and beyond

Guido Altarelli
Roma Tre/CERN

The LHC physics run is going on, ... finally!

3.5 TeV per beam. Goal 1fb^{-1} by the end of 2011

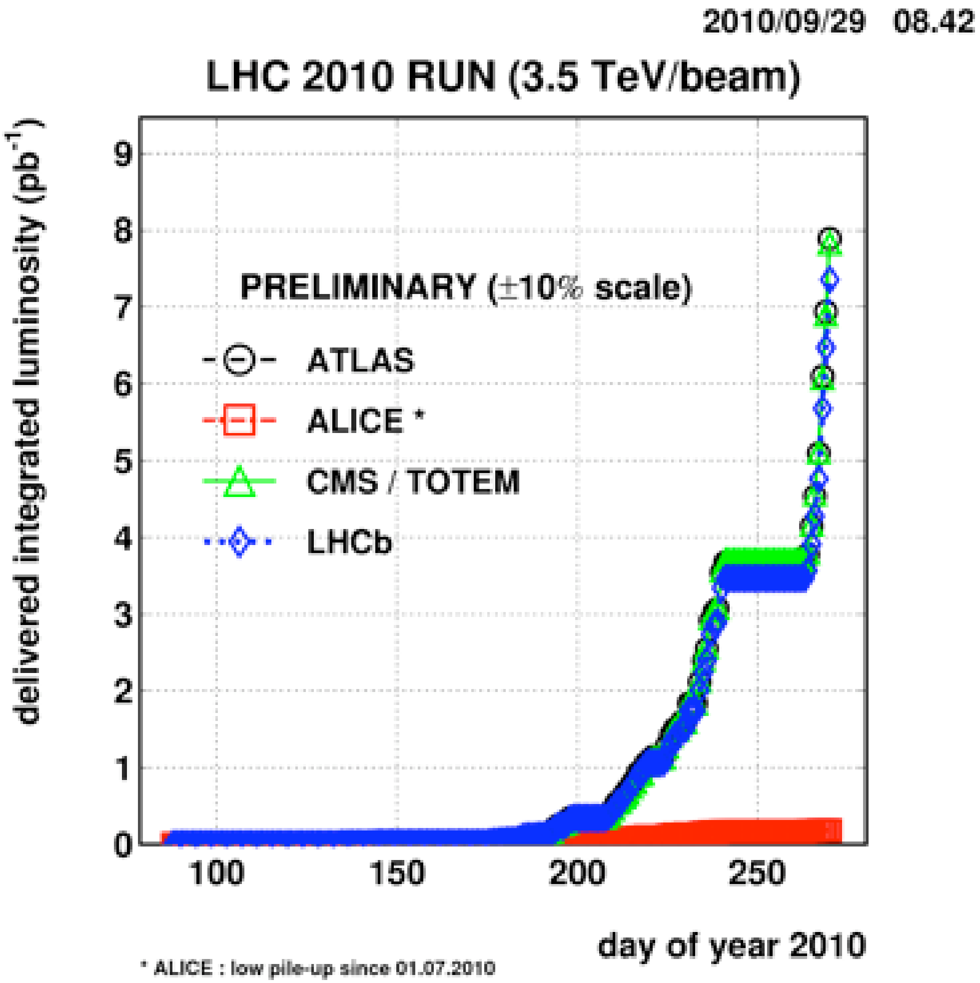
Top physics priorities at the LHC (ATLAS&CMS):

- Clarify the EW symmetry breaking sector
- Search for new physics at the TeV scale
- Identify the particle(s) that make the Dark Matter in the Universe

Also:

- LHCb: precision B physics (CKM matrix and CP violation)
- ALICE: Heavy ion collisions & QCD phase diagram

⊕ At this point, fresh input from experiment is badly needed!!



Total integrated luminosity so far ~ 8 pb^{-1}

Saturday 2^{nd} October

02-Oct-2010 05:26:55	Fill #: 1387	Energy: 3500 GeV	I(B1): 1.41e+13	I(B2): 1.43e+13
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi (ub.s)^-1	38.149	0.135	39.007	37.199
BRAN Luminosity (ub.s)^-1	33.126	0.133	39.134	36.521
Fill Luminosity (nb)^-1	36.3	--	31.2	25.1
BKGD 1	0.045	0.015	8.343	0.291
BKGD 2	214.000	0.369	0.002	0.002
BKGD 3	19.000	0.005	0.000	0.217
LHCb VELO Position IN Gap: 0.0 mm	STABLE BEAMS		TOTEM: STANDBY	

peak luminosity ~ 4 10^{31} $cm^{-2}s^{-1}$
152 bunches
1.4 10^{13} protons in total in the beam

Particle physics at a glance

The SM is a low energy effective theory
(nobody can believe it is the ultimate theory)

It happens to be renormalizable, hence highly predictive.
And is well supported by the data.

However, we expect corrections from higher energies

not only from the GUT or Planck scales
but also from the TeV scale (LHC!)

In fact even just as a low energy effective theory
the SM it is not satisfactory

QCD + the gauge part of the EW theory are fine,
but the Higgs sector is so far only a conjecture

The Higgs problem is central in particle physics today

A review: G.A. ArXiv:1003.3180

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ eV)^4$

Origin of quadratic
divergences.
Hierarchy problem

Possible instability
depending on m_H

The flavour problem:
large unexplained ratios
of Y_{ij} Yukawa constants

The Standard EW theory: $\mathcal{L} = \mathcal{L}_{\text{symm}} + \mathcal{L}_{\text{Higgs}}$

$$\mathcal{L}_{symm} = -\frac{1}{4}[\partial_\mu W^A_\nu - \partial_\nu W^A_\mu - ig\varepsilon_{ABC} W^A_\mu W^B_\nu]^2 +$$

$$-\frac{1}{4}[\partial_\mu B_\nu - \partial_\nu B_\mu]^2 +$$

$$+\bar{\psi}\gamma^\mu[i\partial_\mu + gW^A_\mu t^A + g' B_\mu \frac{Y}{2}]\psi$$

$$\mathcal{L}_{Higgs} = |[\partial_\mu - igW^A_\mu t^A - ig' B_\mu \frac{Y}{2}]\phi|^2 +$$

$$+ \; V[\phi^\dagger\phi] + \bar{\psi}\Gamma\psi\phi + \mathrm{h.c}$$

with $V[\phi^\dagger\phi] = \mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4$

$\mathcal{L}_{\text{symm}}$: well tested (LEP, SLC, Tevatron…), $\mathcal{L}_{\text{Higgs}}$: ~ untested

All we know from experiment about the SM Higgs:

No Higgs seen at LEP2 -> m_H > 114.4 GeV (95%cl)

Rad. corr's -> m_H < 186 GeV (95%cl, incl. direct search bound)

$v = \langle\phi\rangle = \sim 174$ GeV ; $m_W = m_Z \cos\theta_W$ ⟶ doublet Higgs

That some sort of spontaneous symmetry breaking mechanism is at work has already been established (couplings symmetric, spectrum totally non symmetric)

The question is on the nature of the Higgs mechanism/particle(s)

- One doublet, more doublets, additional singlets?
- SM Higgs or SUSY Higgses
- Fundamental or composite (of fermions, of WW....)
- Pseudo-Goldstone boson of an enlarged symmetry
- A manifestation of extra dimensions (fifth comp. of a gauge boson, an effect of orbifolding or of boundary conditions....)
- Some combination of the above

Can we do without the Higgs?

Suppose we take the gauge symmetric part of the SM and put masses by hand.

Gauge invariance is broken explicitly. The theory is no more renormalizable. One loses understanding of the observed accurate validity of gauge predictions for couplings.

Still, what is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes

To avoid this either there is one or more Higgs particles or some new states (e.g. new vector bosons)

Thus something must happen at the few TeV scale!!

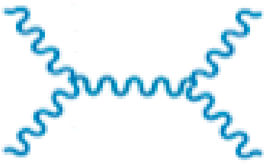
With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

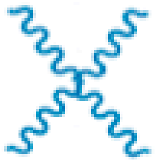
Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons (W_L , Z_L) satisfy (tree-level) unitarity constraints
[Veltman, 1977; Lee-Quigg-Thacker, 1977; ...]

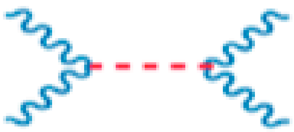
Zwirner

An example: $\mathcal{A}(W_L^+ W_L^- \to Z_L Z_L) \quad (s \gg m_W^2)$





$$i\frac{s}{v^2}$$



$$-i\frac{s^2}{v^2(s-m_h^2)}$$

$$\rightarrow \quad -i\frac{m_h^2}{v^2}\frac{s}{s-m_h^2}$$

If no Higgs then something must happen!

Can we do without the Higgs?

Suppose we take the gauge symmetric part of the SM and put masses by hand.

Gauge invariance is broken explicitly. The theory is no more renormalizable. One loses understanding of the observed accurate validity of gauge predictions for couplings.

Still, what is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes

To avoid this either there is one or more Higgs particles or some new states (e.g. new vector bosons)

Thus something must happen at the few TeV scale!!

A crucial question for the LHC

What saves unitarity?

- the Higgs
- some new vector boson

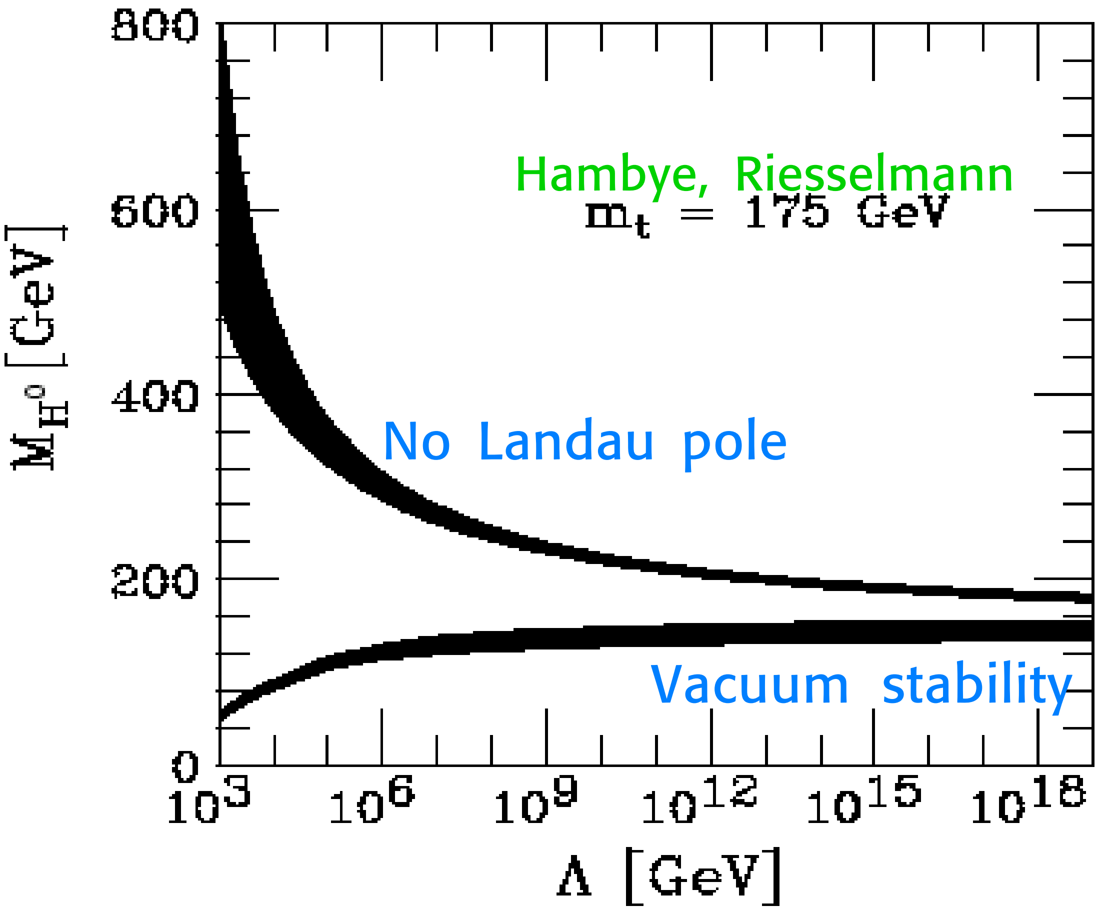
  W′, Z′
  KK recurrences
  resonances from a strong sector
  ......

Theoretical bounds on the SM Higgs mass

Λ: scale of new physics beyond the SM

Upper limit: No Landau pole up to Λ
Lower limit: Vacuum (meta)stability

The LHC was designed to cover the whole range



If the SM would be valid up to M_{GUT}, M_{Pl} then m_H would be limited in a small range

Lower now because of m_t → 128 GeV < m_H < 180 GeV

Status of the SM Higgs fit

Radiative corr's indicate a light H

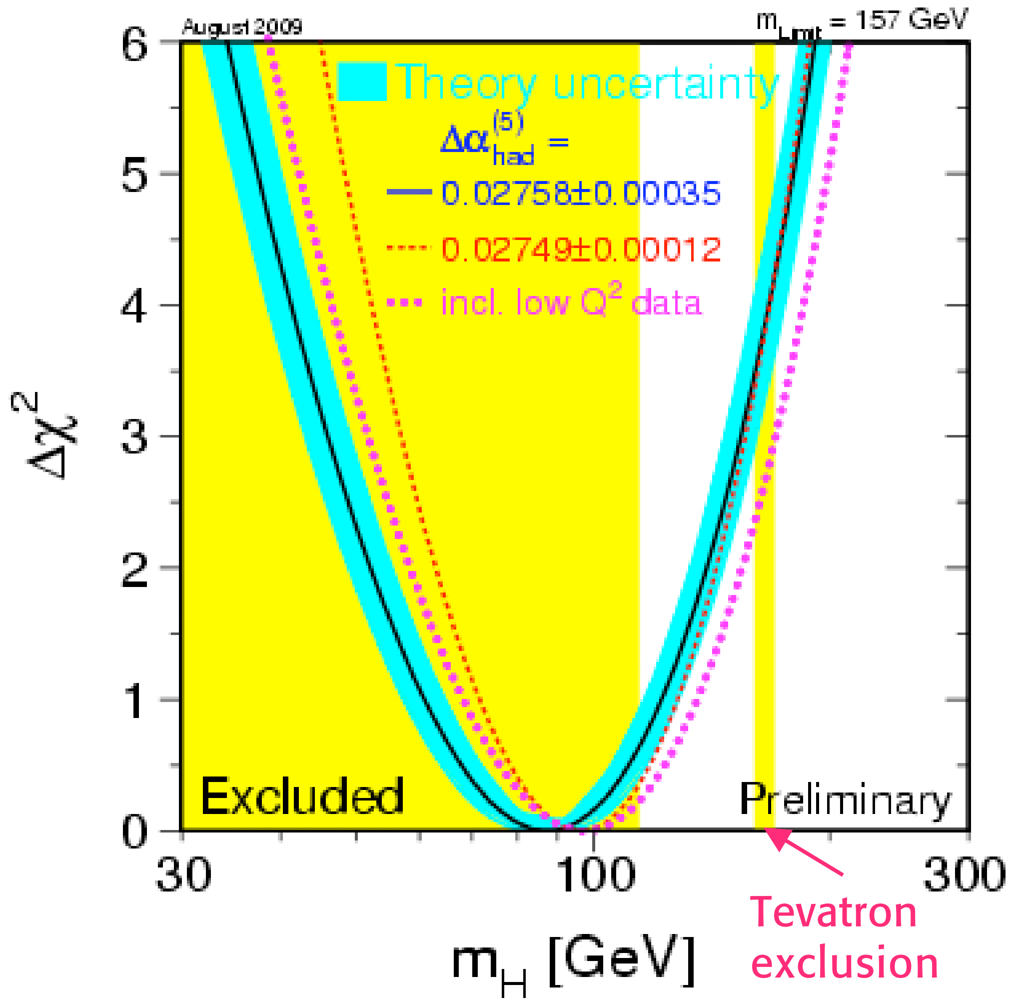
Summer '09

Sensitive to log m_H

Rad Corr.s ->

$\log_{10} m_H(\text{GeV}) = 1.94 \pm 0.15$

$m_H = 87 + 35 - 26$ GeV



Tevatron exclusion

This is a great triumph for the SM: ~right in the narrow allowed range $\log_{10} m_H \sim 2 - 3$

Direct search: $m_H > 114.4$ GeV

At 95 % cl

$m_H < 157$ GeV (rad corr.'s)

$m_H < 186$ GeV (incl. direct search bound)

Is it possible that the Higgs is not found at the LHC?

Here "Higgs" means the "the EW symmetry breaking mechanism"

Looks pretty unlikely!!

The LHC discovery range is large enough: $m_H < \sim 1$ TeV
the Higgs should be really heavy!

Rad. corr's indicate a light Higgs (whatever its nature)

A heavy Higgs would make perturbation theory to collapse nearby (violations of unitarity for $m_H > \sim$ TeV)

Such nearby collapse of pert. th. is very difficult to reconcile with EW precision tests plus simulating a light Higgs

The SM good agreement with the data favours forms of new physics that keep at least some Higgs light

The Standard Model works very well

So, why not find the Higgs and declare particle physics solved?

First, you have to find it!

→ LHC

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- The flavour puzzle
- •••••

and experimental clues:

- Neutrino masses
- Coupling unification
- Dark matter
- Baryogenesis
- Vacuum energy
- •••••

Some of these problems point at new physics at the weak scale: eg
Hierarchy
Dark matter (perhaps)

Dark Matter

WMAP, SDSS, 2dFGRS….

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.045$, $\Omega_m \sim 0.27$

Most is Dark Matter and Dark Energy

Most Dark Matter is Cold (non relativistic at freeze out)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant: $\Omega_\nu < 0.015$

SUSY has excellent DM candidates: eg Neutralinos (--> LHC)
Also Axions are still viable (introduced to solve strong CPV)
(in a mass window around m $\sim 10^{-4}$ eV and $f_a \sim 10^{11}$ GeV
but these values are simply a-posteriori)

Identification of Dark Matter is a task of enormous importance for particle physics and cosmology

LHC?

LHC has good chances because it can reach any kind of WIMP:

WIMP: Weakly Interacting Massive Particle
with m ~ 10^1-10^3 GeV

For WIMP's in thermal equilibrium after inflation the density is:

$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}$$

can work for typical weak cross-sections!!!

This "coincidence" is a good indication in favour of a WIMP explanation of Dark Matter

A crucial question for the LHC

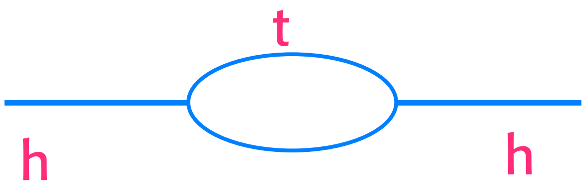
Is Dark Matter a WIMP?

LHC will tell yes or no to WIMPS

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

$\Lambda \sim o(1\mathrm{TeV})$

Λ: scale of new physics beyond the SM

- $\Lambda >> m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim o(1\mathrm{TeV})$ 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.)

  ......

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  exact (unrealistic): cancellation of Λ^2 in δm_h^2

  approximate (possible): $\Lambda \sim m_{SUSY}-m_{ord}$ → top loop $\Lambda \sim m_{stop}$

  The most widely accepted

- The Higgs is a $\bar{\psi}\psi$ condensate. No fund. scalars. But needs new very strong binding force: $\Lambda_{new} \sim 10^3 \Lambda_{QCD}$ (technicolor).

  Strongly disfavoured by LEP. Coming back in new forms

- Models where extra symmetries allow m_h only at 2 loops and non pert. regime starts at $\Lambda \sim 10$ TeV

  "Little Higgs" models. Some extra trick needed to solve problems with EW precision tests

- Extra spacetime dim's that "bring" M_{Pl} down to o(1TeV)

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

- Ignore the problem: invoke the anthropic principle

The anthropic route

The scale of the cosmological constant is a big mystery.

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

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

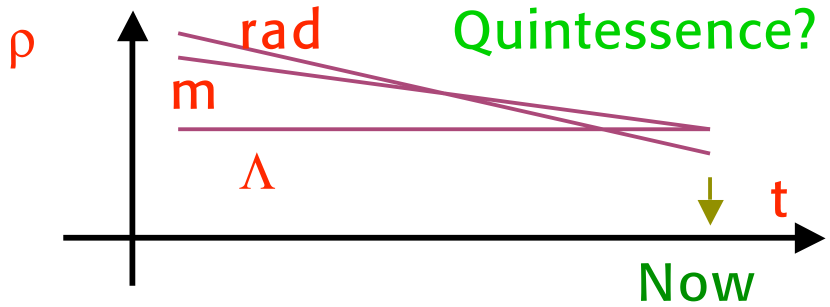
If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123} \rho_{obs}$

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

But SUSY is broken: $\rho_\Lambda \sim (\Lambda_{SUSY})^4 \sim 10^{59} \rho_{obs}$

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?

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

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....)

SUSY: boson fermion symmetry

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

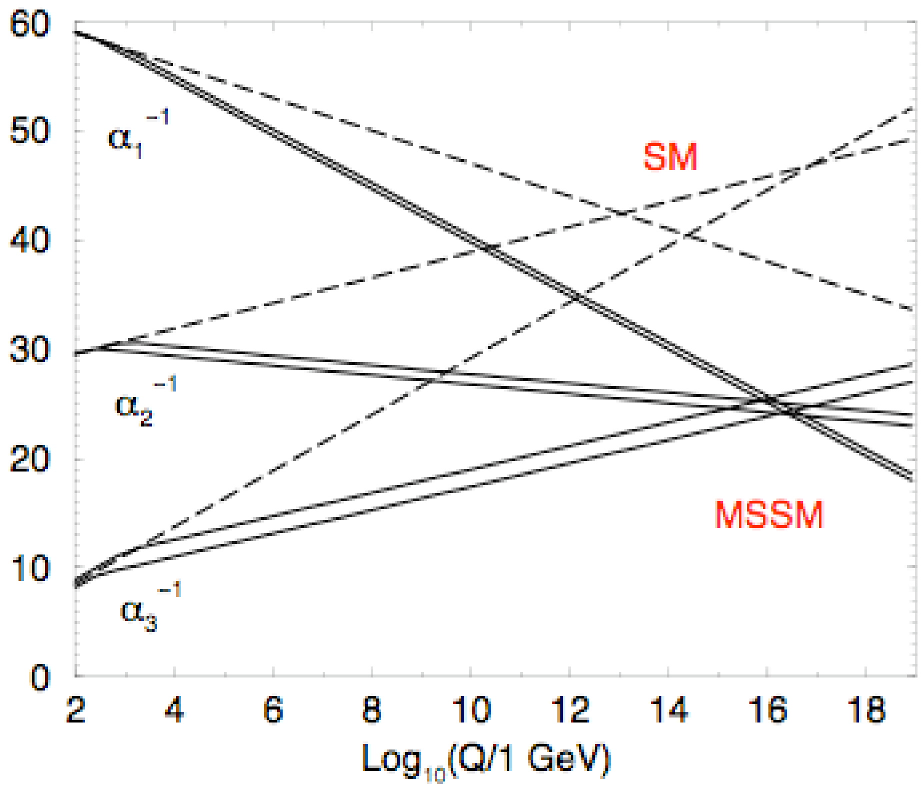
In broken SUSY Λ^2 is replaced by $(m_{stop}^2 - m_t^2)\log\Lambda$

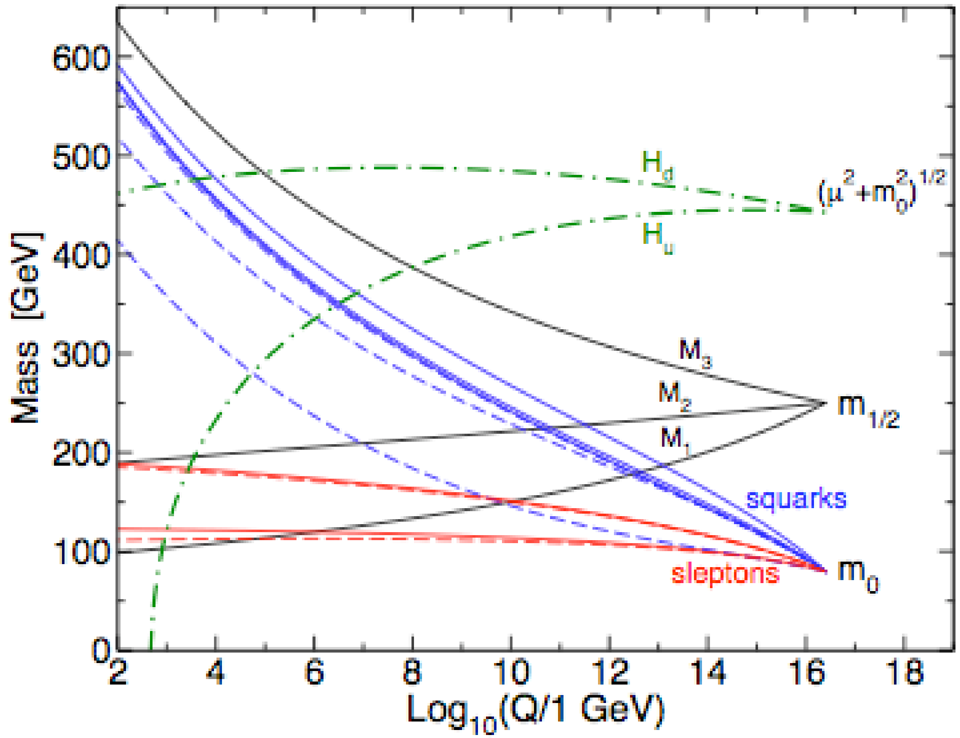
$m_H > 114.4$ GeV, $m_{\chi+} > 100$ GeV, EW precision tests, success of CKM, absence of FCNC, all together, impose sizable Fine Tuning (FT) particularly on minimal realizations (MSSM, CMSSM…).

Yet SUSY is a completely specified, consistent, computable model, perturbative up to M_{Pl} quantitatively in agreement with coupling unification (GUT's) (unique among NP models) and has a good DM candidate: the neutralino (actually more than one).

Remains the reference model for NP

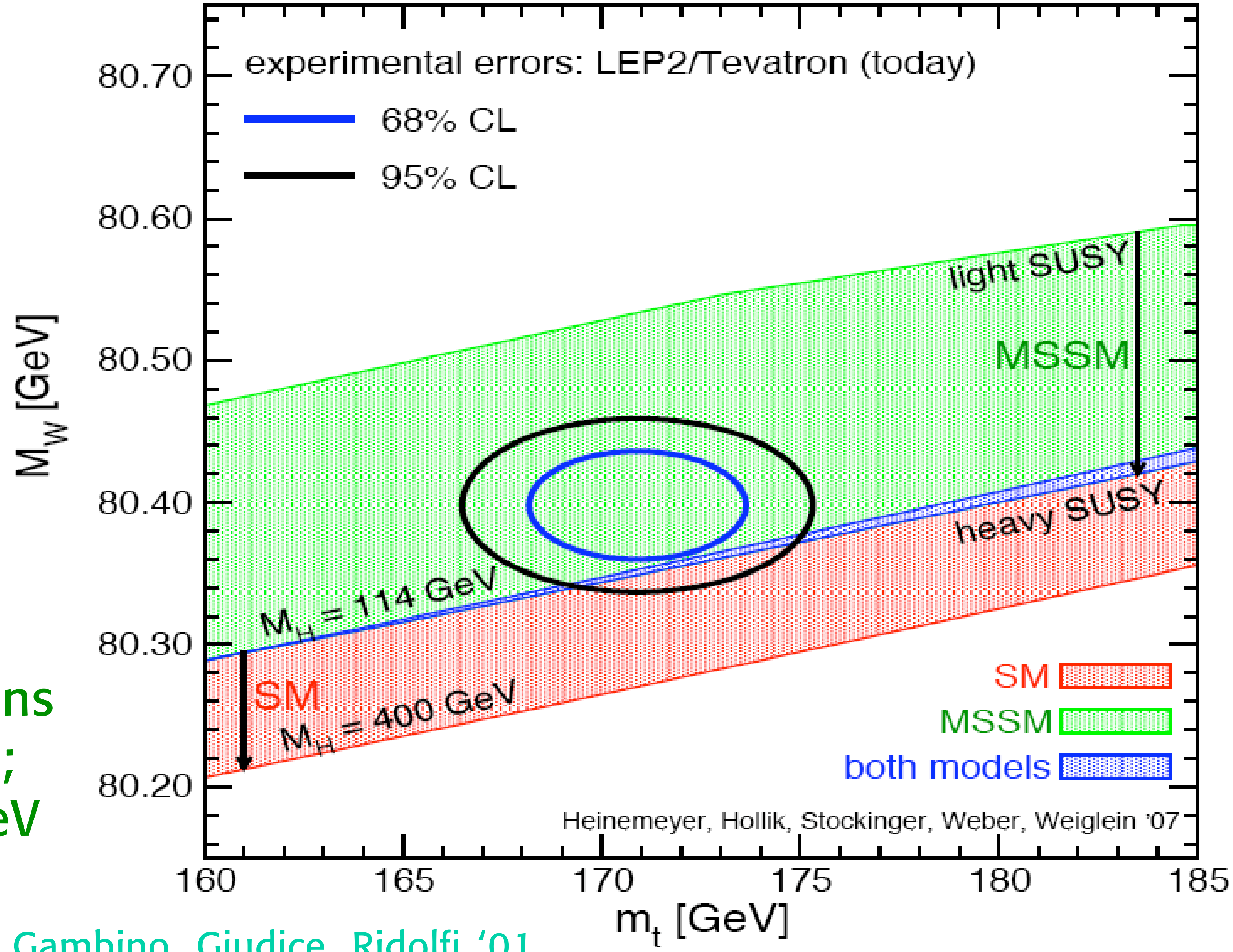
SUSY is unique in providing a weakly interacting theory up to the GUT/Planck scale





Other BSM models (little Higgs, composite Higgs, Higgsless....) all become strongly interacting at a multi-TeV scale

SUSY effects could modify the SM fit



"light SUSY"=
= light s-leptons
and charginos;
s-quarks ~1 TeV

G.A, Caravaglios, Gambino, Giudice, Ridolfi '01

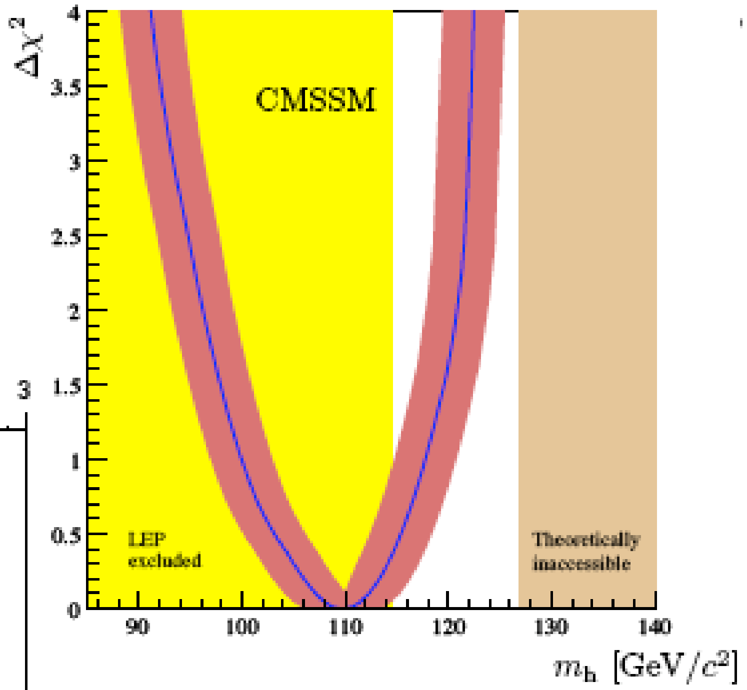
A recent study indicates that m_h goes up in CMSSM when b->sγ, a_μ, Ω_{DM} are added

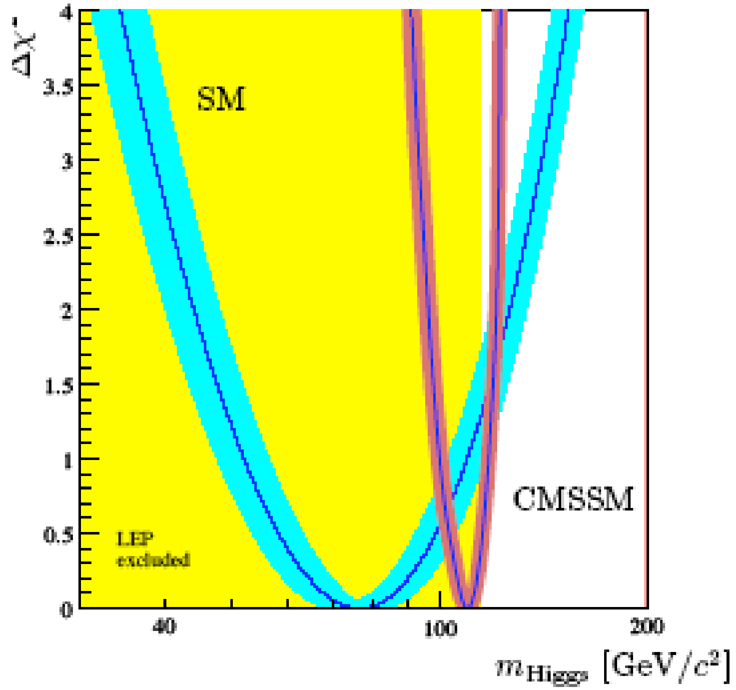
O. Buchmuller et al '07, '08 [0808.4128]

also:
J. Ellis et al '07

CMSSM

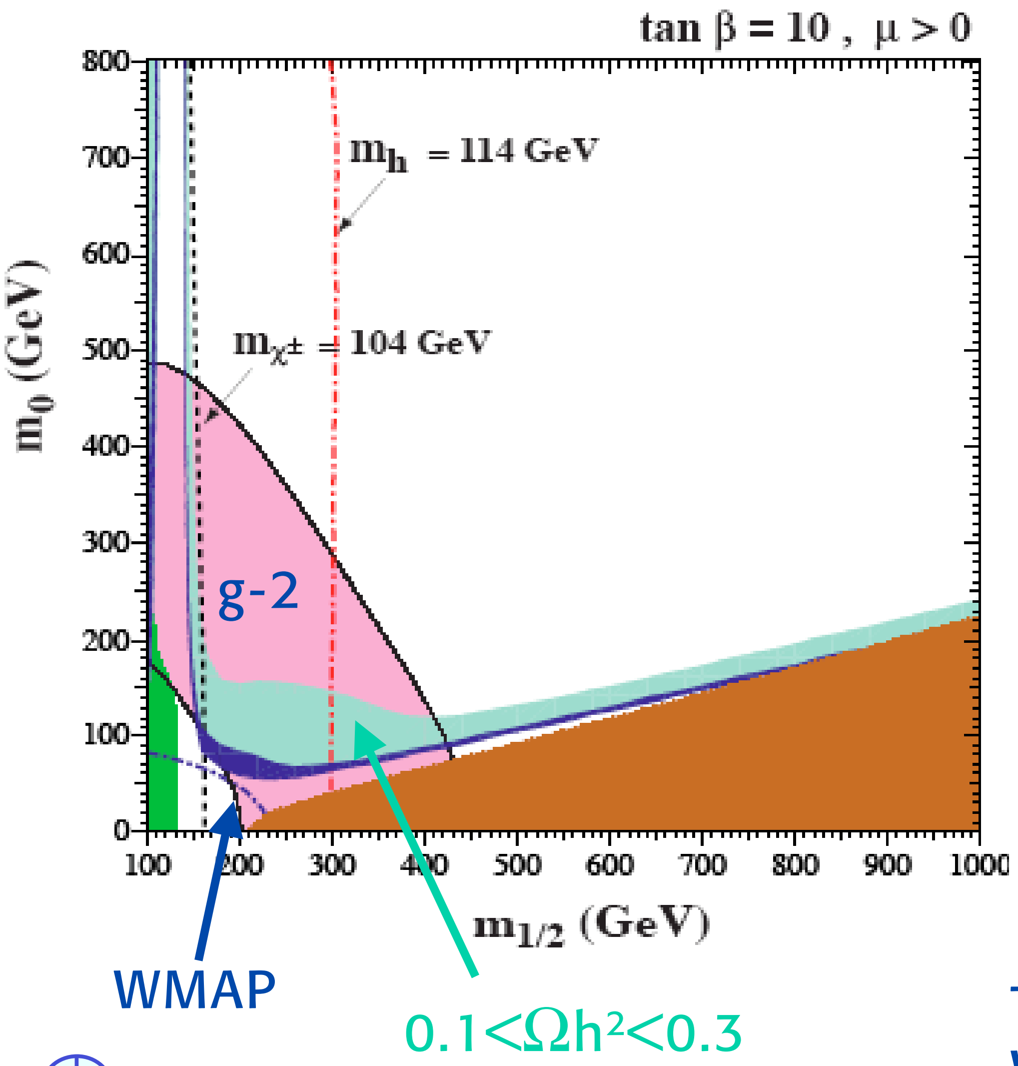
Variable	Measurement	Fit	$\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	
σ^0_{had} [nb]	41.540 ± 0.037	41.486	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21613	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1479	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.382	
m_t [GeV]	170.9 ± 1.8	170.8	
$R(b\to s\gamma)$	1.13 ± 0.12	1.12	
$B_s\to\mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	



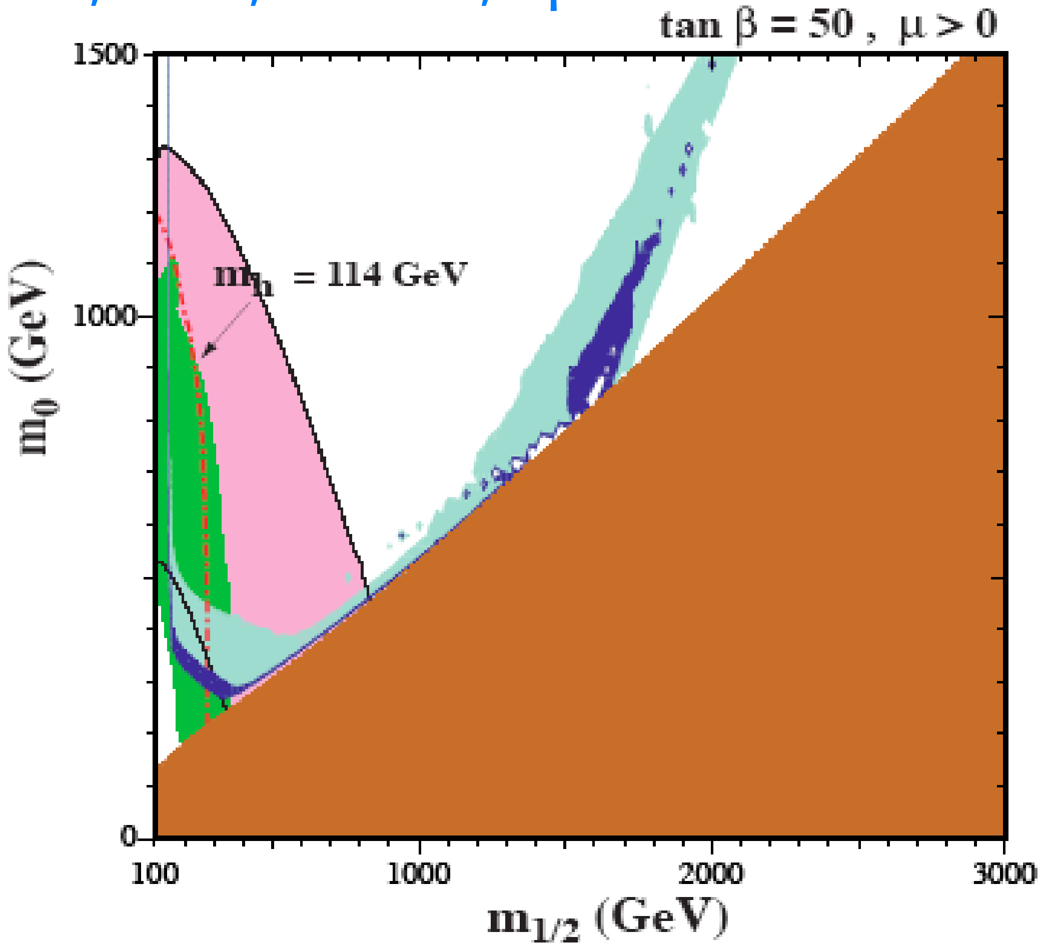


SUSY Dark Matter: best candidate the neutralino

[in SUSY the gravitino is a non-WIMP alternative]

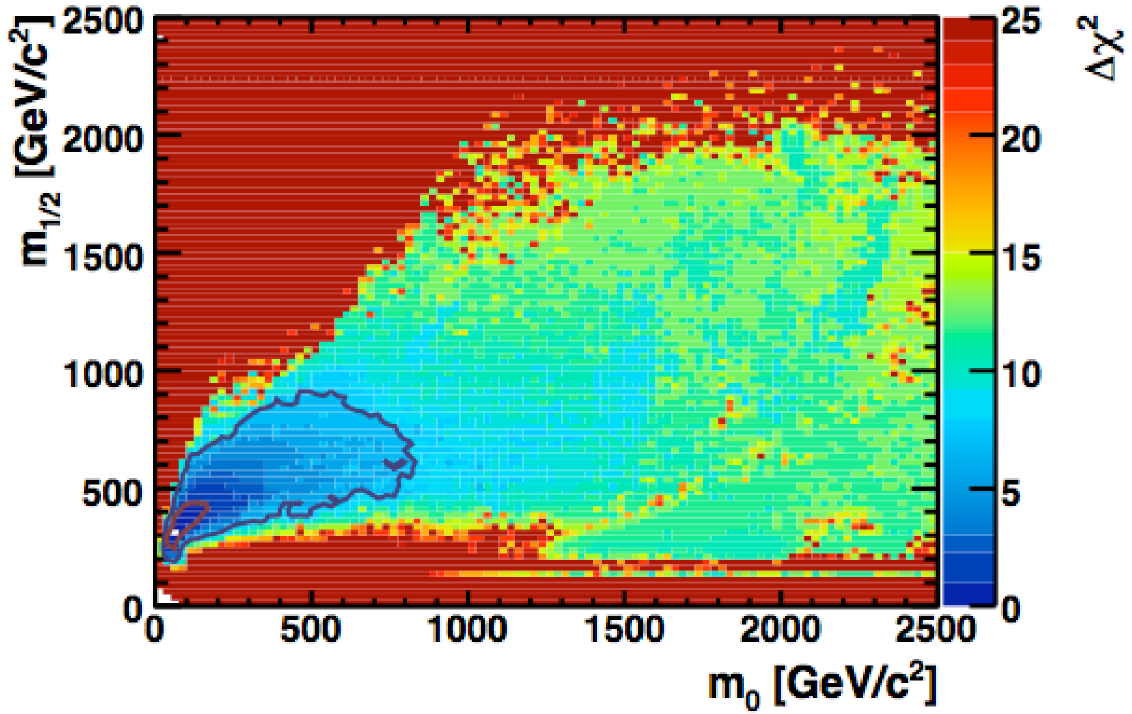


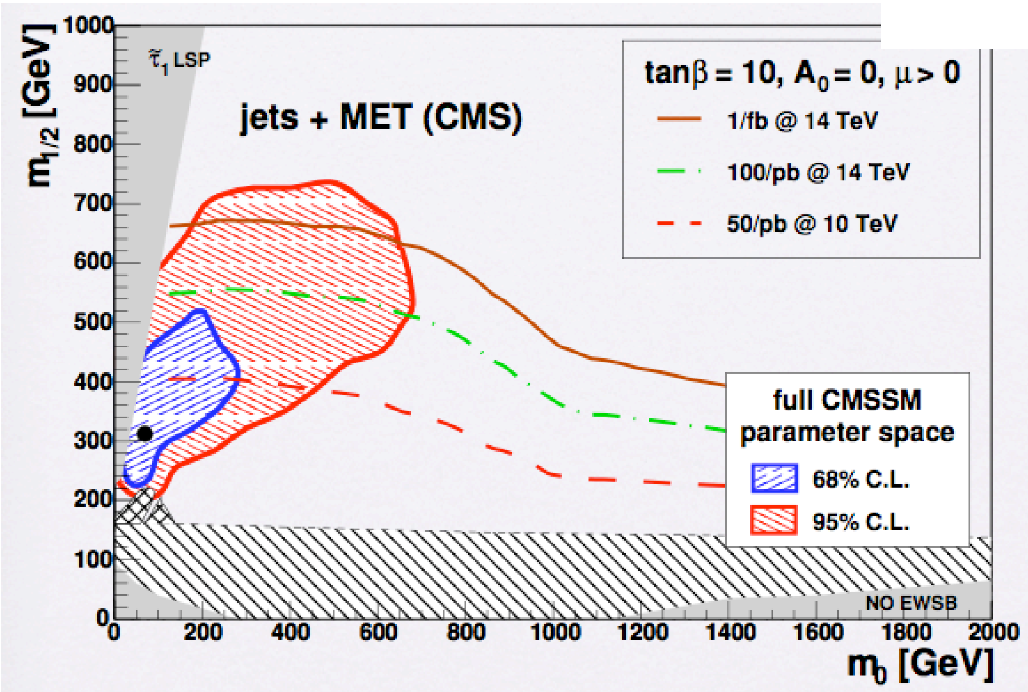
Ellis, Olive, Santoso, Spanos



This is for the CMSSM
With less constraints, more space

relatively light SUSY
is indicated





accesssible at the LHC

Muon g-2 and SUSY

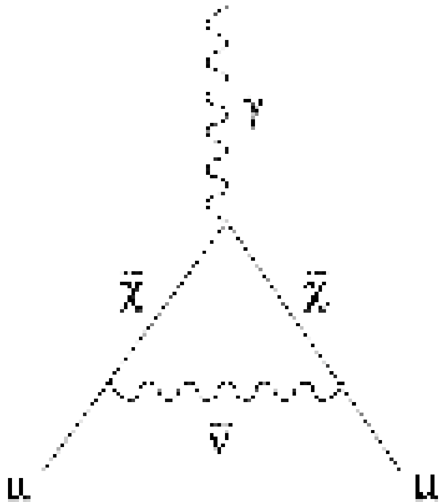
Observed Difference with Experiment:

$$a_\mu^{exp} - a_\mu^{SM} = (27.5 \pm 8.4) \times 10^{-10}$$

➡ 3.3 "standard deviations"

Could be new physics
eg light SUSY

$$\delta a_\mu = 13 \cdot 10^{-10} \left(\frac{100 GeV}{M_{SUSY}} \right)^2 tg\beta$$



a_μ is a plausible location for a new physics signal!!

Little Higgs Models

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

$$G \supset [SU(2) \otimes U(1)]^2 \supset SU(2) \otimes U(1)$$

global (G) — gauged ($[SU(2) \otimes U(1)]^2$) — SM ($SU(2) \otimes U(1)$)

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

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

cutoff Λ ~10 TeV

Λ^2 divergences canceled by:

$\delta m^2_{H|top}$ new coloured fermion χ with Q=2/3

$\delta m^2_{H|gauge}$ W', Z', γ'

$\delta m^2_{H|Higgs}$ new scalars

} ~1 TeV

$\oplus$ 2 Higgs doublets ~0.2 TeV

With some tension, Little Higgs models technically can work.

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

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)

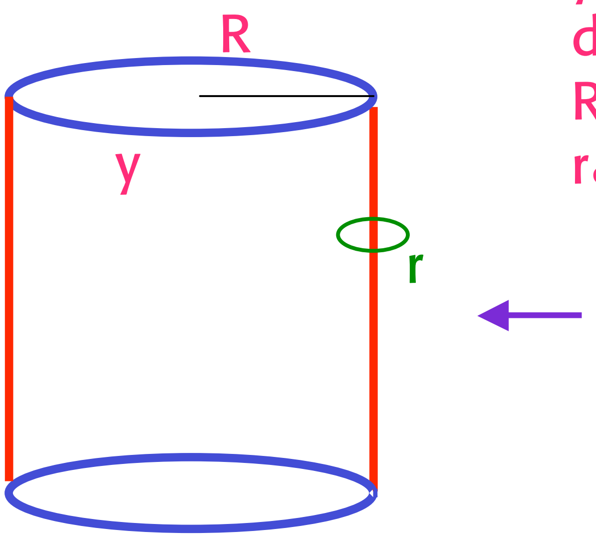
- GUT's in ED (M_{GUT})
- ED as (part of the) solution of the hierarchy probem (M_{EW})
- EW symmetry breaking from ED (M_{EW})

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: 1/R <~ 1 TeV
- SM fields are on a brane
- Gravity propagates in the whole bulk



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

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)

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

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

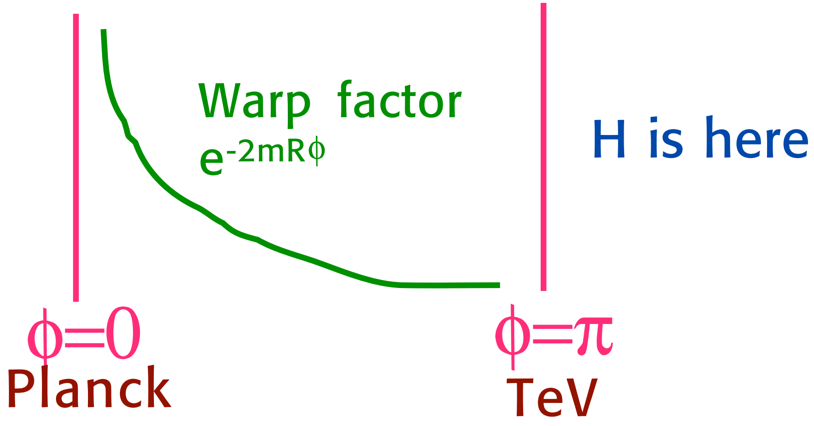
emerges as the most promising formulation

A more promising scheme (warped ED)

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

Randall-Sundrum:

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 ~ 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

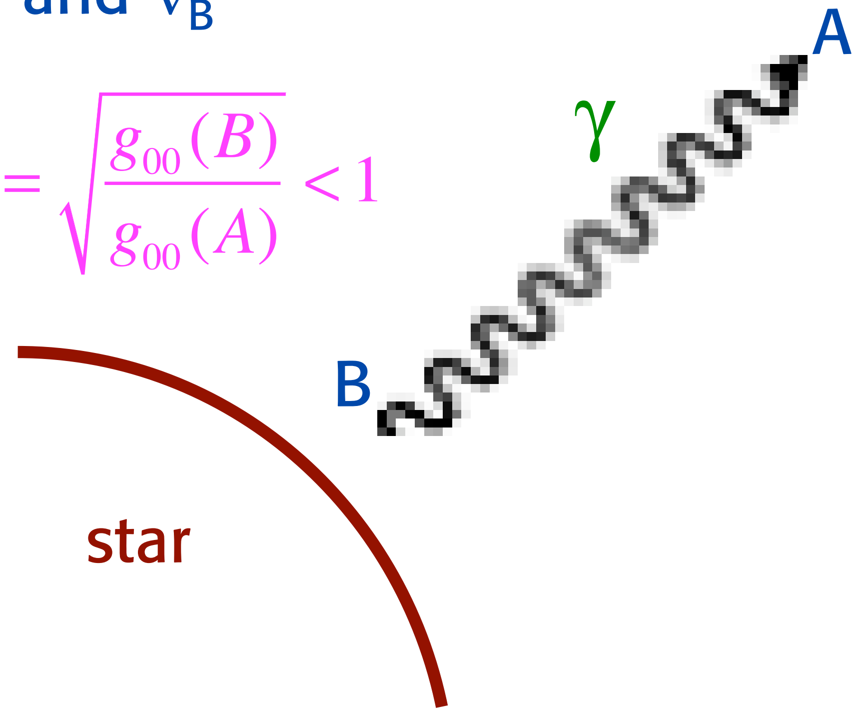
"radion"

Goldberger, Wise

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

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

seen from A the B frequency is smaller: as if the photon kinetic energy lost by climbing out of grav. field



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

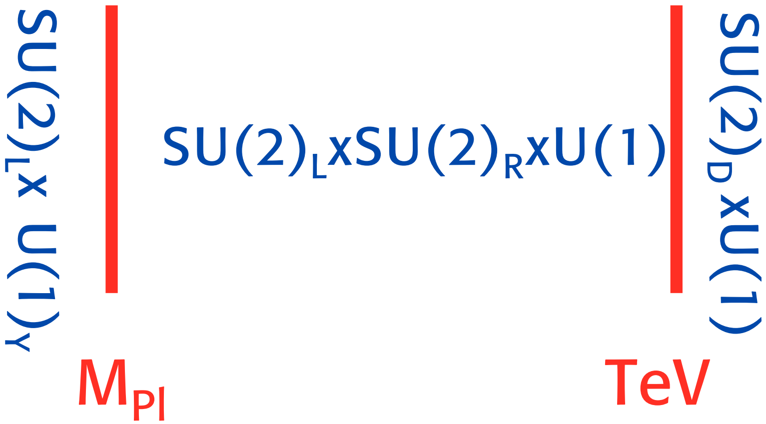
Good tutorials:
R. Sundrum '04 TASI lectures
R. Rattazzi '05 Cargese Lectures
Csaki et al '05
Gherghetta'06

Applications

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

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

The only 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 brane

With no Higgs unitarity violations, eg:

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

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

$$g_{WWWW}^2 - e^2 - \sum_k g_{WWZ_k}^2 = 0\ ;$$

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

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)

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

Serious problems with EW precision tests

e.g. Chivukula et al ‘02, Barbieri, Pomarol, Rattazzi '03;

also with Z->bb

m_W fixes the KK gap and it is not sufficiently large

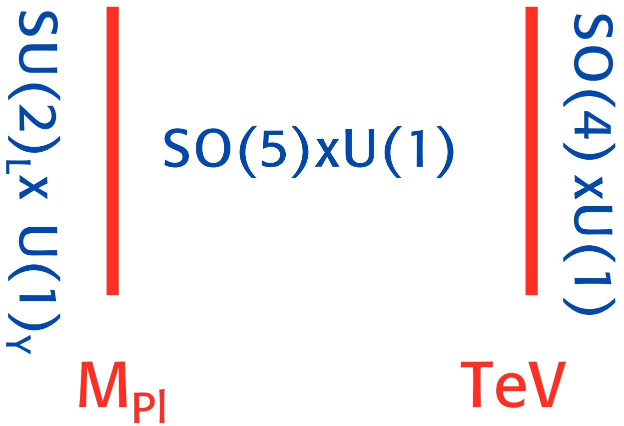
Substantial fine tuning required

Best try: Cacciapaglia et al '06

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

• Composite Higgs in a 5-dim holographic theory

Agashe, Contino, Pomarol......



Warped R-S background

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)

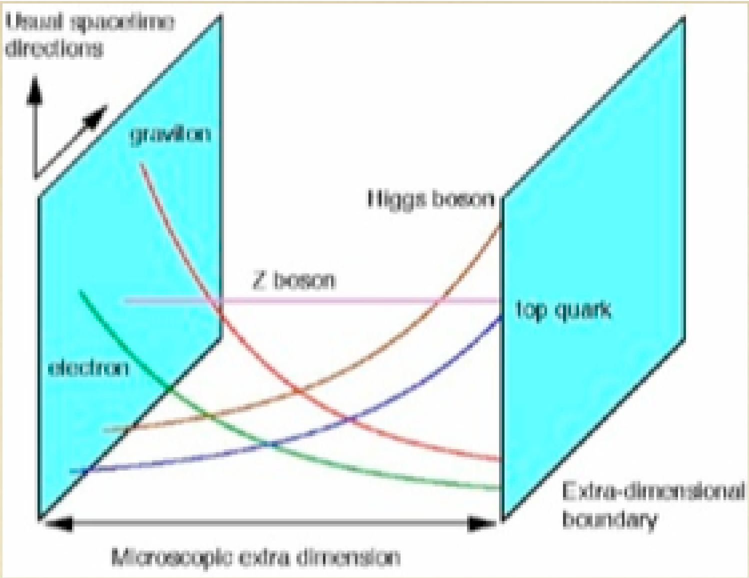
As in Little Higgs models

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: $m_H < 185$ GeV

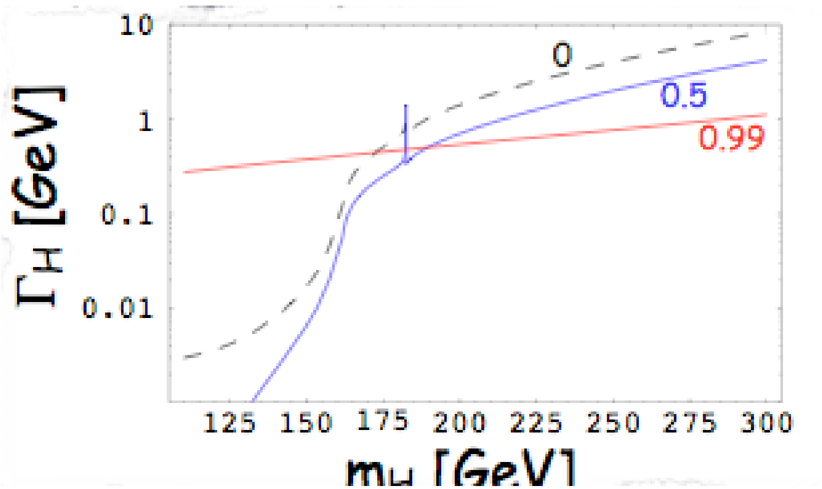
Also in these models a sizable fine-tuning is required

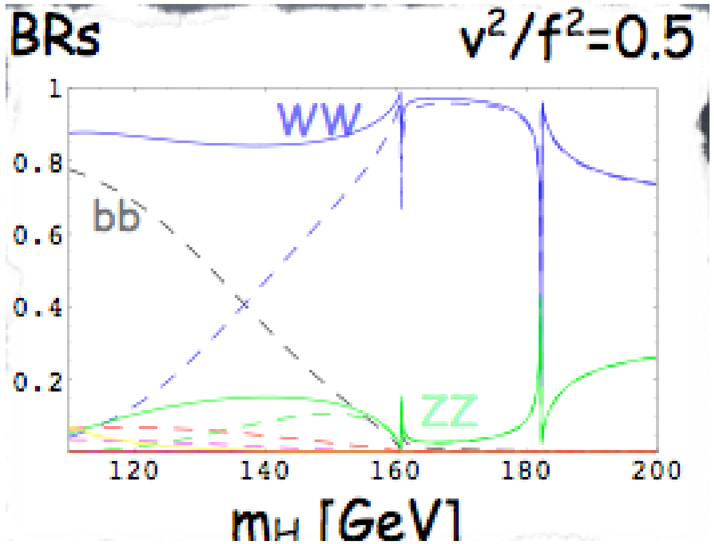


A qualitative description of flavour

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)

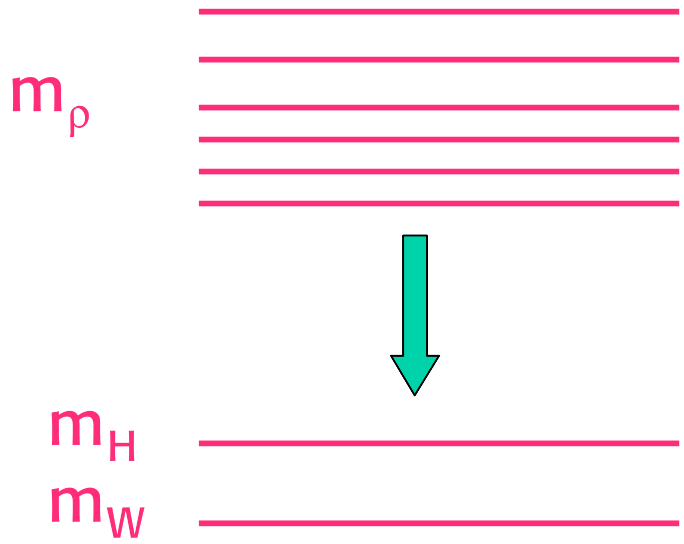
Agashe/ Contino/Pomarol/Sundrum/ Grojean/Rattazzi....

v ~ EW scale f ~ SI scale

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

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

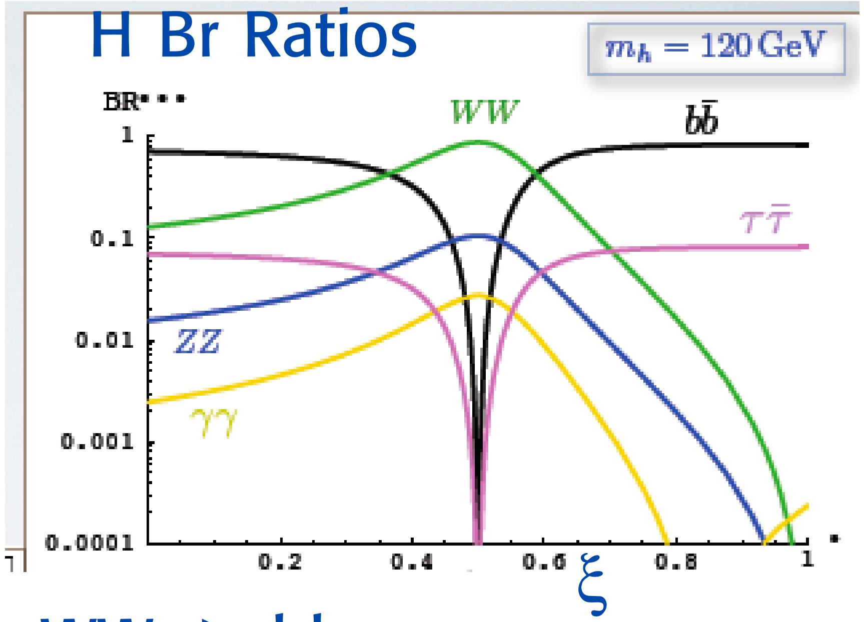
ξ interpolates between SM [$\xi \sim 0$] and some degree of compositeness [$\xi \sim o(1)$ limited by precision EW tests]



Detectable ξ effects at the LHC

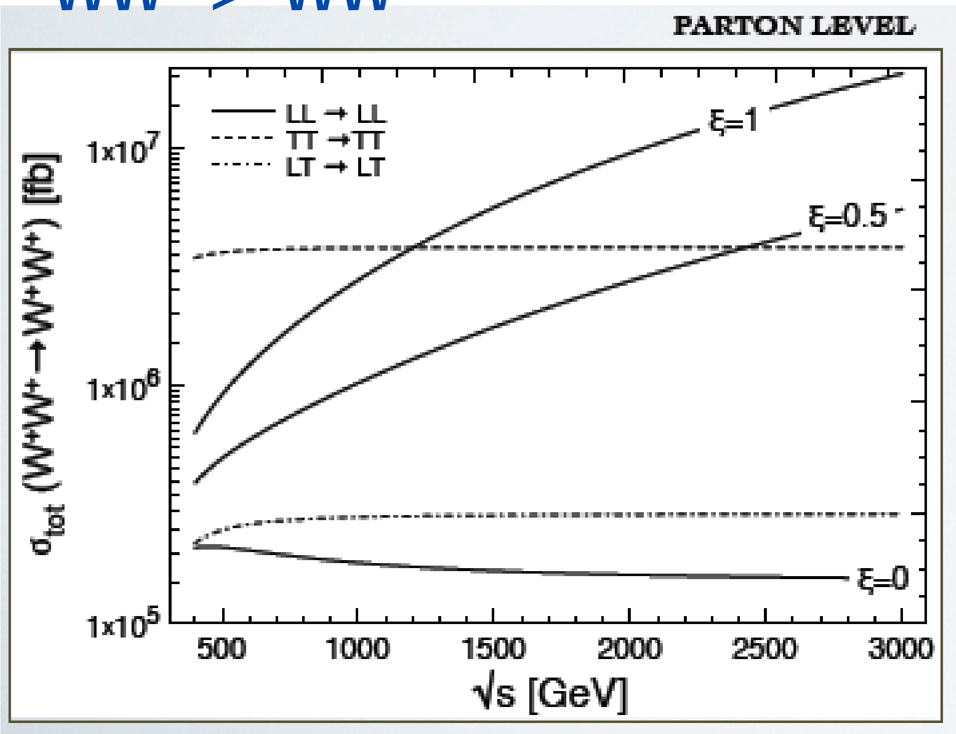
- Higgs couplings
- WW scattering
- 2-Higgs Production

H Br Ratios

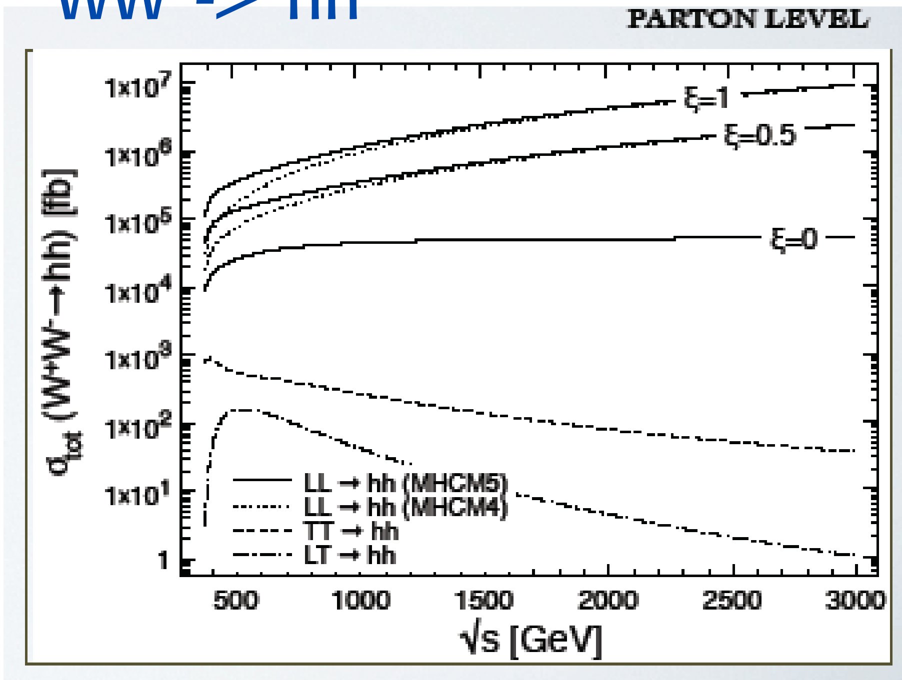


Contino et al

WW -> WW



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

In conclusion

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"