

Corfu'09 - 1 September '09

*The Electroweak
Symmetry Breaking
Riddle*

Guido Altarelli
Roma Tre/CERN

The LHC physics run will soon start, hopefully!

After the incident on Sept.19 '08 we must wait till Nov. '09
[LEP was closed at the end of 2000] Start at 3.5 TeV per beam

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

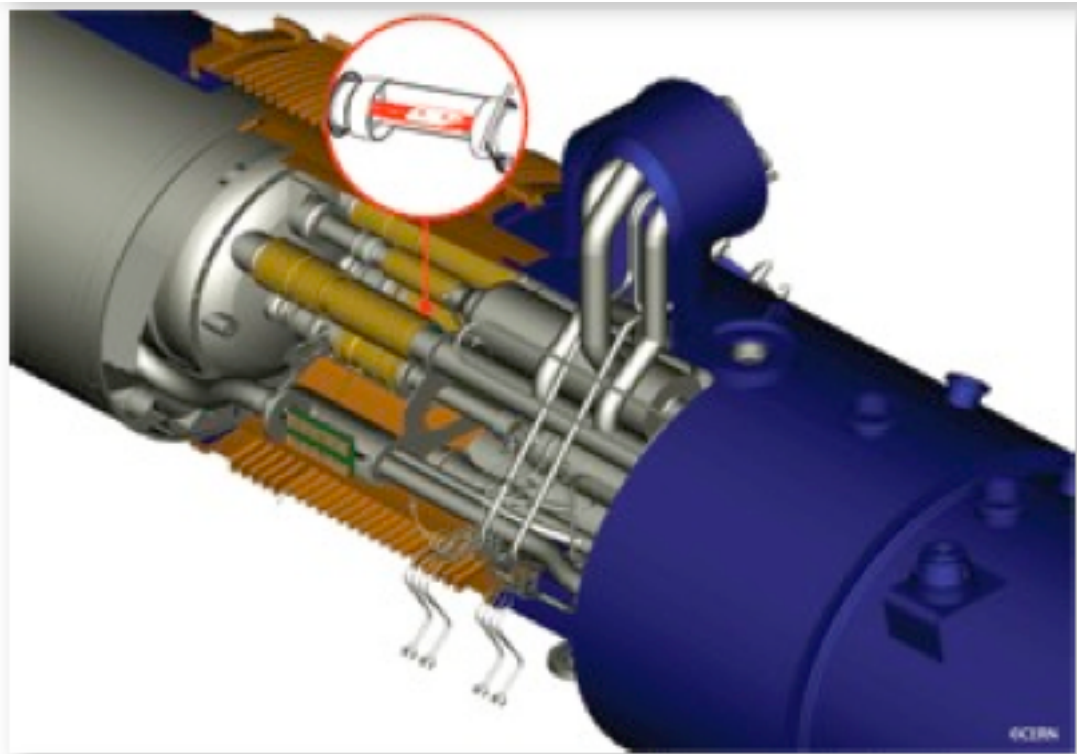
- Clarify the EW symmetry breaking sector
- Search for new physics at the TeV scale
- Identify the particle(s) that make the Dark Matter in the Universe

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

The LHC is scheduled to restart in mid November'09. First collisions will be at injection energy and the first high energy physics run at 3.5 TeV beam energy. During 2010 the energy will be increased towards 5 TeV. A run with lead-ions is scheduled towards the end of the run later in 2010.



Aiming at collecting
 $\sim 200 \text{ pb}^{-1}$ of data
in the run

The experiments are ready

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

e.g. from the TeV scale (LHC!)
the GUT scale
the Planck scale

But even as a low energy effective theory 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

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

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

Vacuum energy
 $V_{0\text{exp}} \sim (2 \cdot 10^{-3} \text{ eV})^4$

Possible instability
depending on m_H

Origin of quadratic
divergences.
Hierarchy problem

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



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

$$\mathcal{L}_{\text{symm}} = -\frac{1}{4}[\partial_\mu W_\nu^A - \partial_\nu W_\mu^A - ig\epsilon_{ABC}W_\mu^AW_\nu^B]^2 +$$

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

$$+\bar{\psi}\gamma^\mu[i\partial_\mu + gW_\mu^At^A + g'B_\mu\frac{Y}{2}]\psi$$

$$\mathcal{L}_{\text{Higgs}} = |[\partial_\mu - igW_\mu^At^A - ig'B_\mu\frac{Y}{2}]\phi|^2 +$$

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

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

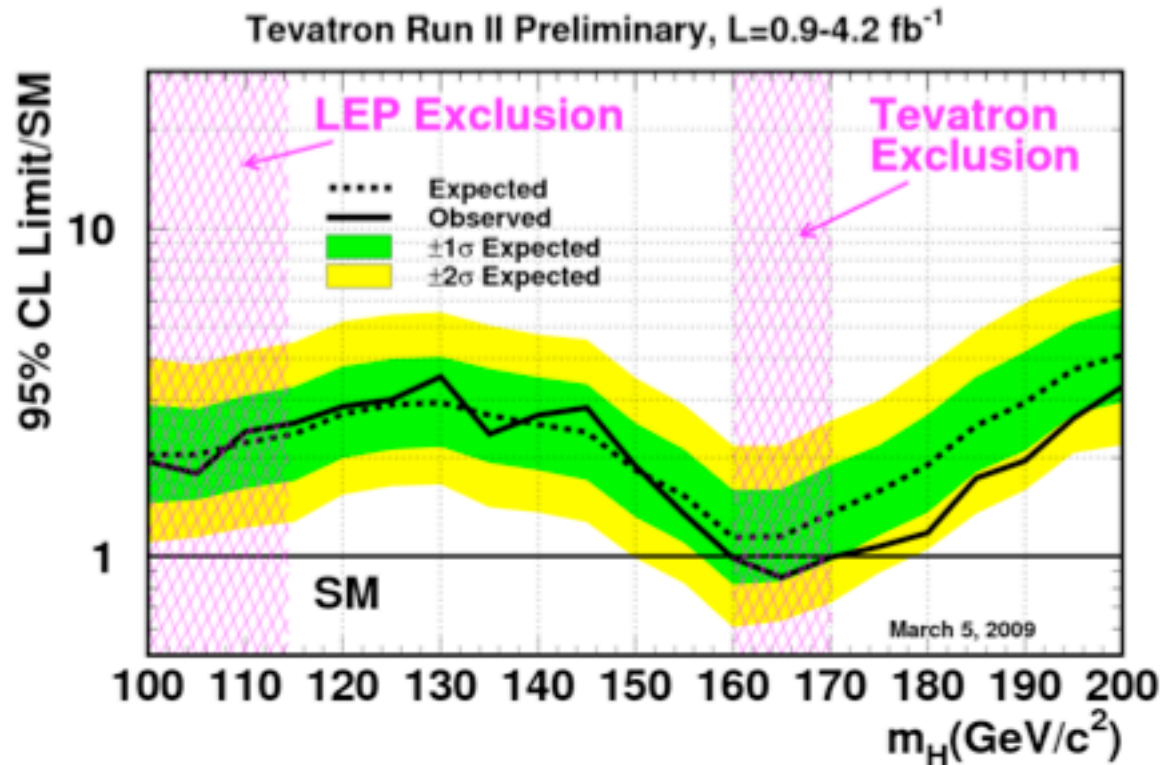
All we know from experiment about the SM Higgs:

No Higgs seen at LEP2 $\rightarrow m_H > 114.4$ GeV (95%cl)

Rad. corr's $\rightarrow m_H < 186$ GeV (95%cl, incl. direct search bound)

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

In the H search the Tevatron is now reaching the SM sensitivity



- The Tevatron experiments are now in position to put constraints on the SM Higgs from direct searches
- **SM Higgs with $160 < m_H < 170 \text{ GeV}$ excluded at 95% CL**



12 fb^{-1} by '11: could exclude $115 < m_H < 185 \text{ GeV}$!!!

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

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 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!!

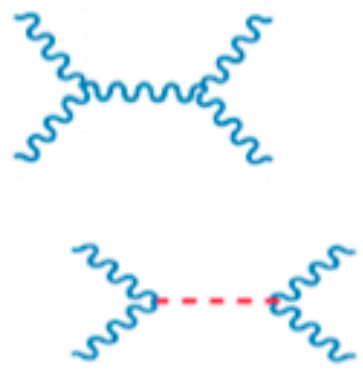


With no Higgs unitarity violations for $E_{\text{CM}} \sim 1\text{-}3 \text{ TeV}$

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



$$\begin{aligned}
 & i \frac{s}{v^2} \\
 & -i \frac{s^2}{v^2(s - m_h^2)} \quad \rightarrow \quad -i \frac{m_h^2}{v^2} \frac{s}{s - m_h^2}
 \end{aligned}$$



If no Higgs then something must happen!

A crucial question for the LHC

What saves unitarity?

- the Higgs
- some new vector boson
 - W', Z'
 - KK recurrences
 - resonances from a strong sector
 -



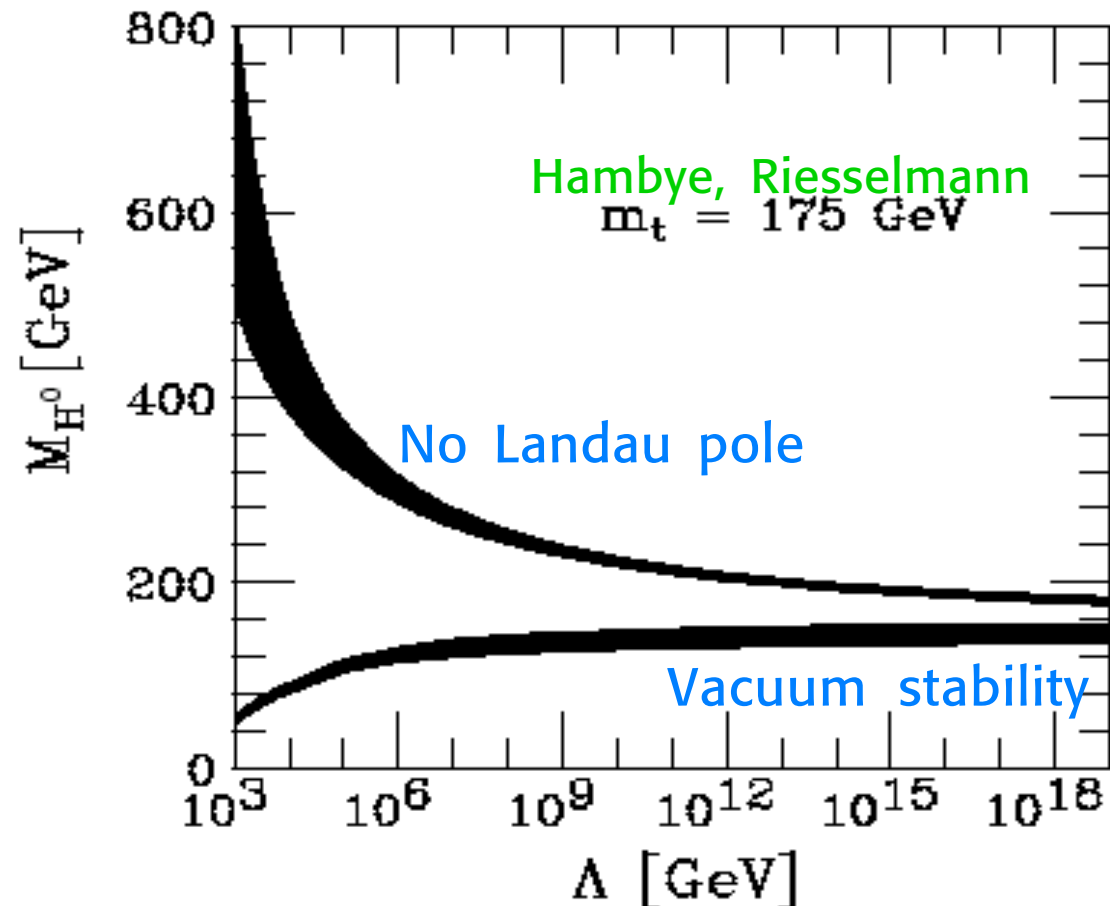
Theoretical bounds on the SM Higgs mass

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



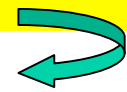
If the SM would be valid up to M_{GUT} , M_{Pl} then m_H would be limited in a small range



Lower now
because of m_t



$$128 \text{ GeV} < m_H < 180 \text{ GeV}$$



Status of the SM Higgs fit

F. Canelli

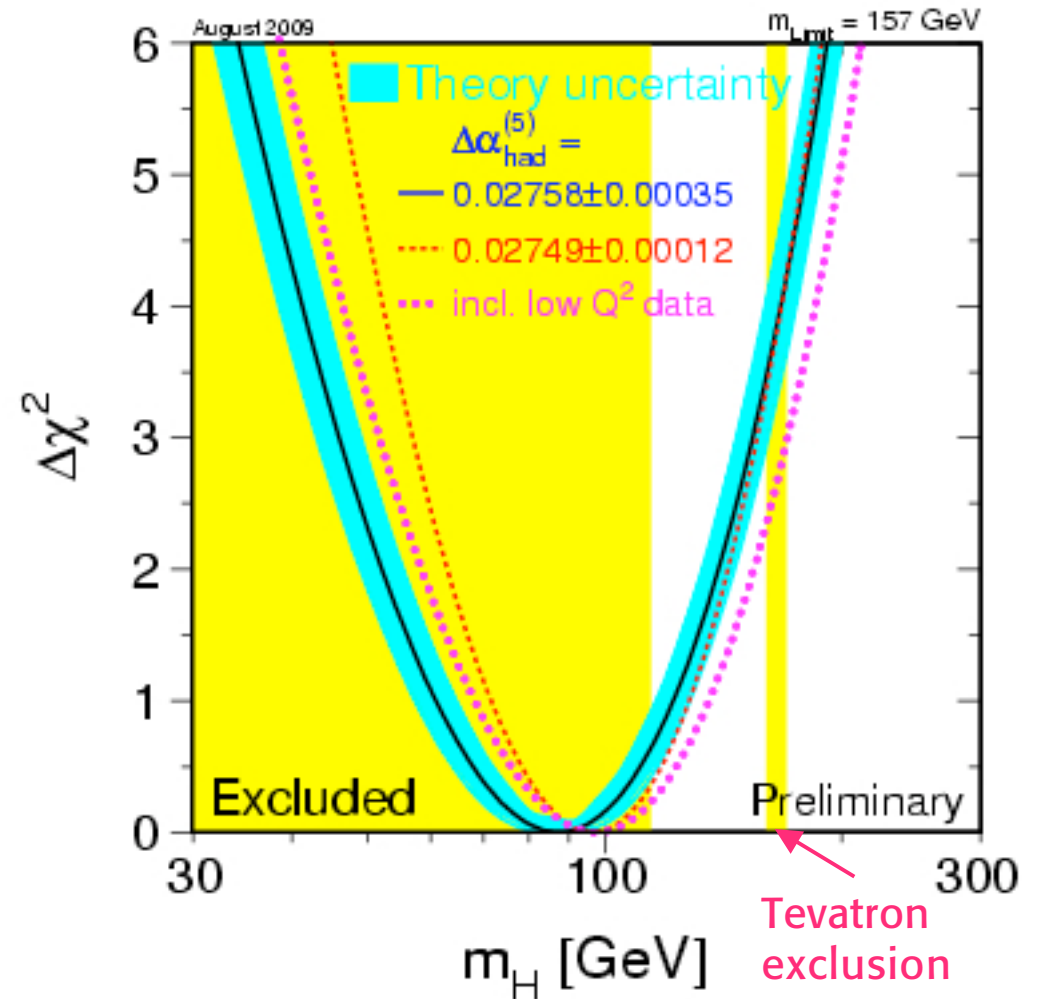
Winter '09

Rad Corr.s -> Sensitive to $\log m_H$
 $\log_{10} m_H (\text{GeV}) = 1.94 \pm 0.15$
 $m_H = 87^{+35}_{-26} \text{ GeV}$

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

Direct search: $m_H > 114.4 \text{ GeV}$

Radiative corr's indicate a light H



At 95 % cl

$m_H < 157 \text{ GeV}$ (rad corr.'s)

$m_H < 186 \text{ GeV}$ (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: $m_H < \sim 1 \text{ TeV}$
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 $m_H > \sim \text{TeV}$)

e.g. strongly interacting WW or WZ scattering

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 problem

.....

and experimental clues:

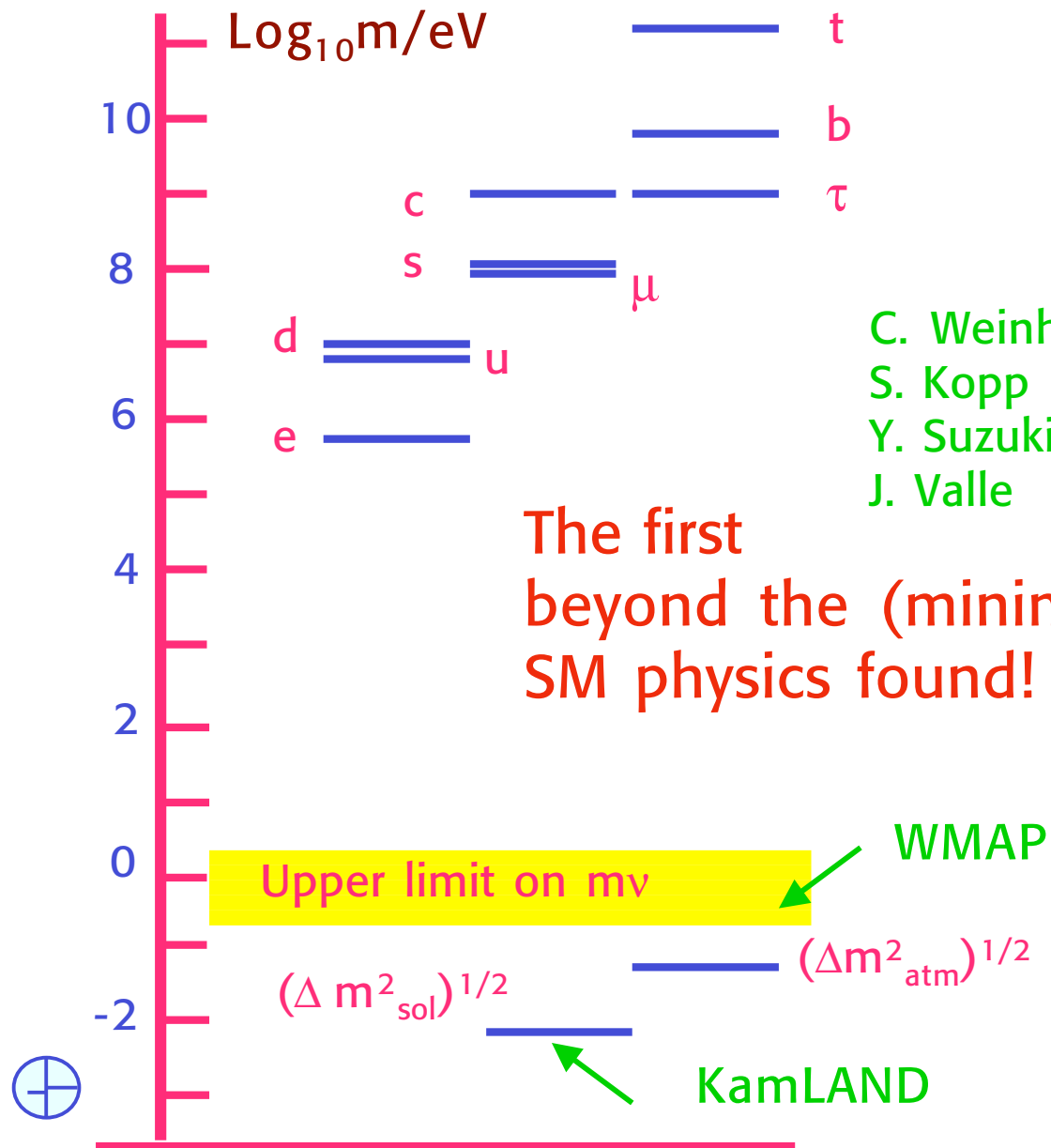
- Coupling unification
- Neutrino masses
- Baryogenesis
- Dark matter
- Vacuum energy

.....

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



ν masses and mixings



Neutrino masses are really special!

$$m_t/(\Delta m^2_{\text{atm}})^{1/2} \sim 10^{12}$$

Massless ν 's?

- no ν_R
- L conserved

Small ν masses?

- ν_R very heavy
- L not conserved

Neutrino masses point to M_{GUT} , well fit into the SUSY picture and in GUT's

A very natural and appealing explanation:

ν 's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale $M \sim M_{\text{GUT}}$

$$m_\nu \sim \frac{m^2}{M}$$

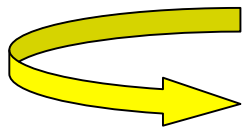
$$m: \leq m_t \sim v \sim 200 \text{ GeV}$$

M: scale of L non cons.

Note:

$$m_\nu \sim (\Delta m^2_{\text{atm}})^{1/2} \sim 0.05 \text{ eV}$$

$$m \sim v \sim 200 \text{ GeV}$$



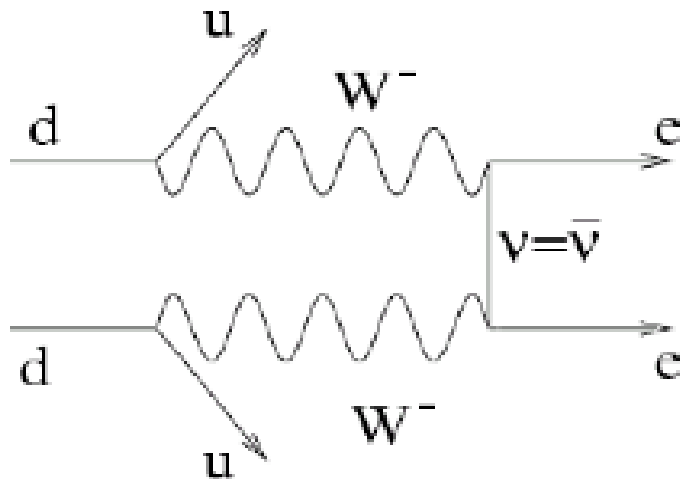
$$M \sim 10^{14} - 10^{15} \text{ GeV}$$

Neutrino masses are a probe of physics at M_{GUT} !

⊕ A signal in $0\nu\beta\beta$ would be an essential confirmation

All we know from experiment on ν masses strongly indicates that ν 's are Majorana particles and that L is not conserved (but a direct proof still does not exist).

Detection of $0\nu\beta\beta$ would be a proof of L non conservation. Thus a big effort is devoted to improving present limits and possibly to find a signal.



Heidelberg-Moscow
IGEX
Cuoricino
Nemo
Sokotvina
CUORE
GERDA
.....



$$0\nu\beta\beta = dd \rightarrow uue^-e^-$$

Baryogenesis by decay of heavy Majorana ν 's

J. Valle

BG via Leptogenesis near the GUT scale

$T \sim 10^{12 \pm 3}$ GeV (after inflation)

Buchmuller, Yanagida,
Plumacher, Ellis, Lola,
Giudice et al, Fujii et al

Only survives if $\Delta(B-L)$ is not zero
(otherwise is washed out at T_{ew} by instantons)

....

Main candidate: decay of lightest ν_R ($M \sim 10^{12}$ GeV)

L non conserv. in ν_R out-of-equilibrium decay:

B-L excess survives at T_{ew} and gives the obs. B asymmetry.

Quantitative studies confirm that the range of m_i from
 ν oscill's is compatible with BG via (thermal) LG

In particular the bound
was derived for hierarchy

$$m_i < 10^{-1} \text{ eV}$$

Can be relaxed for degenerate neutrinos
So fully compatible with oscill'n data!!

Buchmuller, Di Bari, Plumacher;
Giudice et al; Pilaftsis et al;
Hambye et al

Dark Matter

WMAP, SDSS,
2dFGRS....

Most of the Universe is not made up of
atoms: $\Omega_{\text{tot}} \sim 1$, $\Omega_b \sim 0.045$, $\Omega_m \sim 0.27$
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 (\rightarrow 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 $m \sim 10^1\text{-}10^3$ GeV

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

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

can work for typical weak cross-sections!!!

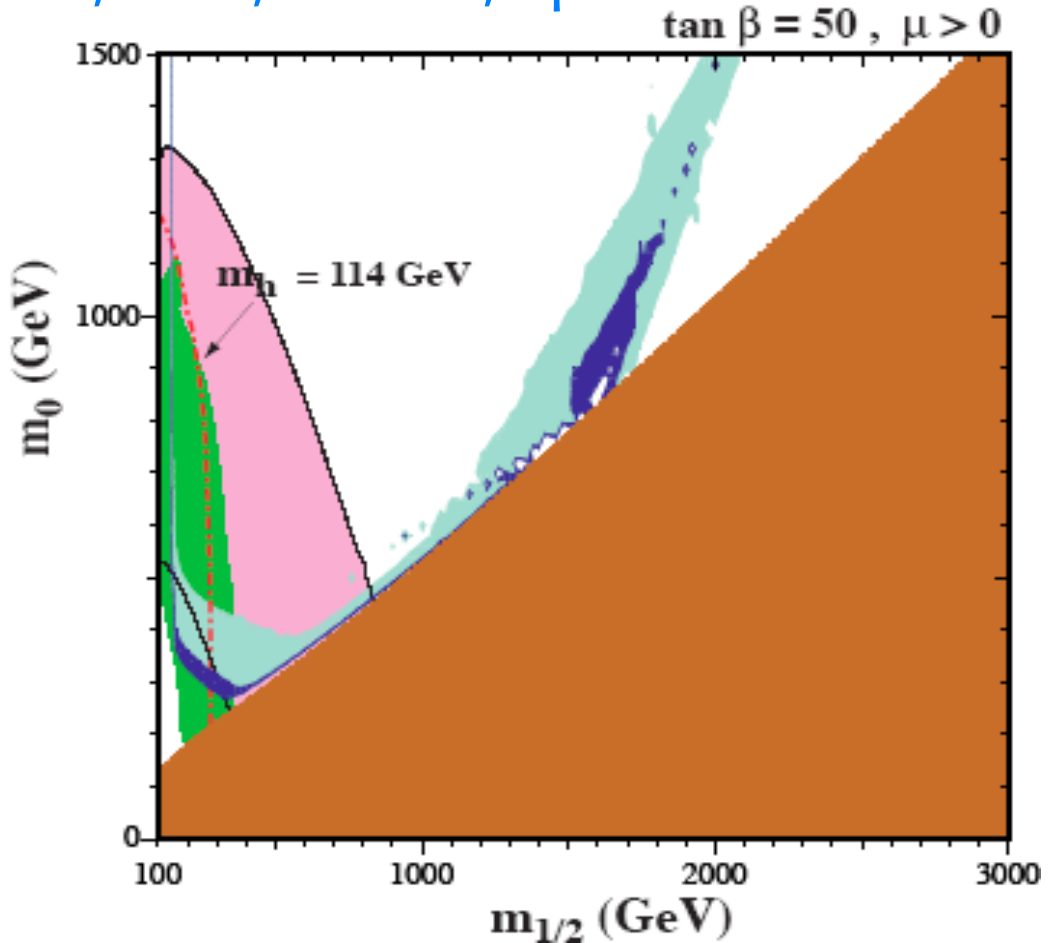
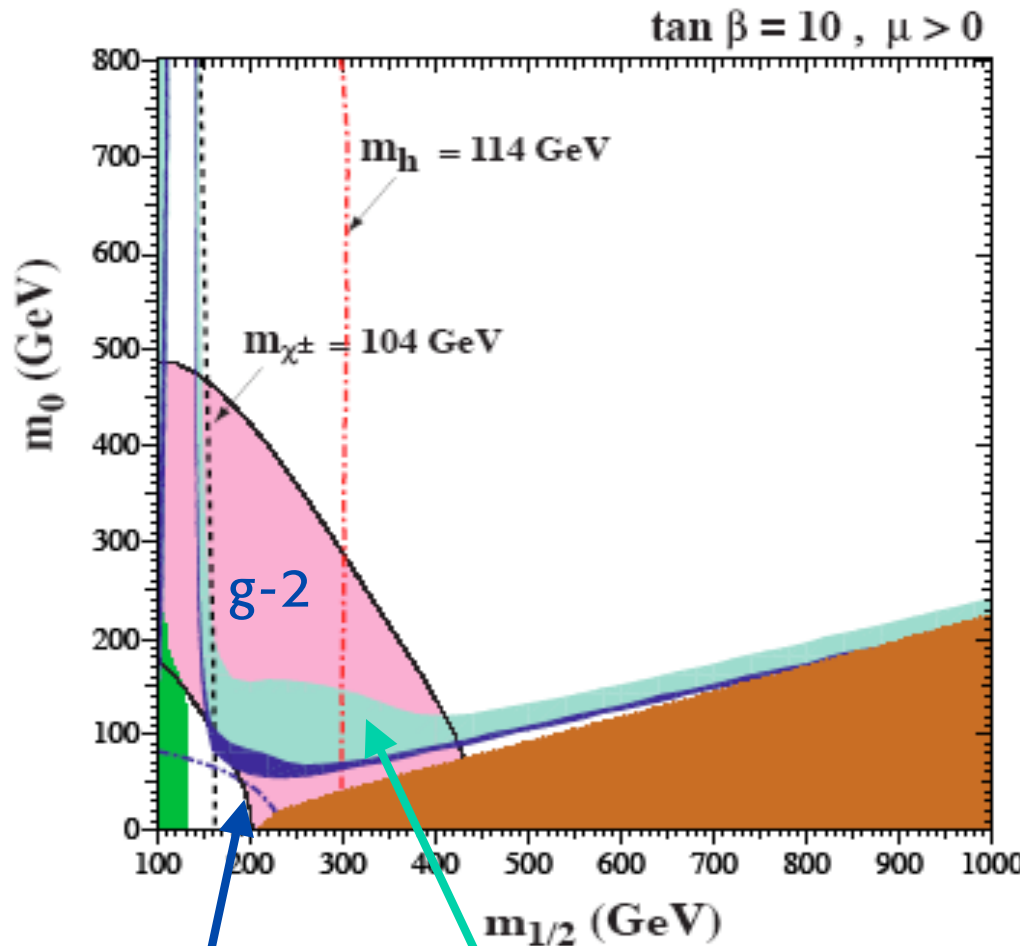
This “coincidence” is a good indication in favour of a WIMP explanation of Dark Matter

LHC will tell yes or no to WIMPS



SUSY Dark Matter: best candidate the neutralino
[in SUSY the gravitino is a non-WIMP alternative]

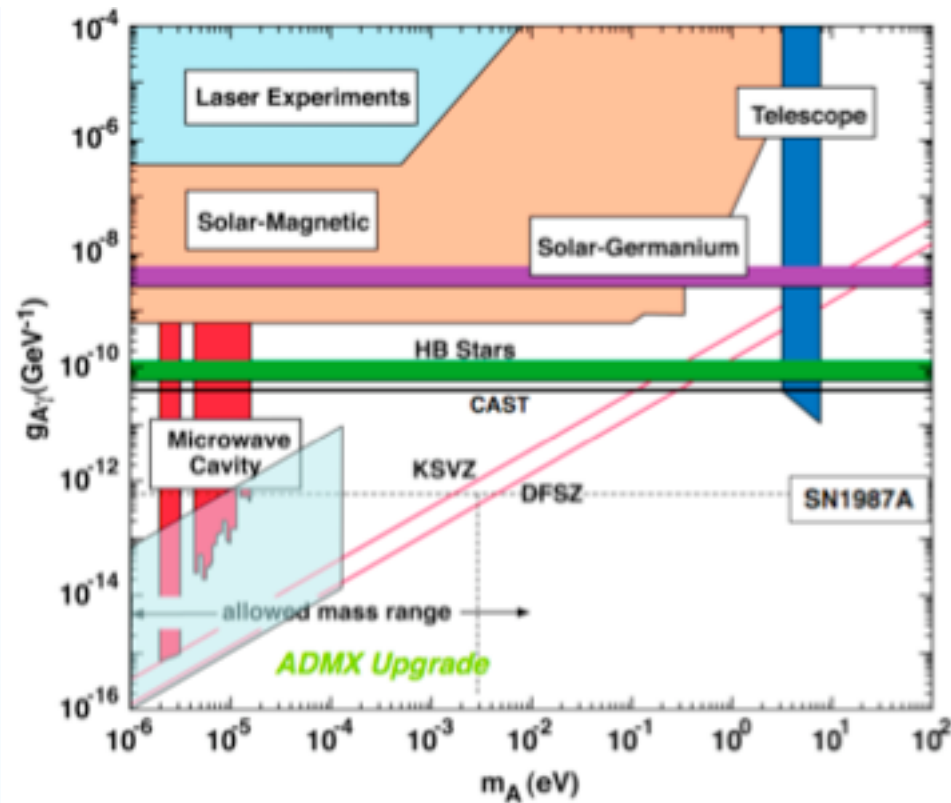
Ellis, Olive, Santoso, Spanos



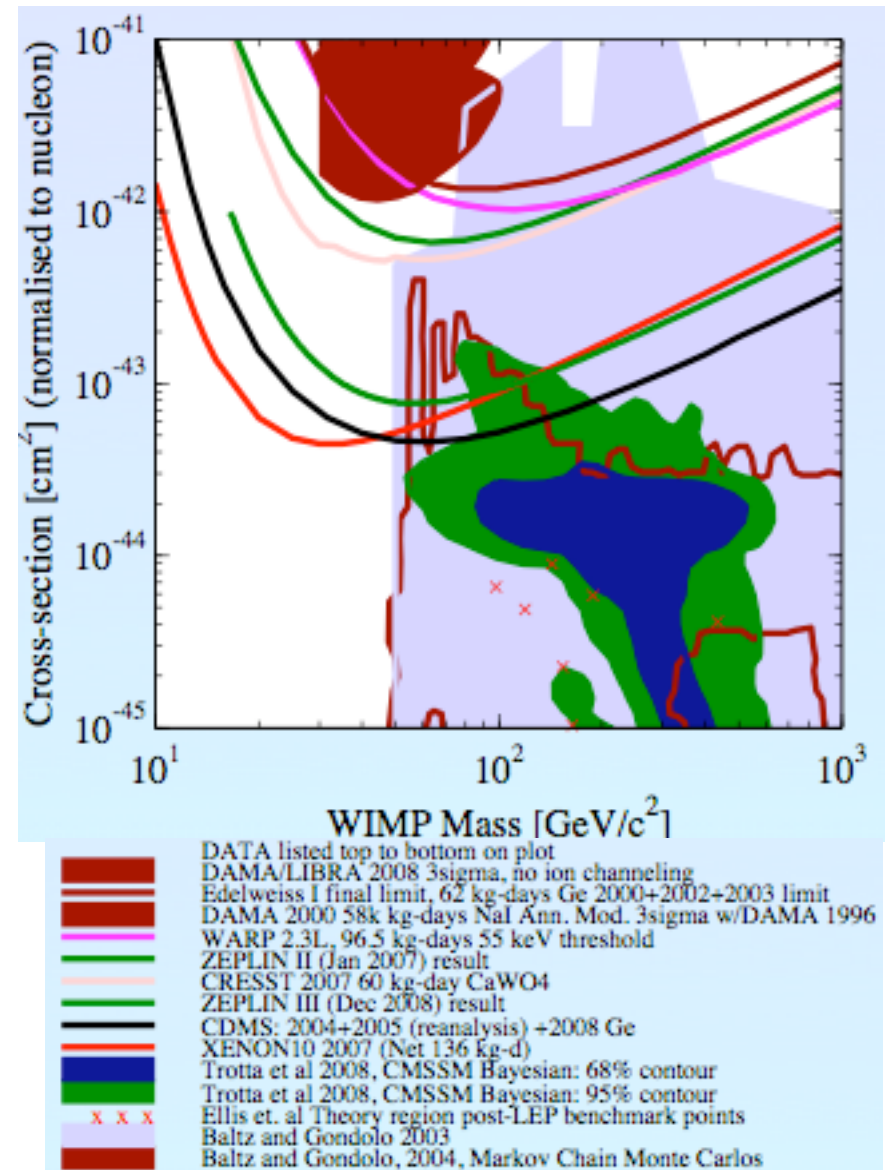
This is for the CMSSM
With less constraints, more space



It is not easy to reach the sensitivity for Axions as DM



Direct WIMP search



Experimental hints for dark matter?

Annual modulations (DAMA/LIBRA)

e^+ excess in cosmic rays detectors (PAMELA)

ATIC bump **now disfavoured** (FERMI)

γ excess (EGRET) **now disfavoured** (FERMI)

.....

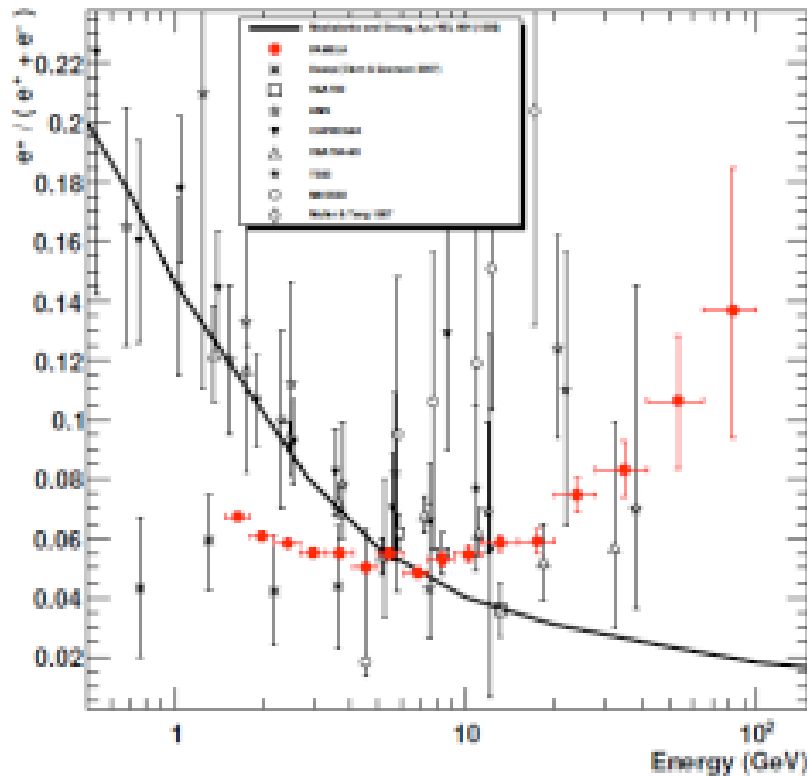
If really those effects are signals of DM, they point to more exotic forms of DM

Arkani-Hamed et al, '08

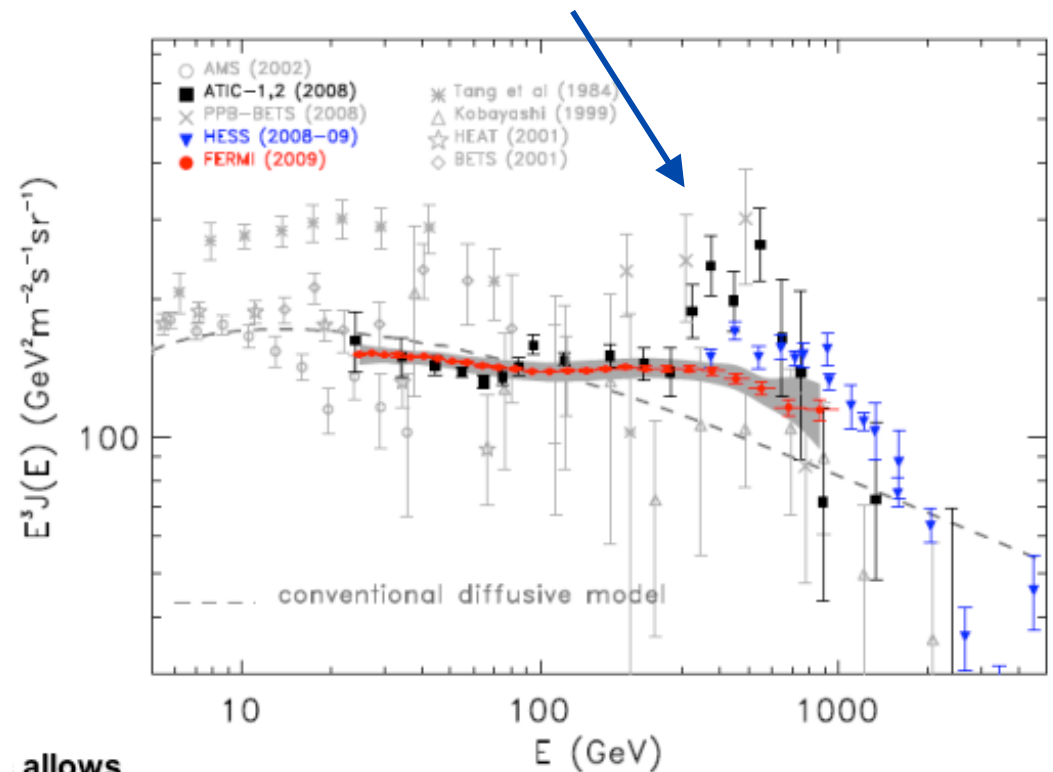
Cirelli et al, '08



The PAMELA e^+ excess



The ATIC bump in e spectrum not confirmed by FERMI



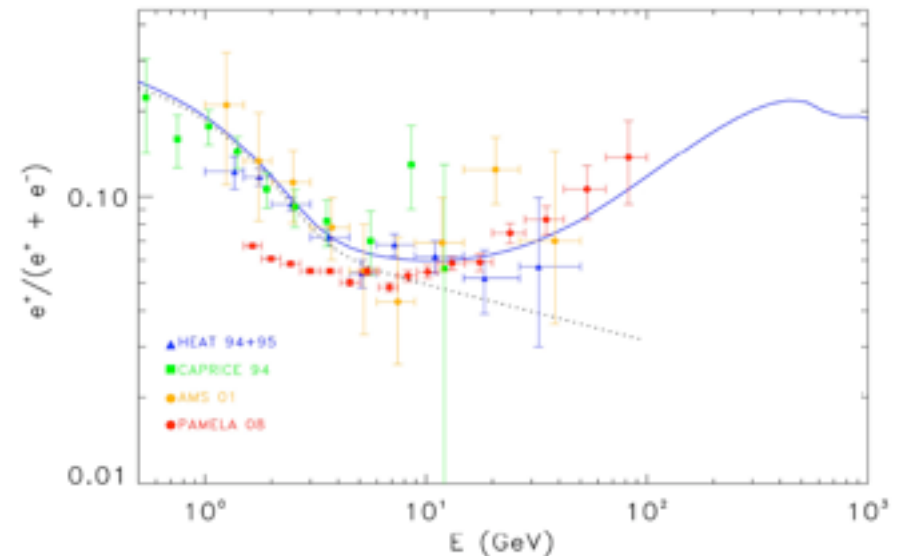
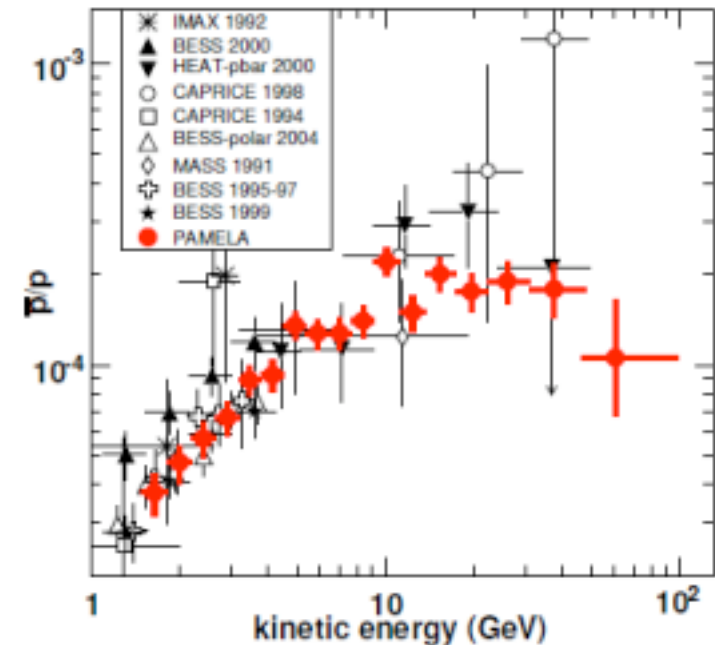
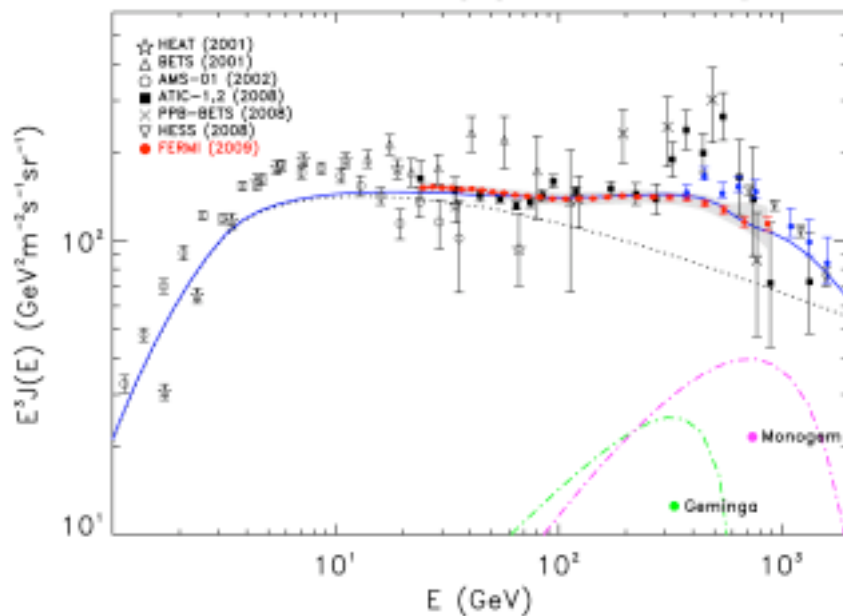
allows

> 200 papers

If DM would need large masses and
enhanced rates

An astrophysical interpretation appears possible

nothing in antiprotons (PAMELA)

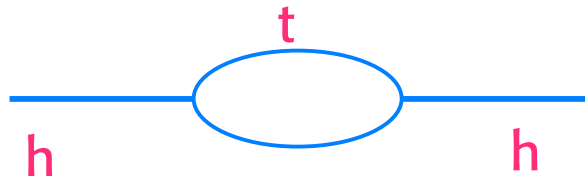


the blu curves:
pulsars within 1Kpc
with some parameter fitting



For the low energy theory: the “little hierarchy” problem:

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



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

$$m_h^2 = m_{bare}^2 + \delta m_h^2$$

This hierarchy problem demands new physics near the weak scale

Λ : scale of new physics beyond the SM

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

Barbieri, Strumia

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

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

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

A crucial question for the LHC

What damps the top loop Λ^2 dependence?

- the s-top
- some new fermion

t'

KK recurrences of the top

.....



Precision Flavour Physics

Another area where the SM is good, too good.....

With new physics at $\sim \text{TeV}$ one would expect the SM suppression of FCNC and the CKM mechanism for CP violation to be sizably modified.

But this is not the case

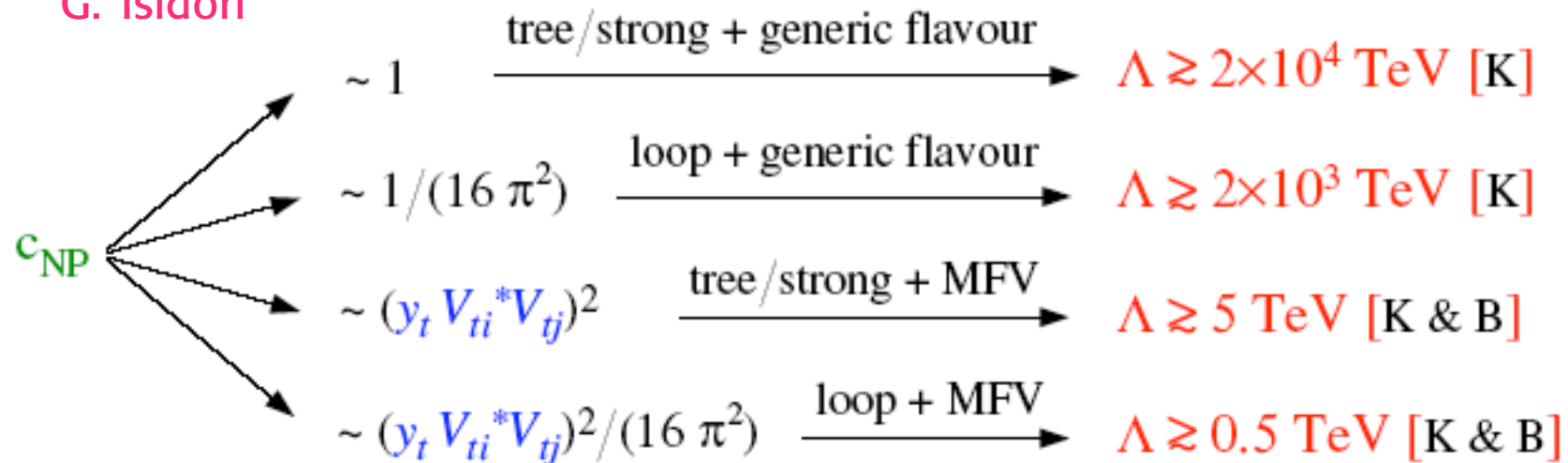
an intriguing mystery and a major challenge for models of new physics



Adding effective operators to SM generally leads to very large Λ

$$M(B_d - \bar{B}_d) \sim \frac{(y_t V_{tb}^* V_{td})^2}{16 \pi^2 M_W^2} + \left(c_{NP} \frac{1}{\Lambda^2} \right)$$

G. Isidori



But the hierarchy problem demands Λ in the few TeV range
 only assuming $c_{NP} \sim (y_t V_{tb}^* V_{td})^2$ (or anyway small)
 we get a bound on Λ in the TeV range

eg in Minimal Flavour Violation (MFV) models
 D'Ambrosio, Giudice, Isidori, Strumia'02



Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.
exact (**unrealistic**): cancellation of Λ^2 in δm_h^2
approximate (**possible**): $\Lambda \sim m_{\text{SUSY}} - m_{\text{ord}}$ \longrightarrow top loop
 $\Lambda \sim m_{\text{stop}}$
The most widely accepted

- The Higgs is a $\bar{\psi}\psi$ condensate. No fund. scalars. But needs new very strong binding force: $\Lambda_{\text{new}} \sim 10^3 \Lambda_{\text{QCD}}$ (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 $o(1\text{TeV})$

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.

$$\Omega_\Lambda \sim 0.75 \quad \longrightarrow \quad \rho_\Lambda \sim (2 \cdot 10^{-3} \text{ eV})^4 \sim (0.1 \text{ mm})^{-4}$$

In Quantum Field Theory: $\rho_\Lambda \sim (\Lambda_{\text{cutoff}})^4$ Similar to m_ν !?

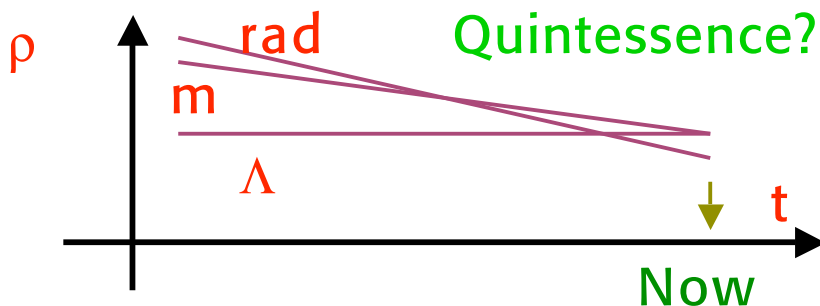
If $\Lambda_{\text{cutoff}} \sim M_{\text{Pl}}$ \longrightarrow $\rho_\Lambda \sim 10^{123} \rho_{\text{obs}}$

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

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

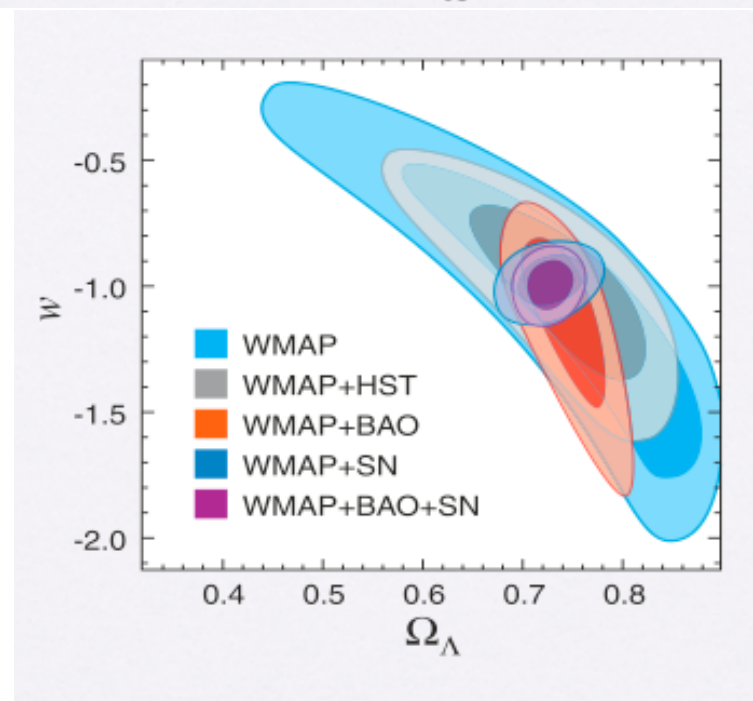
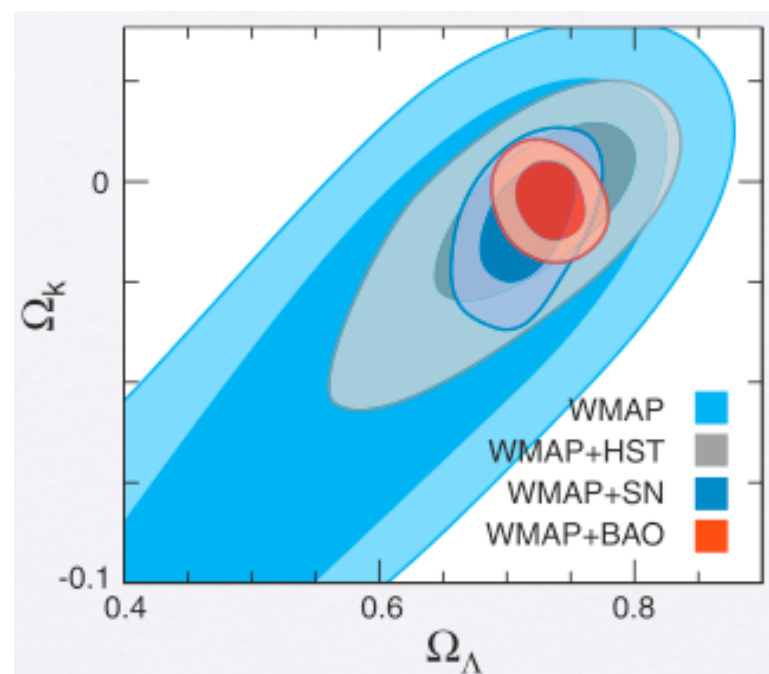
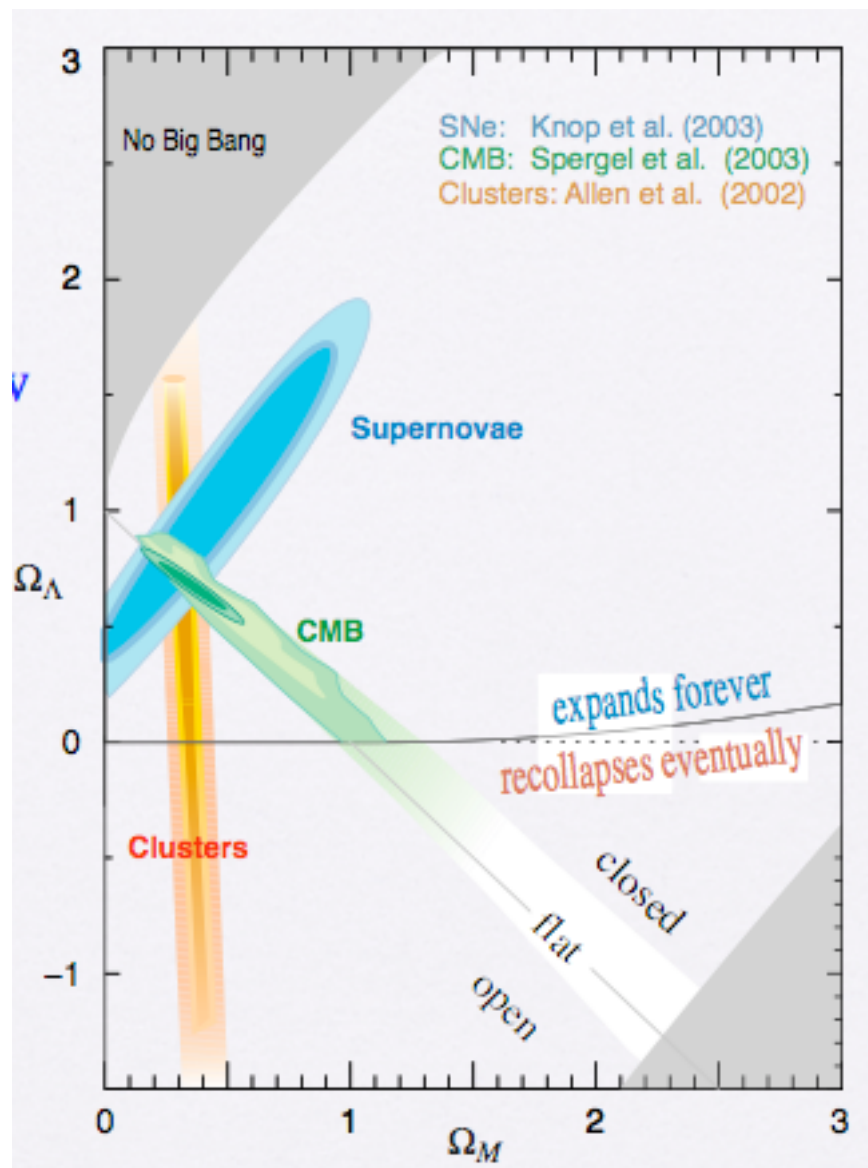
It is interesting that the correct order is $(\rho_\Lambda)^{1/4} \sim (\Lambda_{\text{EW}})^2 / M_{\text{Pl}}$

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

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).

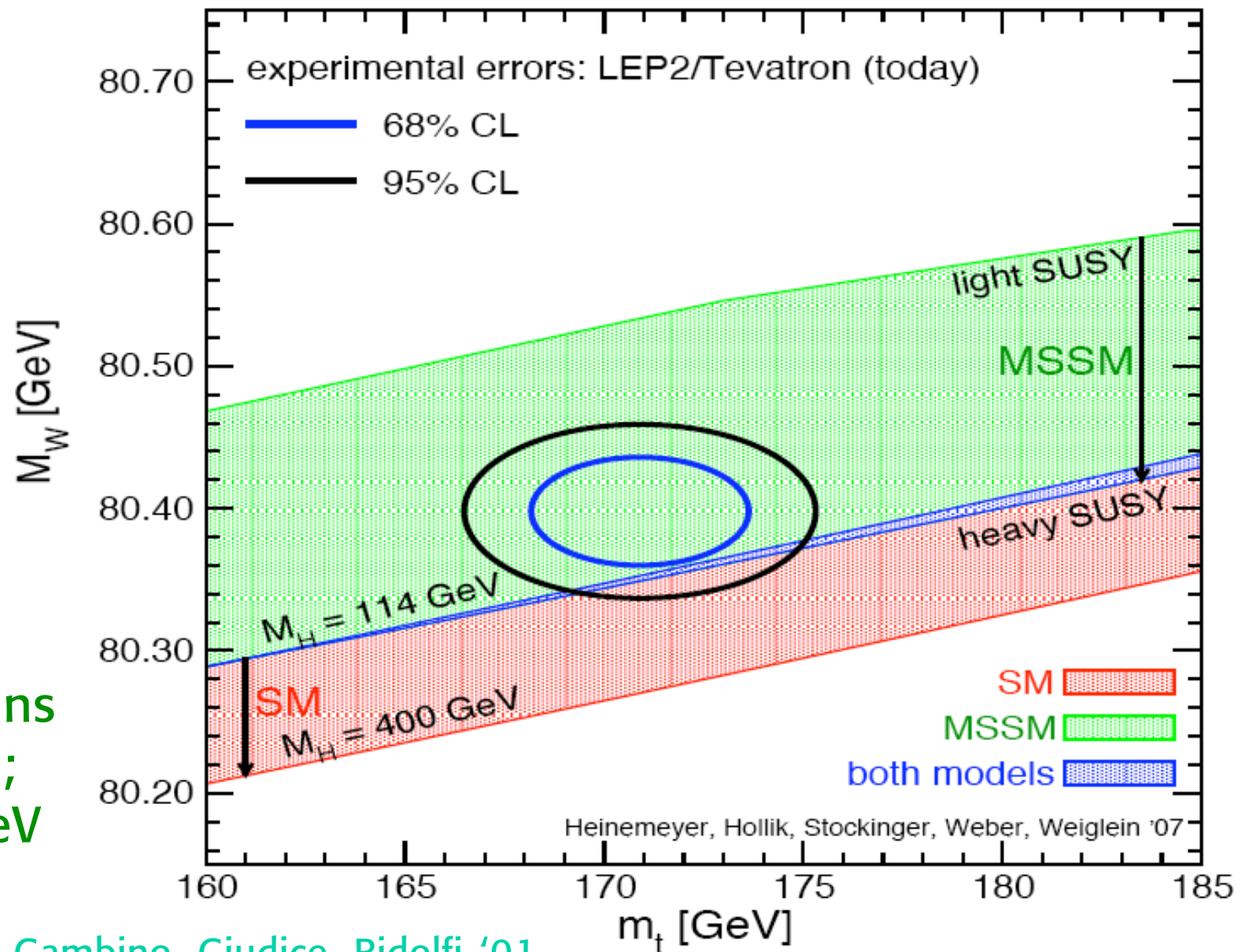


Remains the reference model for NP

SUSY effects could modify the SM fit

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

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

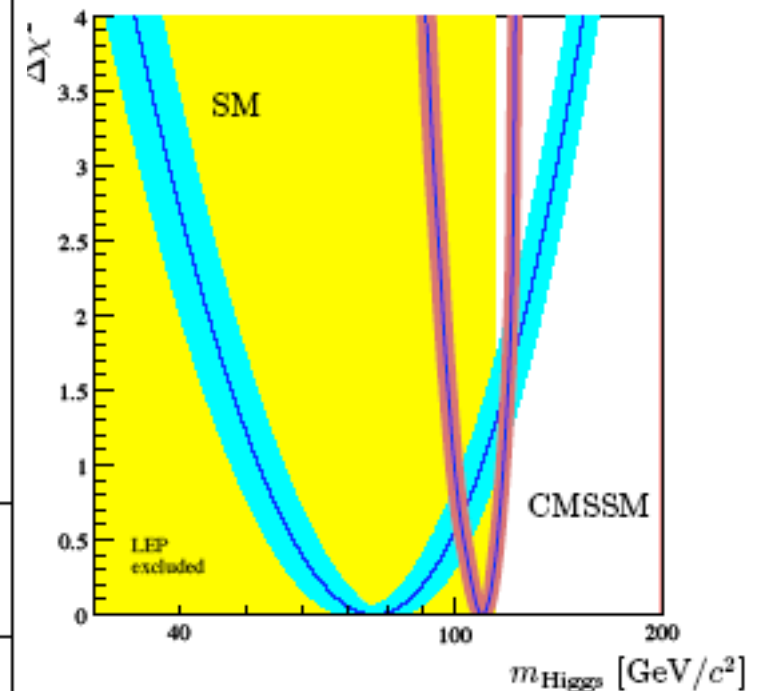
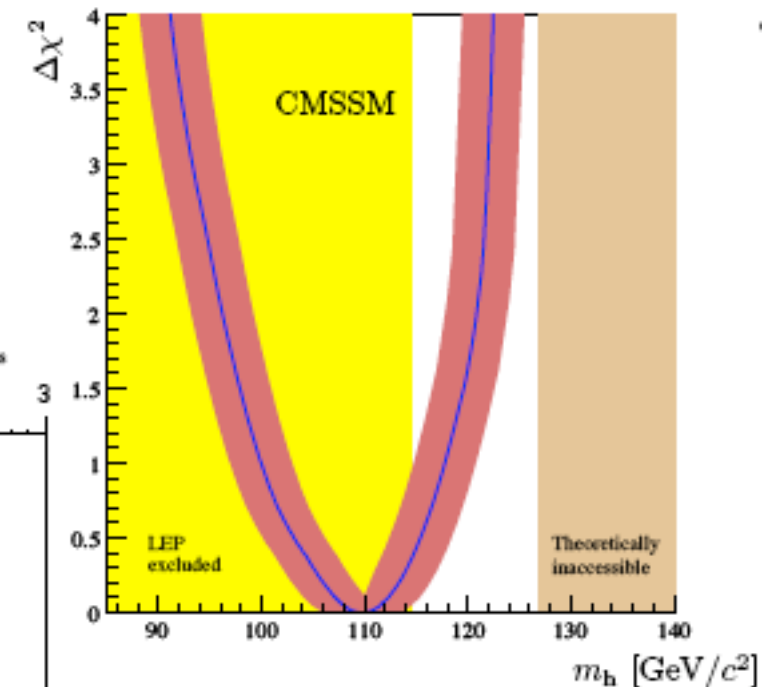


A recent study indicates that m_h goes up in CMSSM when $b \rightarrow s\gamma$, a_μ , Ω_{DM} are added

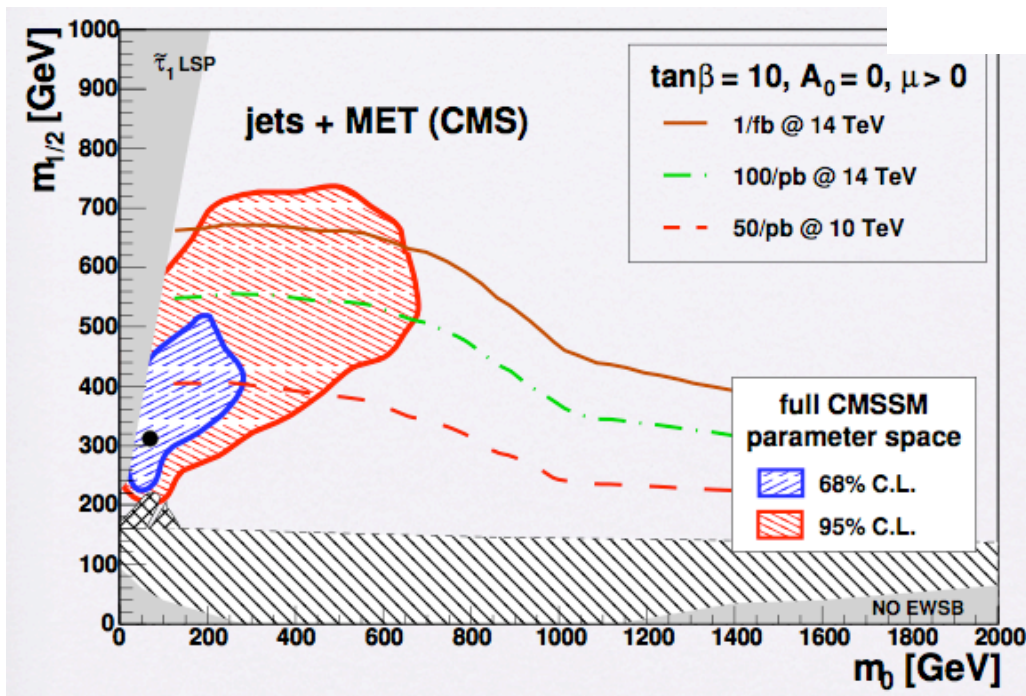
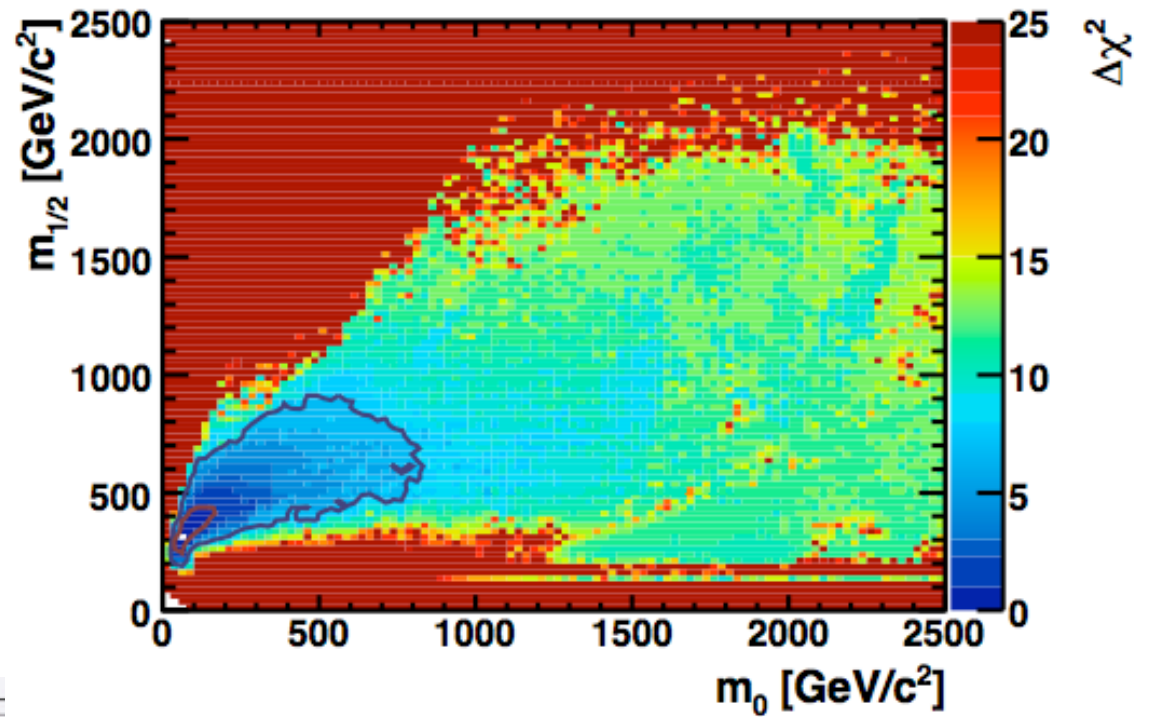
O. Buchmuller
et al '07, '08
[0808.4128]

also:
J. Ellis et al '07

CMSSM			$10^{10} \text{meas} - O_{\text{fit}} / \sigma_{\text{meas}}$			
Variable	Measurement	Fit	0	1	2	3
$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	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_{had}^0 [nb]	41.540 ± 0.037	41.486				
R_1	20.767 ± 0.025	20.744				
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01641				
$A_1(P_\tau)$	0.1465 ± 0.0032	0.1479				
R_b	0.21629 ± 0.00066	0.21613				
R_c	0.1721 ± 0.0030	0.1722				
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037				
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741				
A_b	0.923 ± 0.020	0.935				
A_c	0.670 ± 0.027	0.668				
$A_1(\text{SLD})$	0.1513 ± 0.0021	0.1479				
$\sin^2\theta_{\text{eff}}^{\text{lep}}(Q_b)$	0.2324 ± 0.0012	0.2314				
m_W [GeV]	80.398 ± 0.025	80.382				
m_t [GeV]	170.9 ± 1.8	170.8				
$R(b \rightarrow s\gamma)$	1.13 ± 0.12	1.12				
$B_s \rightarrow \mu\mu$ [$\times 10^{-8}$]	< 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				



relatively light SUSY
is indicated



accessible at the LHC

Status of MEG $\mu^+ \rightarrow e^+ \gamma$

Large neutrino mixing angles + SUSY GUT's make a signal near the present limit plausible

Present limit on Br $1.1 \cdot 10^{-11}$

MEG 2008 $3 \cdot 10^{-11}$

Present MEG sensitivity $1-2 \cdot 10^{-11}$

Data taking resumes in September

Ultimate sensitivity $10^{-12} - 10^{-13}$



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 ↑ gauged ↑ SM

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

$$\text{recall: } \delta m_{h|top}^2 = -\frac{3G_F}{2\sqrt{2}\pi} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

cutoff Λ

$$G_F \sim g^2 \rightarrow g^4$$

$\sim 10 \text{ TeV}$

Λ^2 divergences canceled by:

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

$\delta m_{H|gauge}^2$ W', Z', γ'

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

} $\sim 1 \text{ TeV}$



2 Higgs doublets

$\sim 0.2 \text{ TeV}$

With some tension Little Higgs models can work.

T parity interchanges the two $SU(2) \times U(1)$ groups Cheng, Low

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

Lightest T-odd particle stable \rightarrow 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}

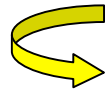
Exciting possibilities (a large domain of contemporary BSM)

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



Generic feature of extra dim. models:

compact dim. \longrightarrow Kaluza-Klein (KK) modes



$$p=n/R$$

$$m^2=n^2/R^2$$

(quantization in a box)

Many possibilities:

emerges as the most promising



- SM fields on a brane or in bulk

cfr: • Gravity always on bulk

- Factorized metric:

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

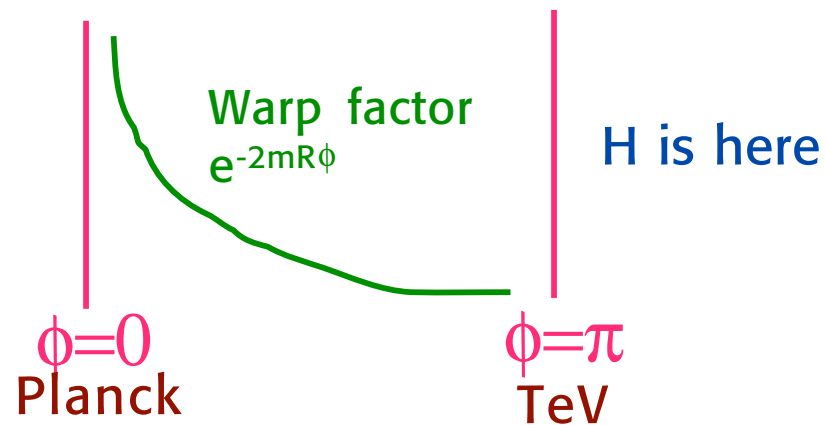
- Warped metric: Randall-Sundrum (R-S)

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



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

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



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"

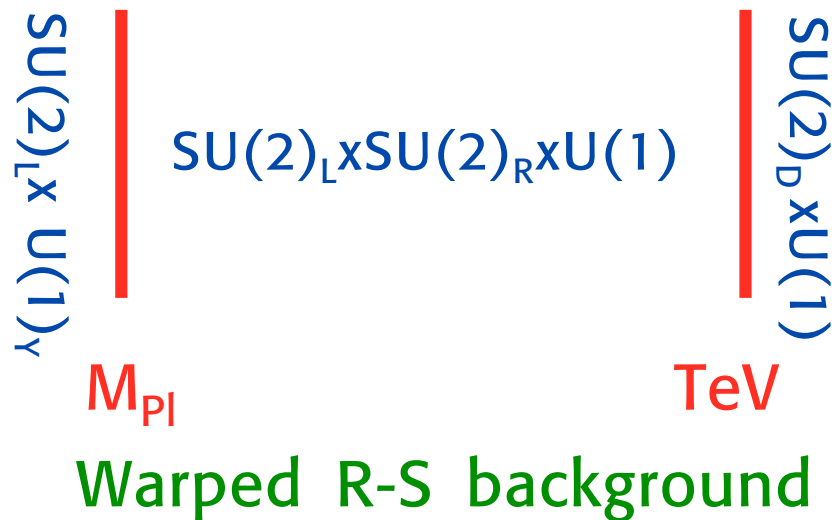
Goldberger, Wise

Applications

- Gauge Symmetry Breaking (Higgsless theories)

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

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



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 \oplus chirality has a zero mode on the brane

With no Higgs unitarity violations, eg:

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

At $E \sim 1.2$ TeV unitarity is violated

In Higgsless models unitarity is restored by exchange of infinite KK recurrences, or the breaking is delayed by a finite number

Cancellation guaranteed
by sum rules implied
by 5-dim symmetry

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

$Z_k = k_{\text{th}}$ KK



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 $Z \rightarrow b\bar{b}$

m_W fixes the KK gap and it is not sufficiently large

Substantial fine tuning required

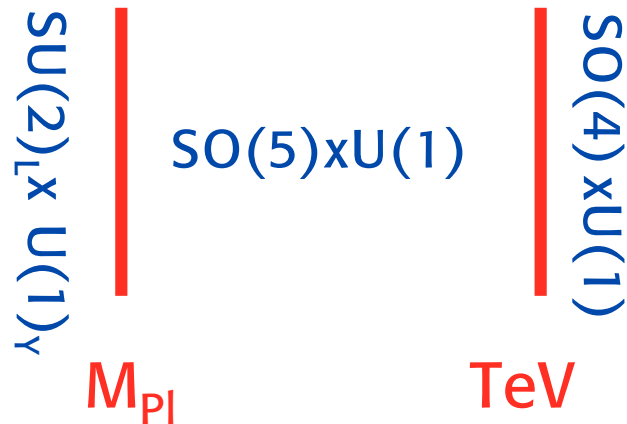
Best try: Cacciapaglia et al '06

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



- Composite Higgs in a 5-dim holographic theory

Agashe, Contino, Pomarol.....



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).

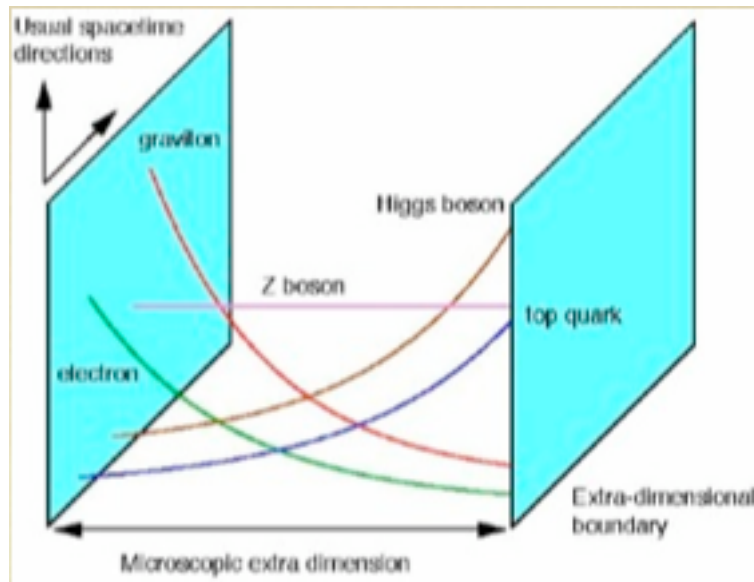
The 5-dim theory is weakly coupled so that the Higgs potential and EW observables can be computed

The Higgs is rather light: $m_H < 185 \text{ GeV}$



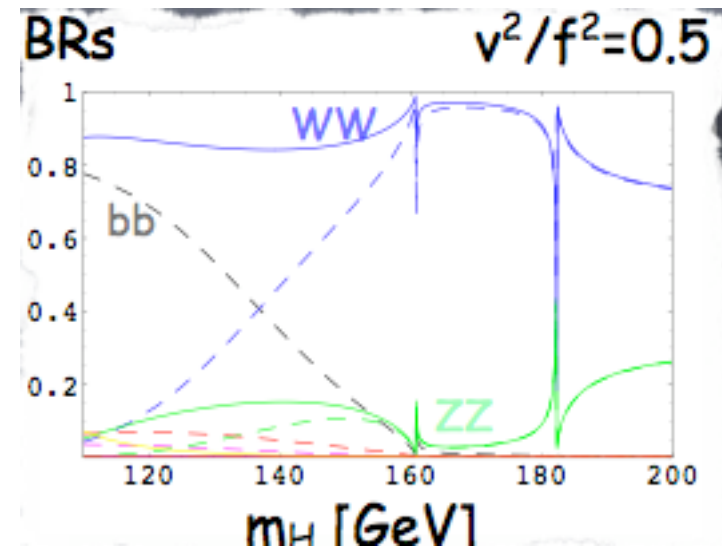
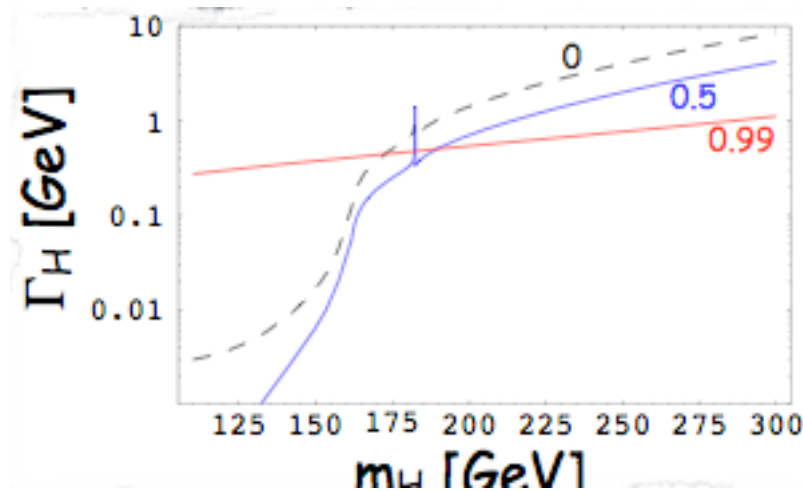
Also in these models a sizable fine-tuning is required

S. Kachru



A qualitative description of flavour

Higgs couplings modified



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 must find something else

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”