Roma “La Sapienza”, 24 October ’08

Particle Physics at the LHC start

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In honour of Edoardo Amaldi

The LHC physics run will soon start,... hopefully.

After the incident on Sept. 19 we must wait till spring 2009

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 Higgs problem is central in particle physics today

The main problems for 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
$V_{0exp} \sim (2.10^{-3}\ \mathrm{eV})^4$

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: $\mathcal{L} = \mathcal{L}_{\text{symm}} + \mathcal{L}_{\text{Higgs}}$

$$\begin{aligned}
\mathcal{L}_{symm} &= -\frac{1}{4}[\partial_\mu W^A_\nu - \partial_\nu W^A_\mu - i g \varepsilon_{ABC} W^A_\mu W^B_\nu]^2 + \\
&\quad -\frac{1}{4}[\partial_\mu B_\nu - \partial_\nu B_\mu]^2 + \\
&\quad + \bar{\psi}\gamma^\mu [i\partial_\mu + g W^A_\mu t^A + g' B_\mu \frac{Y}{2}]\psi \\
\mathcal{L}_{Higgs} &= |[\partial_\mu - i g W^A_\mu t^A - i g' B_\mu \frac{Y}{2}]\phi|^2 + \\
&\quad + V[\phi^\dagger \phi] + \bar{\psi}\Gamma\psi\phi + \mathrm{h.c}
\end{aligned}$$

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:

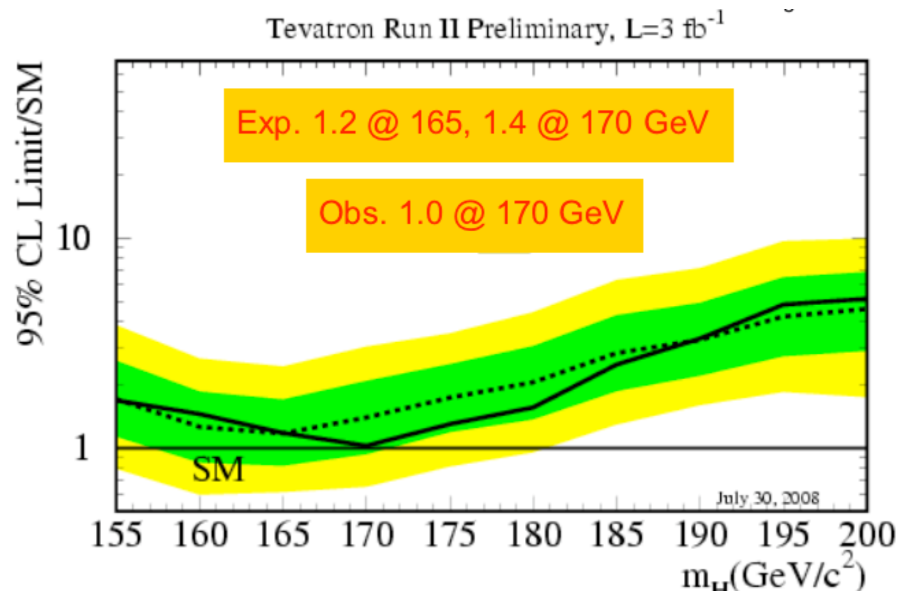
No Higgs seen at LEP2 -> $m_H > 114.4$ GeV (95%cl)

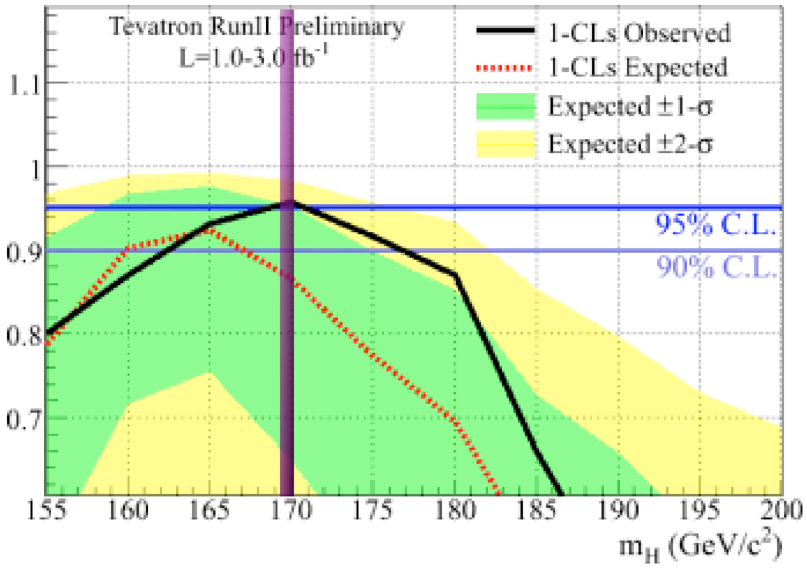
Rad. corr's -> $m_H < 190$ GeV (95%cl, incl. direct search bound)

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

The Tevatron is now reaching the SM sensitivity

Herndon, ICHEP '08





95%CL Limits/SM

M Higgs(GeV)	160	165	170	175
Method 1: Exp	1.3	1.2	1.4	1.7
Method 1: Obs	1.4	1.2	1.0	1.3
Method 2: Exp	1.2	1.1	1.3	1.7
Method 2: Obs	1.3	1.1	0.95	1.2

I quote:

"CDF/D0 exclude at 95% C.L. the production of a SM Higgs boson of 170 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 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!!

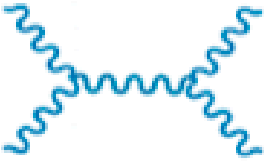
With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

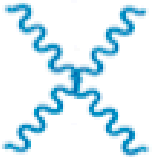
Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

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; …]

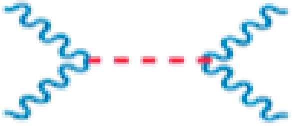
Zwirner

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





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



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

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

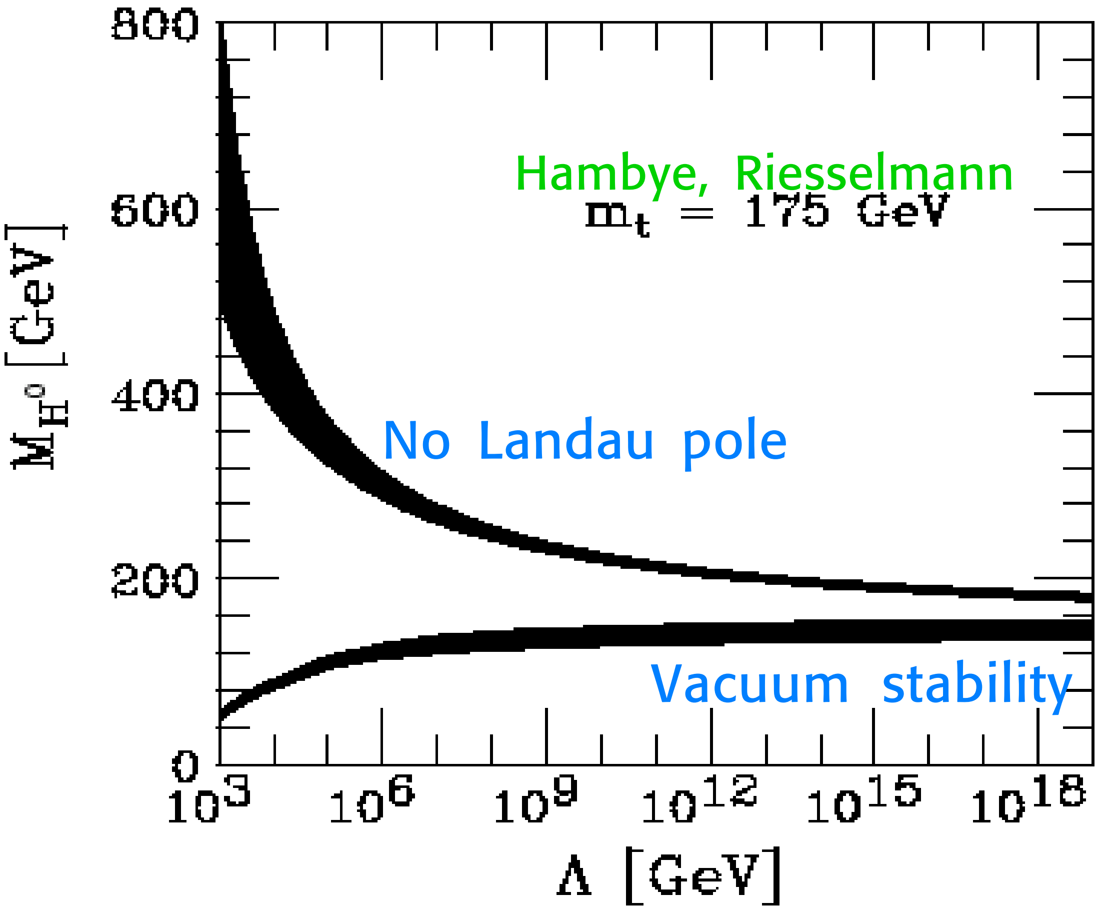
If no Higgs then something must happen!

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

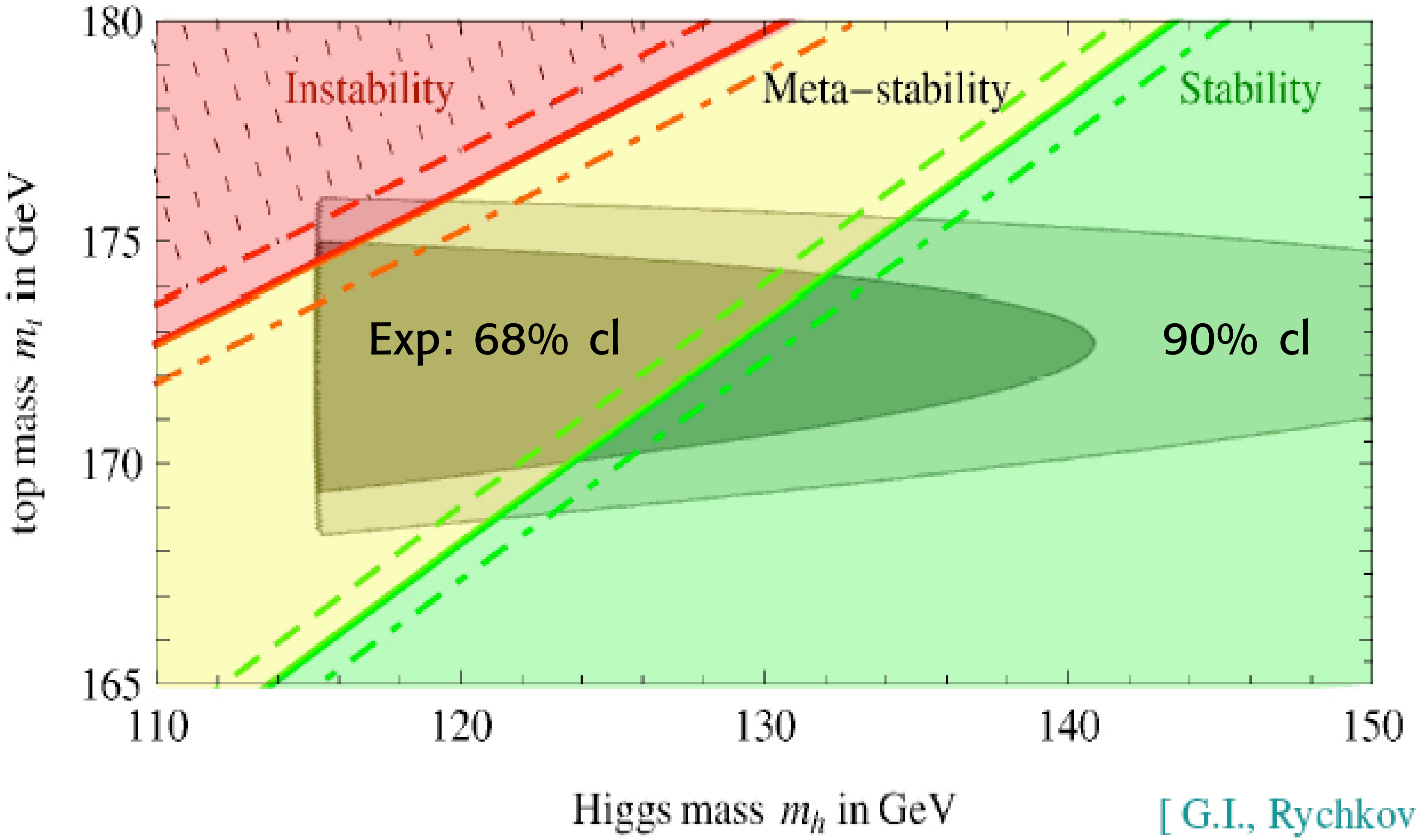


If the SM would be valid up to M_{GUT}, M_{Pl} then m_H would be limited in a small range

Lower now because of m_t → $128 \text{ GeV} < m_H < 180 \text{ GeV}$

Adding the metastable possibility:

Isidori, Ridolfi, Strumia '01



[G.I., Rychkov, Strumia, Tetradis '08]

- The unstable region is almost ruled out

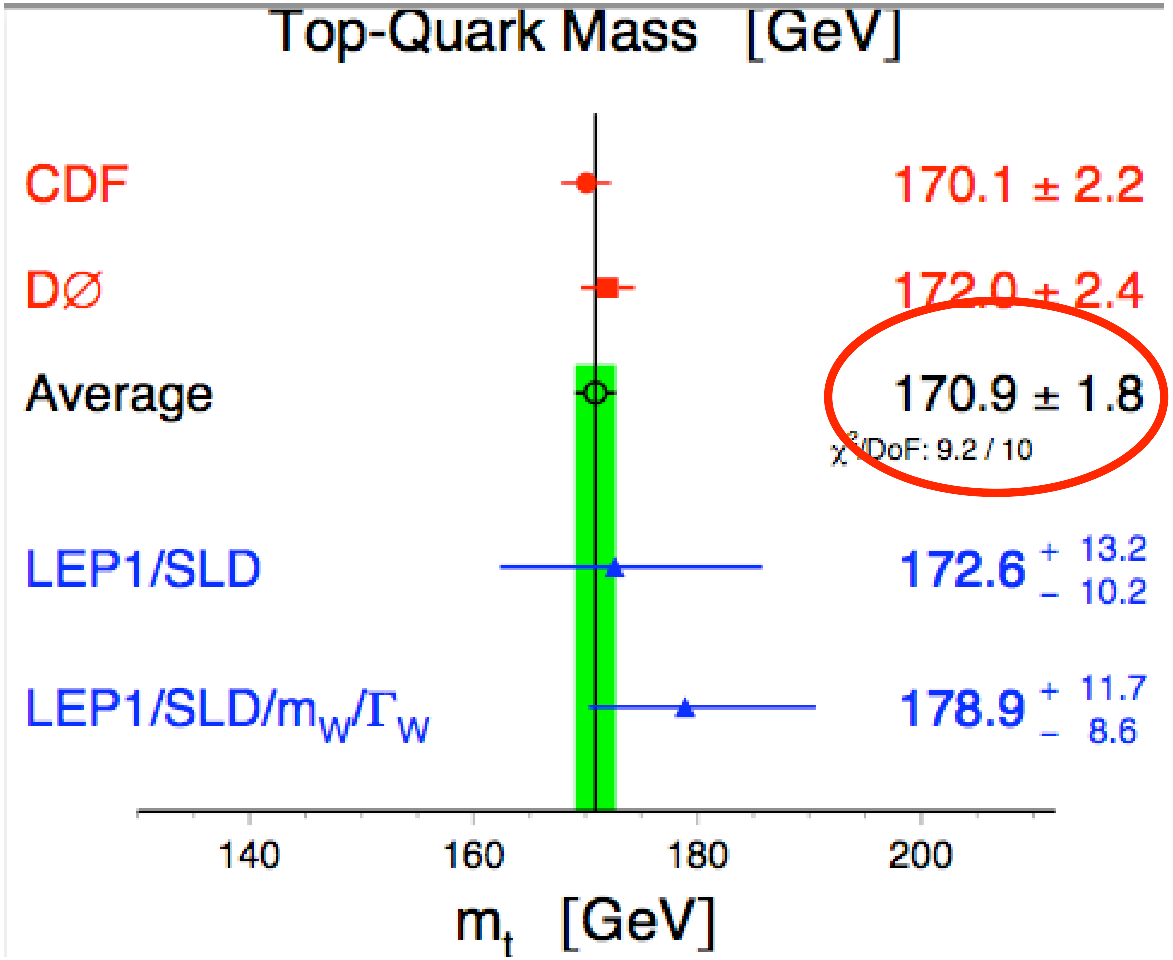
Precision Tests of SM

The only recent development in this domain is the decrease of the experimental value of m_t from CDF& D0 Run II

The error went also much down!

(Run I value: 178.0±4.3 GeV)

Winter'07



This has a small effect on the quality of the SM fit and on the m_H bounds

m_t ↓ : m_H ↓

quality ↓

Overall the EW precision tests support the SM and a light Higgs.

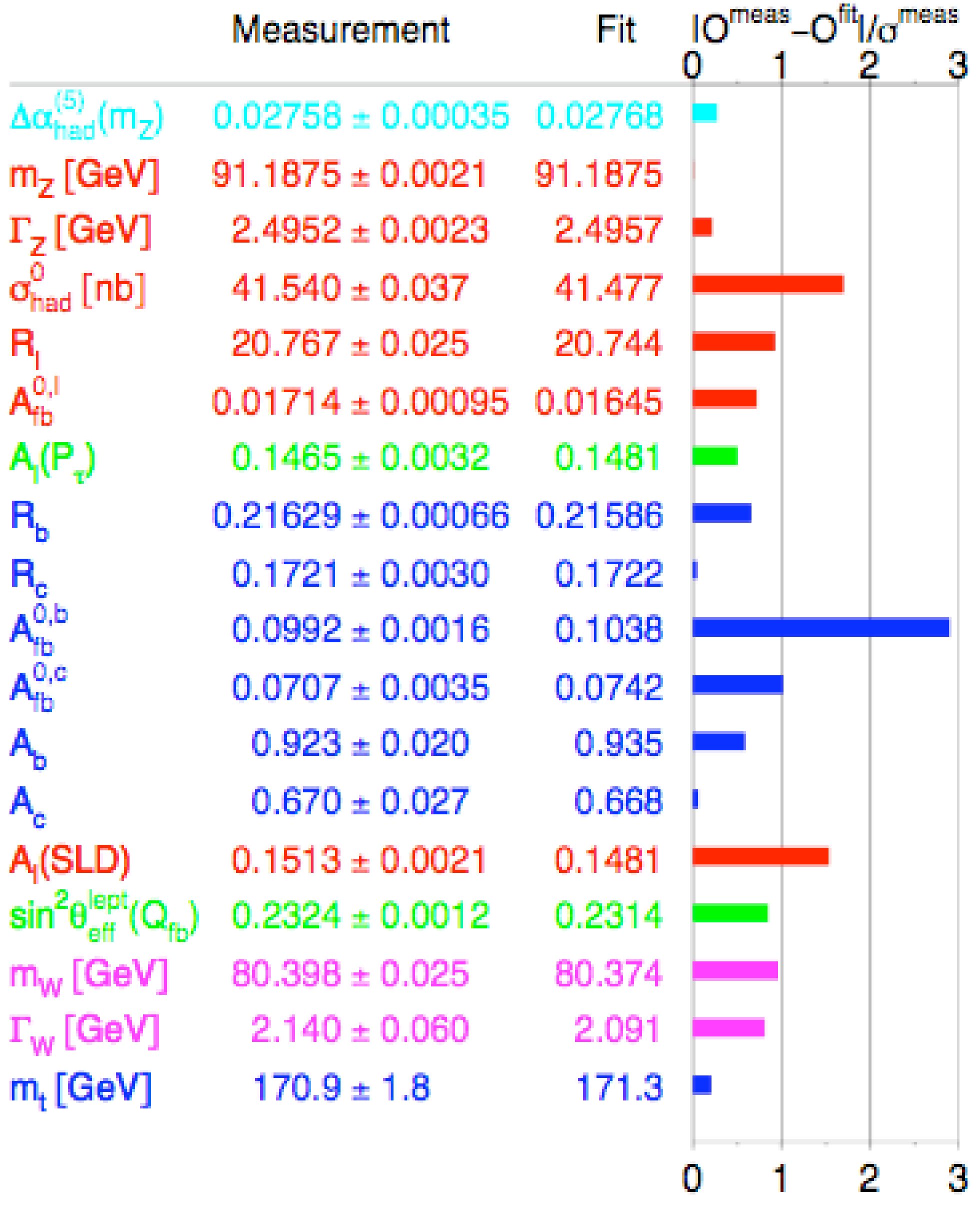
The χ^2 is reasonable:

χ^2/ndof~18.2/13 (~15.1%)

Note: does not include NuTeV, APV, Moeller and $(g\text{-}2)_\mu$

a_μ ~3σ deviation?

Winter '07



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

Electron g-2: A recent measurement

Odom, Hanneke,
D'Urso, Gabrielse '06

$a_e = (g-2)/2 = 11596521808.5(7.6)\ 10^{-13}$

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots$$

$$+\, a_{\mu\tau} + a_{\text{hadronic}} + \cancel{a_{\text{weak}}},$$

δa_h small

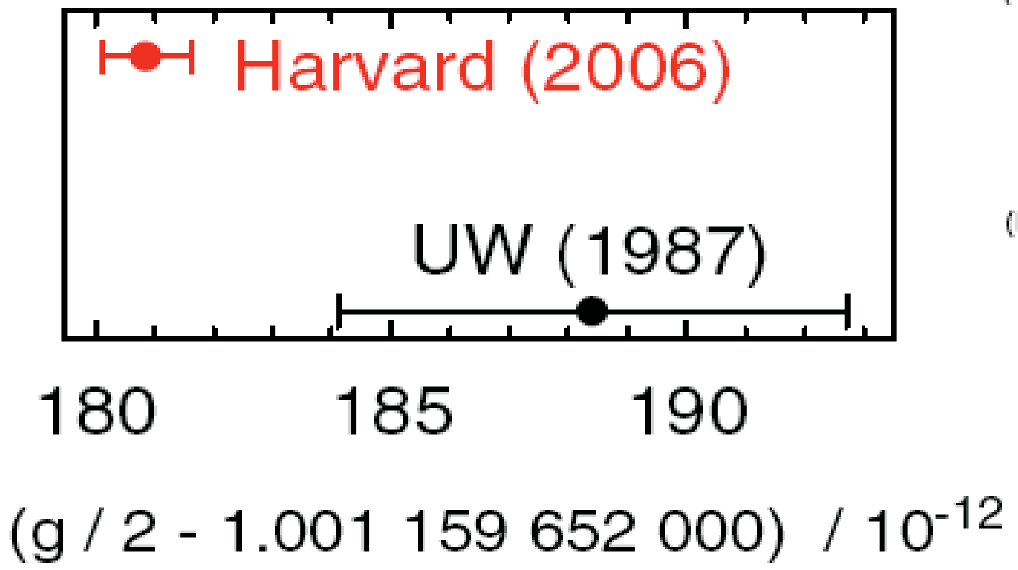
$$a(\text{hadron}) = 1.671\,(19) \times 10^{-12}$$

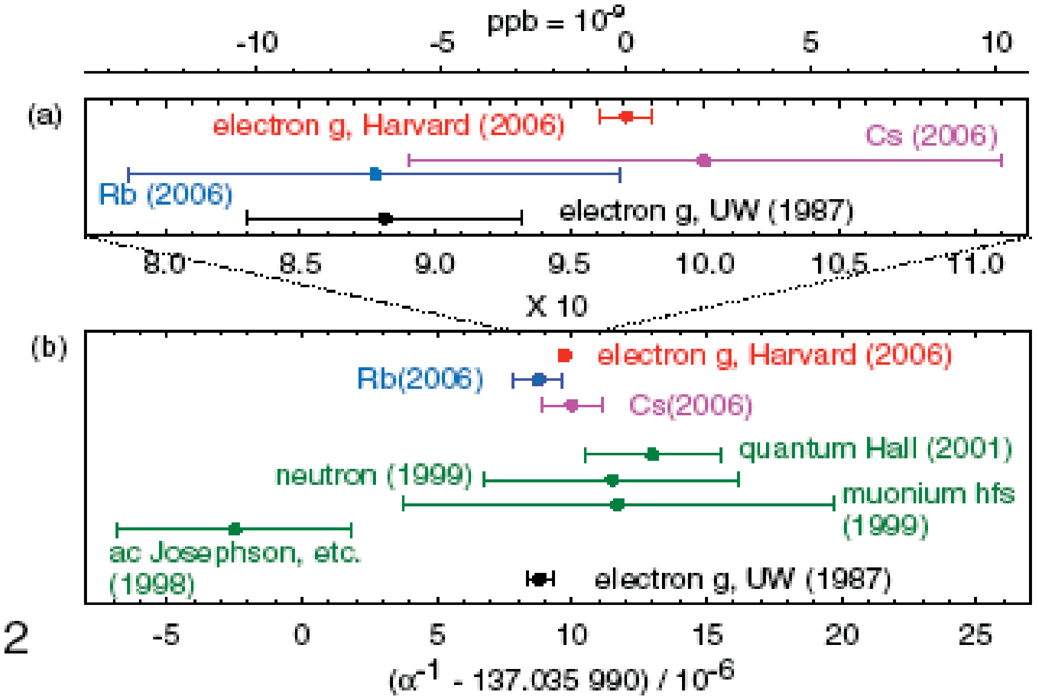
$$a(\text{weak}) = 0.030\,(01) \times 10^{-12}$$

Best determination of α_{QED}

$\alpha^{-1} = 137.035999070(98)$

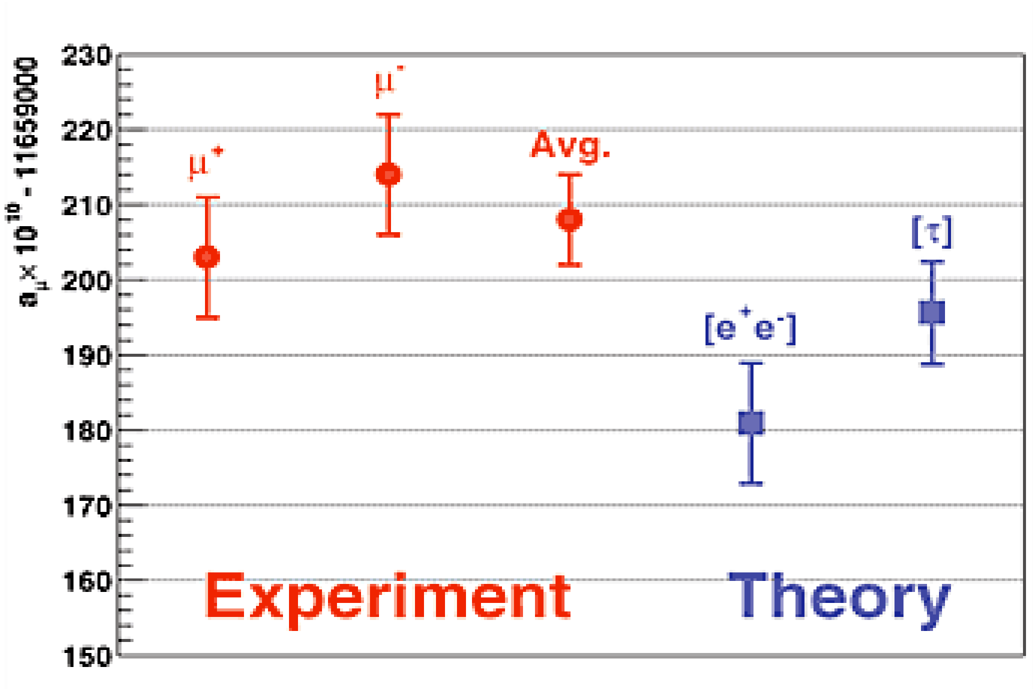
Value given in Aoyama et al '07, after a theory error was corrected



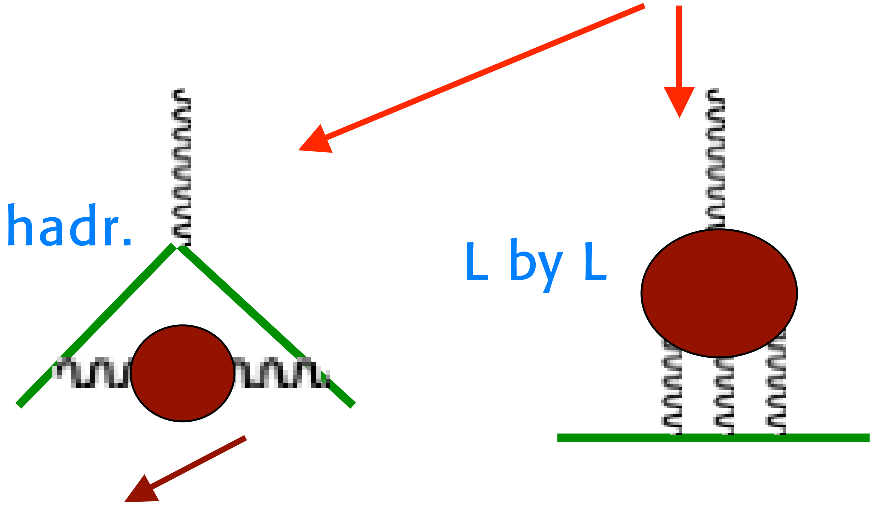


Muon g-2: more sensitive to new physics by $(m_\mu/m_e)^2 \sim 2\ 10^4$

BNL '04-'06: $a_\mu = (11659208.0 \pm 6.3)\ 10^{-10}$



$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had}$$



$$a_\mu^{\rm had,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds\, \frac{R(s)\,K(s)}{s^2},$$

$$R(s) = \frac{\sigma(e^+e^- \to {\rm hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)},$$

From the latest value of a_e (G. Gabrielse et al., 2006):

$$\alpha^{-1} = 137.035999710(96),$$

$$a_\mu^{\text{QED}} = (116584718.09 \pm 0.14 \pm 0.08) \cdot 10^{-11}.$$

Eidelmann, ICHEP'06

Contribution	$a_\mu, 10^{-10}$
Experiment	11659208.0 ± 6.3
QED	11658471.94 ± 0.14
Electroweak	$15.4 \pm 0.1 \pm 0.2$
Hadronic	693.1 ± 5.6
Theory	11659180.5 ± 5.6
Exp.–Theory	$27.5 \pm 8.4\ (3.3\sigma)$

Mostly VP-LO
VP-NLO = -9.8±0.1
LbyL = 12.0±3.5

Knecht, Nyffeler'02
Melnikov, Veinshtein'04
Davier, Marciano '04

'07: 29.5±8.8 (3.4σ) Hertzog et al '07

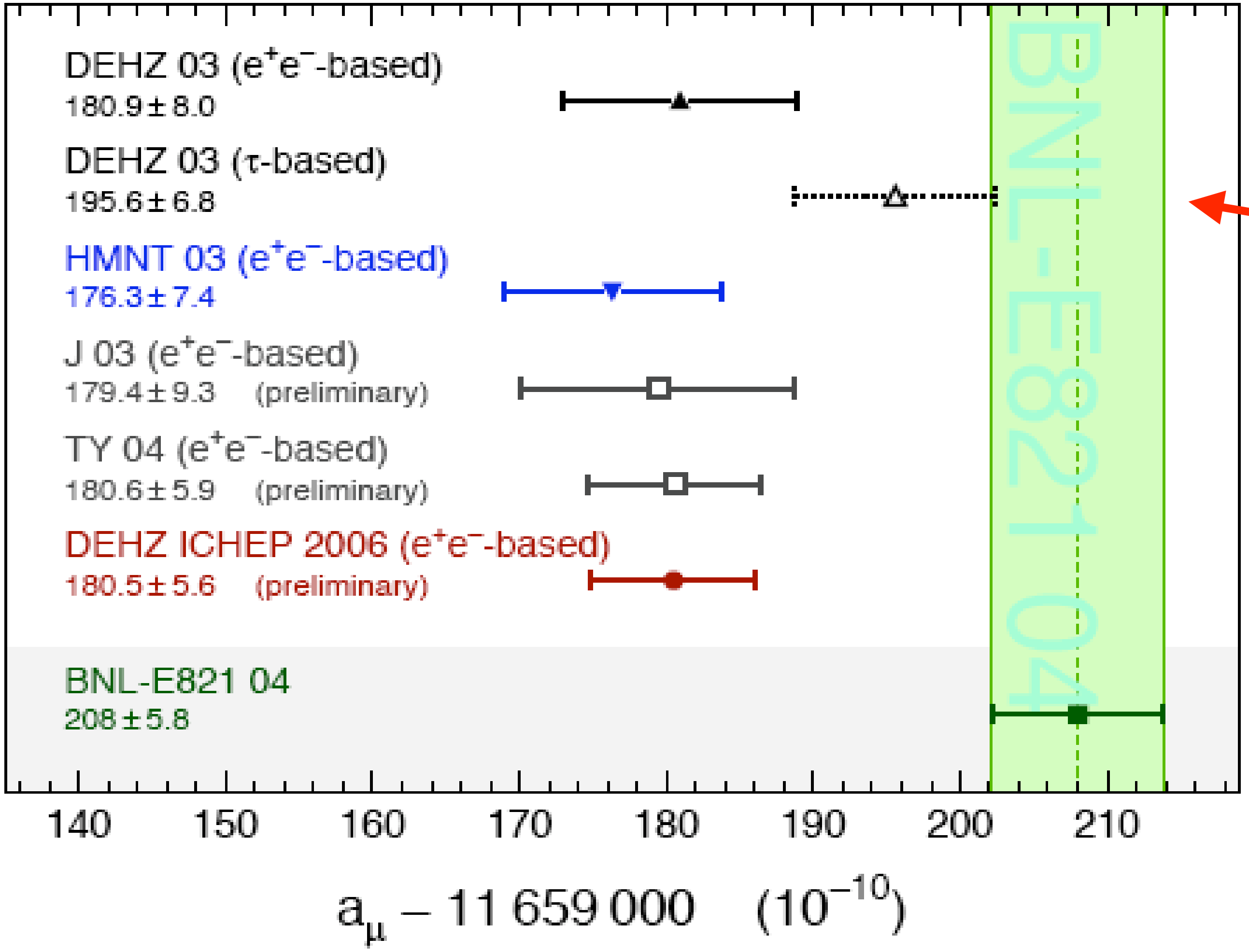
From e+e- data: ~3.3 σ

Observed Difference with Experiment:

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

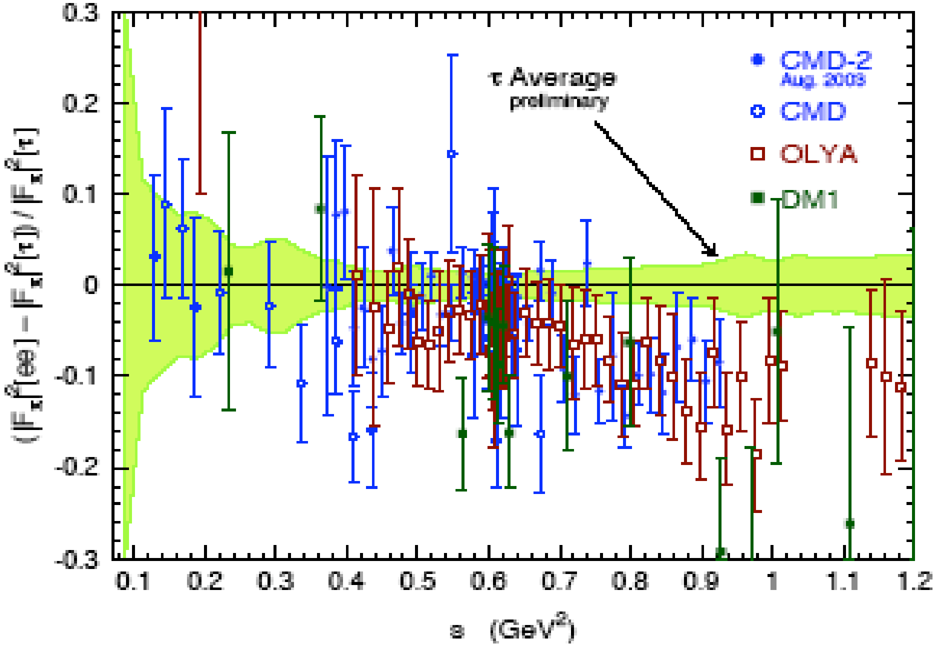
➡ 3.3 "standard deviations"

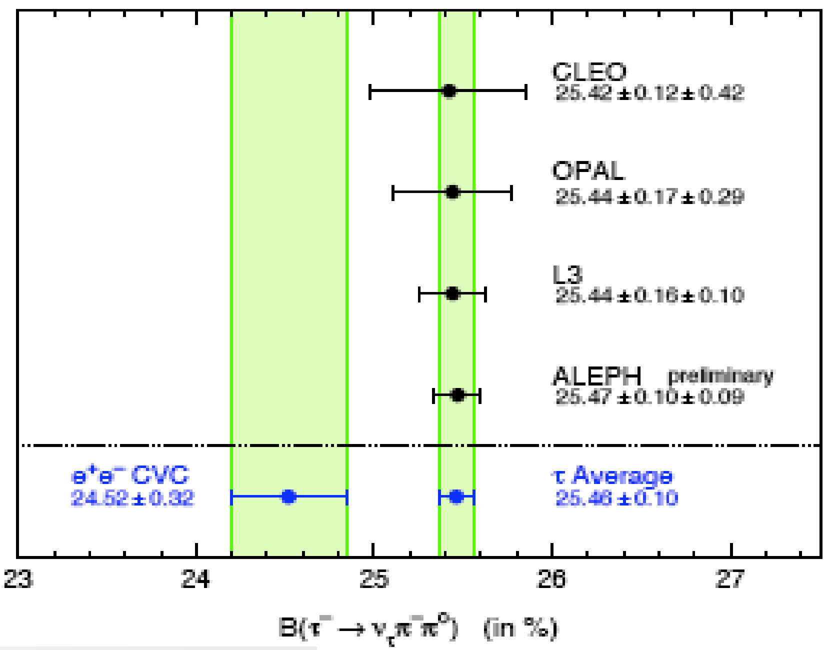
Davier/Hocker



Hadronic contr. from data.
τ vs e+e- discrepancy

CVC in the 2π Channel. e^+e^- vs. τ

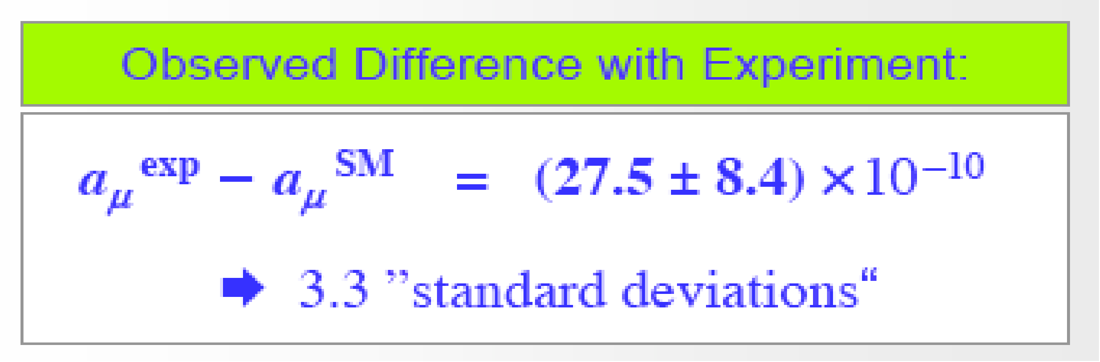




Difference: BR[τ] – BR[e^+e^- (cvc)]:

Mode	$\Delta(\tau - e^+e^-)$	"Sigma"
$\tau^- \to \pi^- \pi^0 \nu_\tau$	$+0.92 \pm 0.21$	4.5
$\tau^- \to \pi^- 3\pi^0 \nu_\tau$	-0.08 ± 0.11	0.7
$\tau^- \to 2\pi^- \pi^+ \pi^0 \nu_\tau$	$+0.91 \pm 0.25$	3.6

e^+e^- data on $\pi^- \pi^+ \pi^0 \pi^0$ not satisfactory



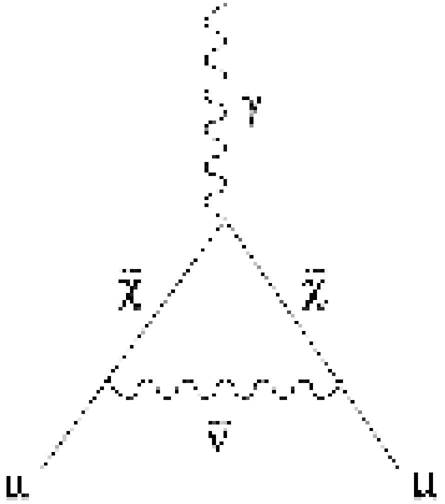
Observed Difference with Experiment:

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

➡ 3.3 "standard deviations"

Could be new physics
eg light SUSY

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

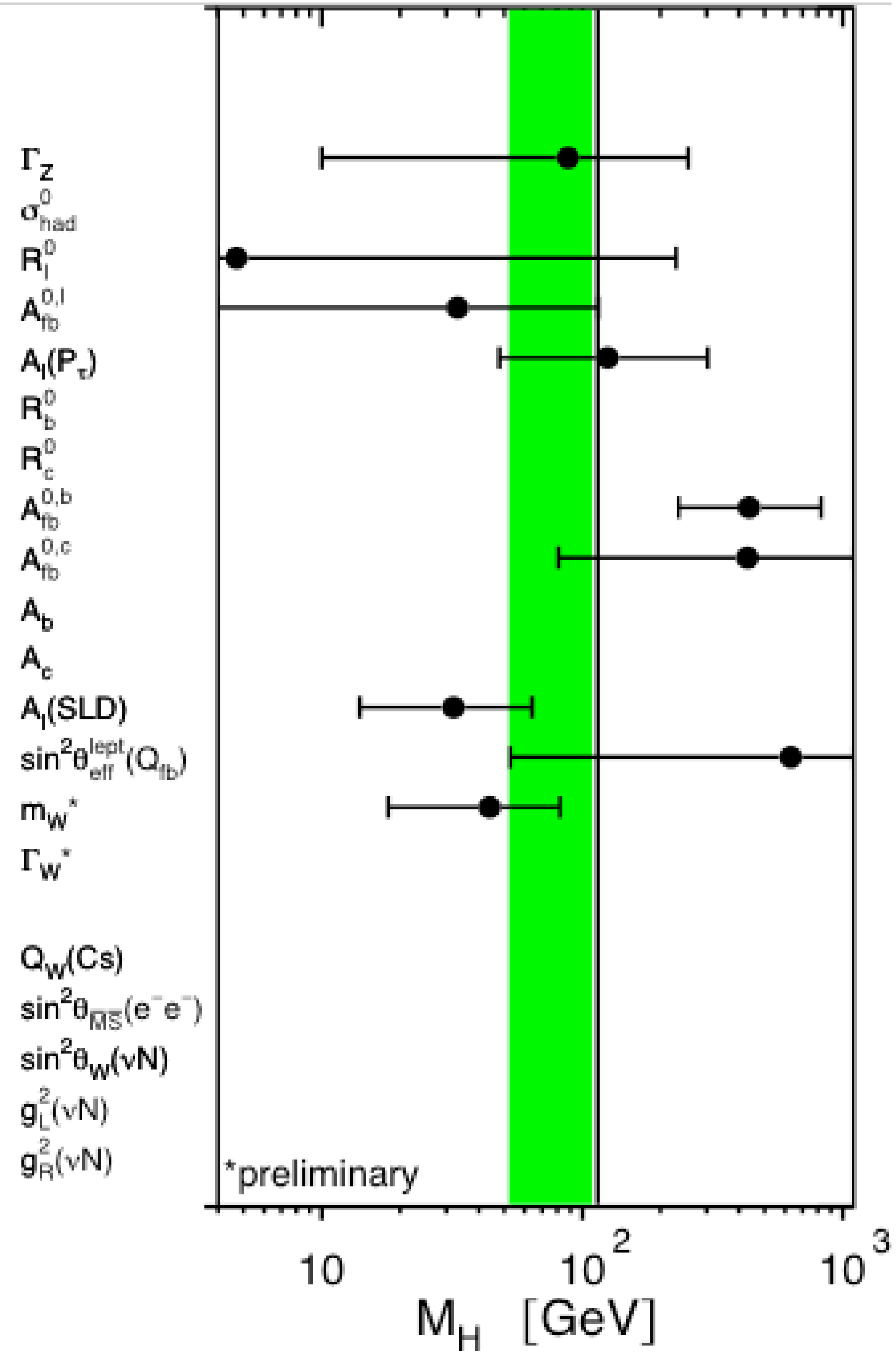


a_μ is a plausible
location for a
new physics signal!!

But the e-τ discrepancy is not understood:
theoretical errors underestimated?

Back to high energy precision tests

Sensitivity to m_H

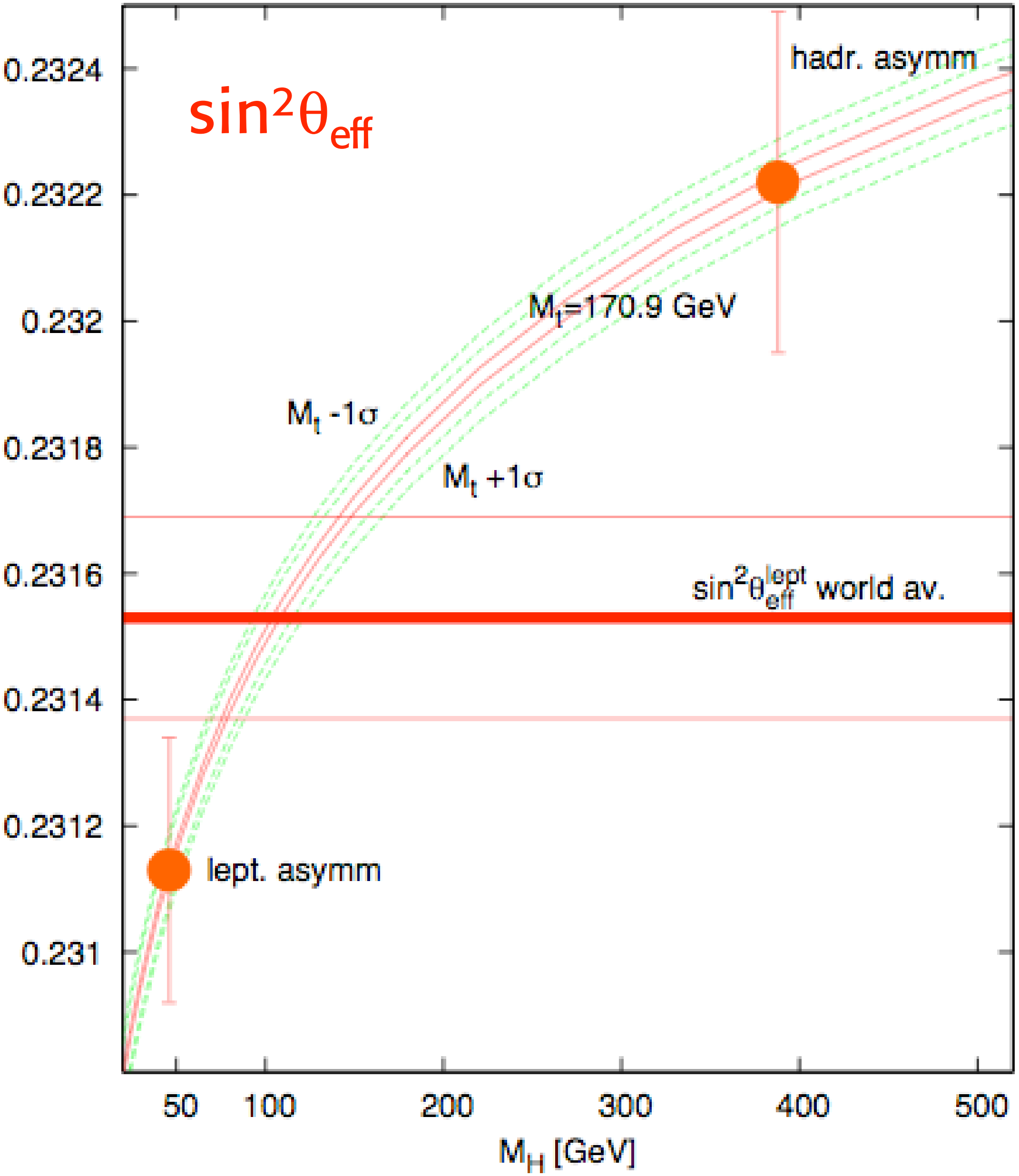


P. Gambino

Plot $\sin^2\theta_{eff}$ vs m_H

Exp. values are plotted at the m_H point that better fits given m_{texp}

Clearly leptonic and hadronic asymm.s push m_H towards different values

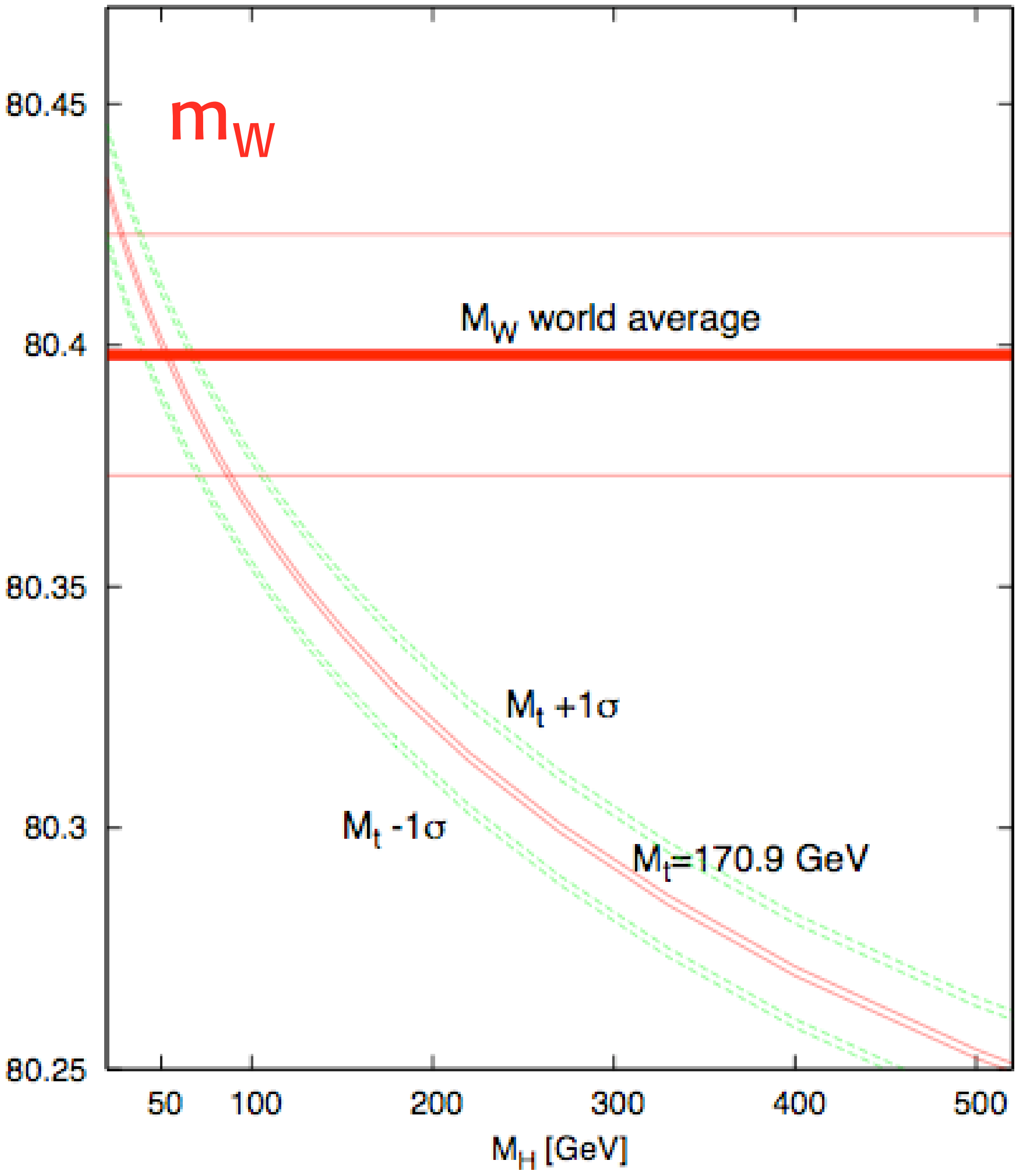


Plot m_W vs m_H

P. Gambino

m_W points to a light Higgs!

Like $[\sin^2\theta_{eff}]_l$



Fit results

Here only m_W and not m_t is used:
shows m_t from rad. corr.s

March '08

	only m_W	only m_t	m_W, m_t
m_t(GeV)	178.7+12-9	172.6±1.4	172.8±1.4
m_H(GeV)	143+236-80	111+56-39	87+36-27
log[m_H(GeV)]	2.16±0.39	2.05 ± 0.18	1.94± 0.16
$\alpha_s(m_Z)$	0.1190(28)	0.1190 (27)	0.1185 (26)
χ^2/dof	16.8/12	16.0/11	17.2/13
m_W(MeV)	80385(19)	80363(20)	80377(15)

WA: m_W=80398(25)

⊕ Rad. corr.'s predict m_t and m_W very well. May be also m_H!

Status of the SM Higgs fit

Winter '07

Sensitive to log m_H

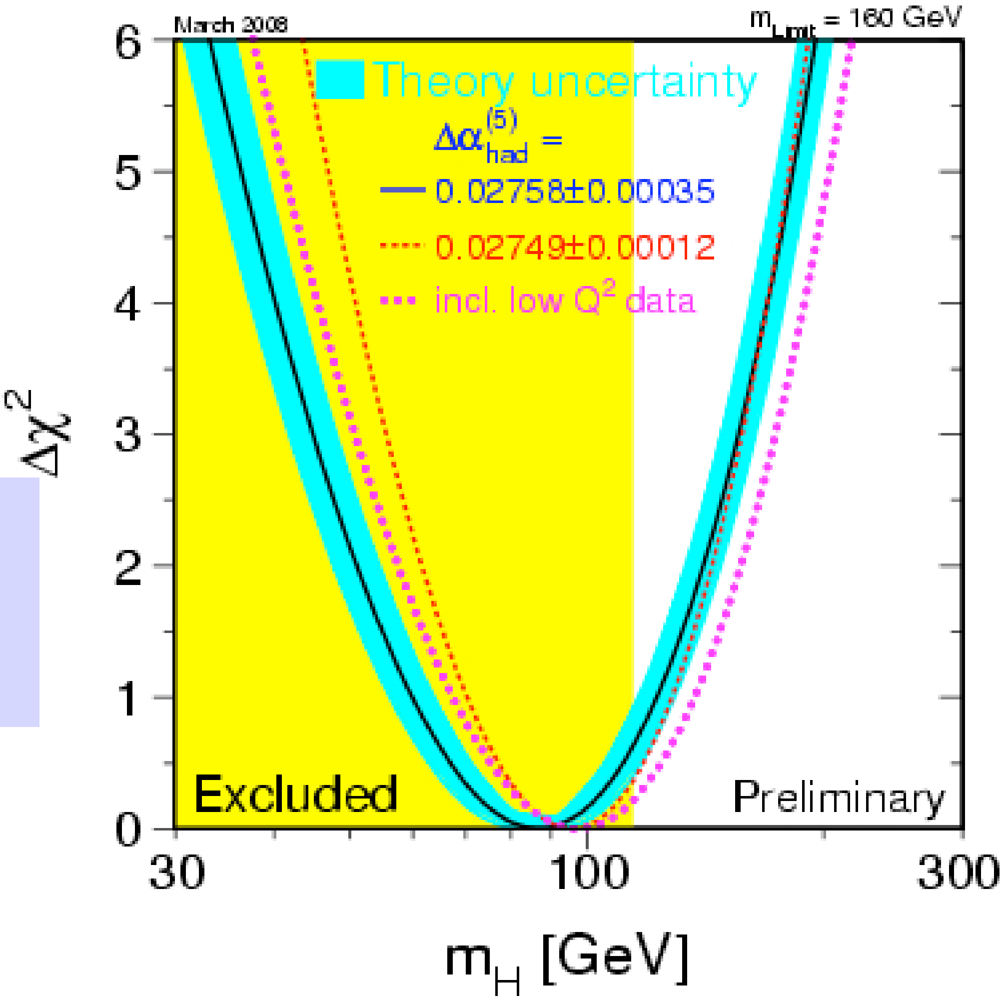
Rad Corr.s ->

$\log_{10} m_H(\mathrm{GeV}) = 1.94 \pm 0.16$

m_H=87+36-27 GeV

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

Direct search: $m_H > 114.4$ GeV



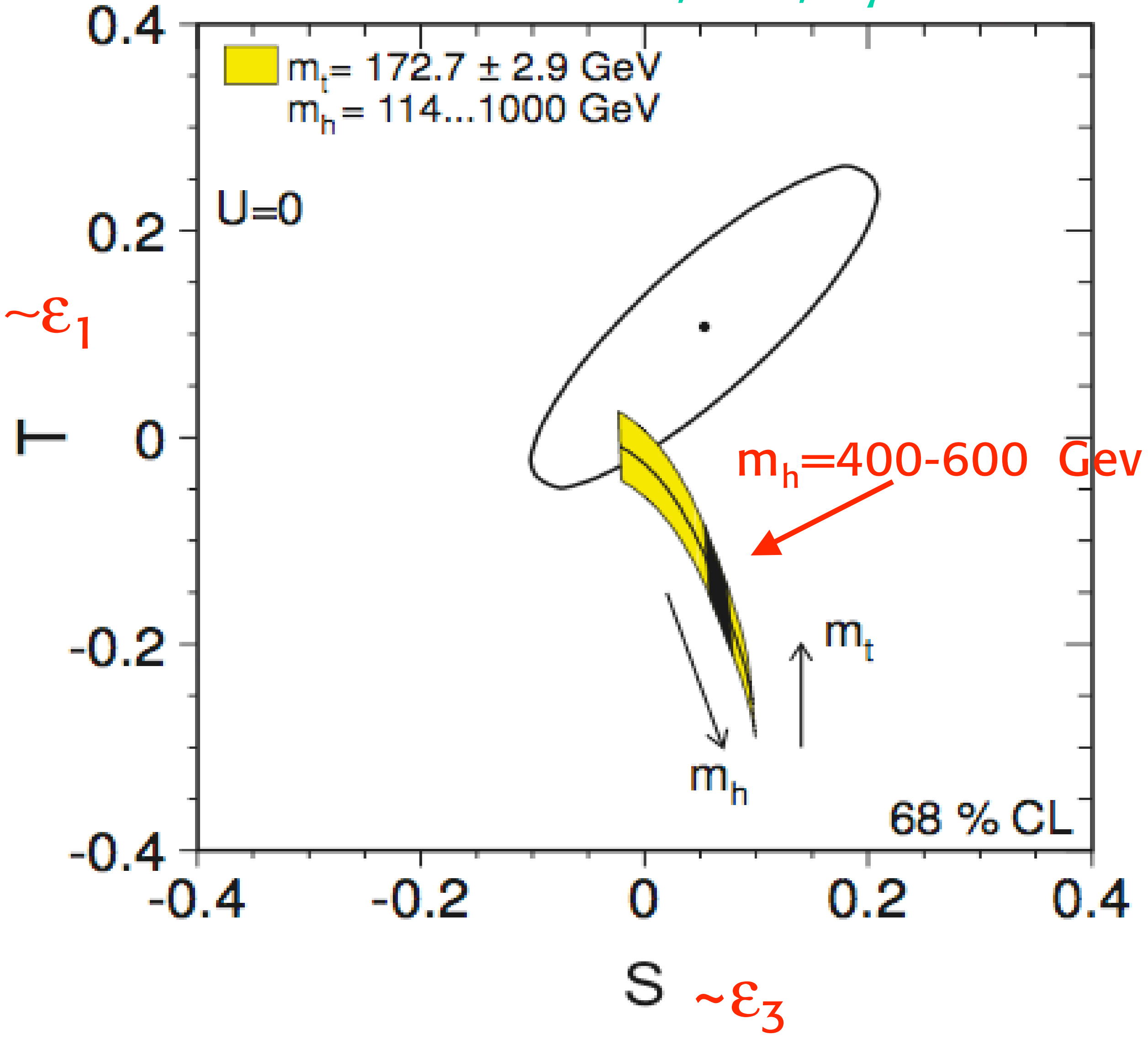
At 95 % cl

$m_H < 160$ GeV (rad corr.'s)

$m_H < 190$ GeV (incl. direct search bound)

We see that to shift m_h up we need a new physics effect that mainly pushes T up

Barbieri, Hall, Rychkov



Here “Higgs” means the “the EW symmetry breaking mechanism”

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

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)

Such a heavy Higgs would make perturbation theory to collapse nearby (violations of unitarity for $m_H > 0.8$ 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

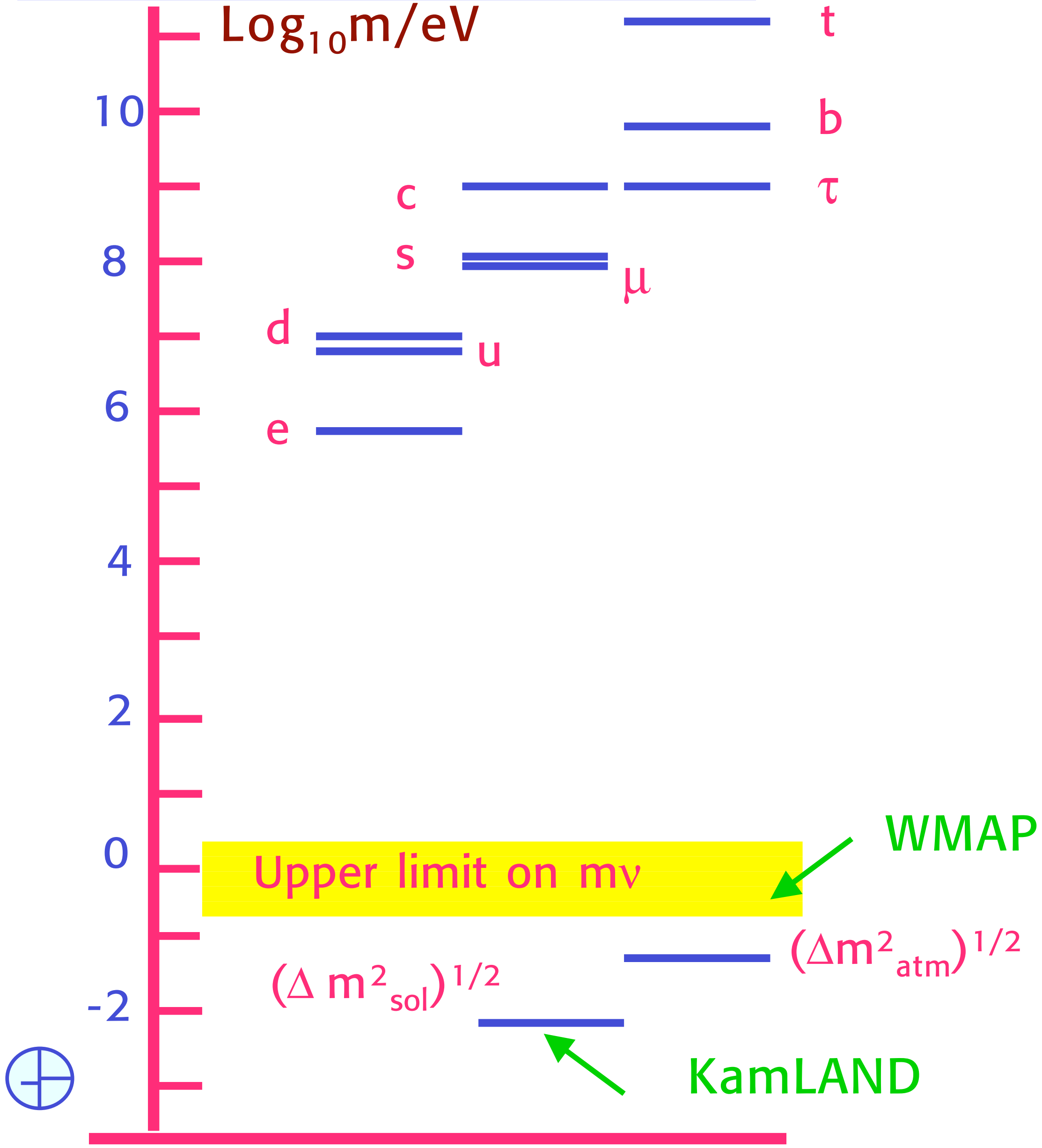
- Quantum gravity
- The hierarchy problem
- The flavour problem
- •••••

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 are new flavour physics!



Neutrino masses are really special!

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

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 ~ M_{GUT}

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

m: $\leq m_t \sim v \sim 200$ GeV
M: scale of L non cons.

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV
m ~ v ~ 200 GeV

M ~ 10^{14} - 10^{15} GeV

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

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

Baryogenesis

$n_B/n_\gamma \sim 10^{-10}$, $n_B >> n_{Bbar}$

Conditions for baryogenesis: (Sacharov '67)

- B non conservation (obvious)
- C, CP non conserv'n ($B-B^{bar}$ odd under C, CP)
- No thermal equilib'm ($n=\exp[\mu-E/kT]$; $\mu_B=\mu_{Bbar}$, $m_B=m_{Bbar}$ by CPT

If several phases of BG exist at different scales the asymm. created by one out-of-equilib'm phase could be erased in later equilib'm phases: BG at lowest scale best

Possible epochs and mechanisms for BG:

- At the weak scale in the SM Excluded
- At the weak scale in the MSSM Disfavoured
- Near the GUT scale via Leptogenesis Very attractive

Baryogenesis by decay of heavy Majorana ν's

BG via Leptogenesis near the GUT scale

$T \sim 10^{12\pm3}$ GeV (after inflation)

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

Only survives if Δ(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

$m_i < 10^{-1}$ eV

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

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

Dark Matter

WMAP, SDSS, 2dFGRS….

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.044$, $\Omega_m \sim 0.27$
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
(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:

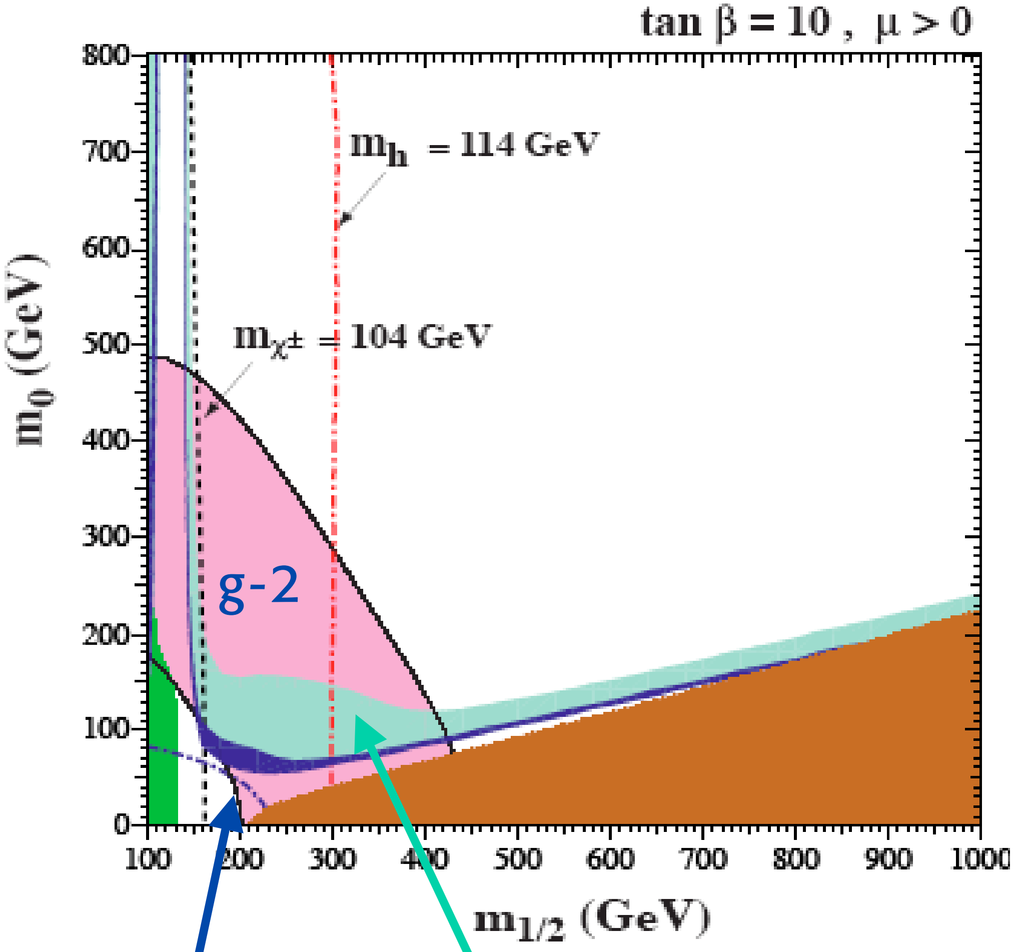
$$\boxed{\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\mathrm{Pl}}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \ \mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}}$$

can work for typical weak cross-sections!!!

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

LHC will tell yes or no to WIMPS

SUSY Dark Matter: we hope it is the neutralino
[the gravitino is a non WIMP alternative]

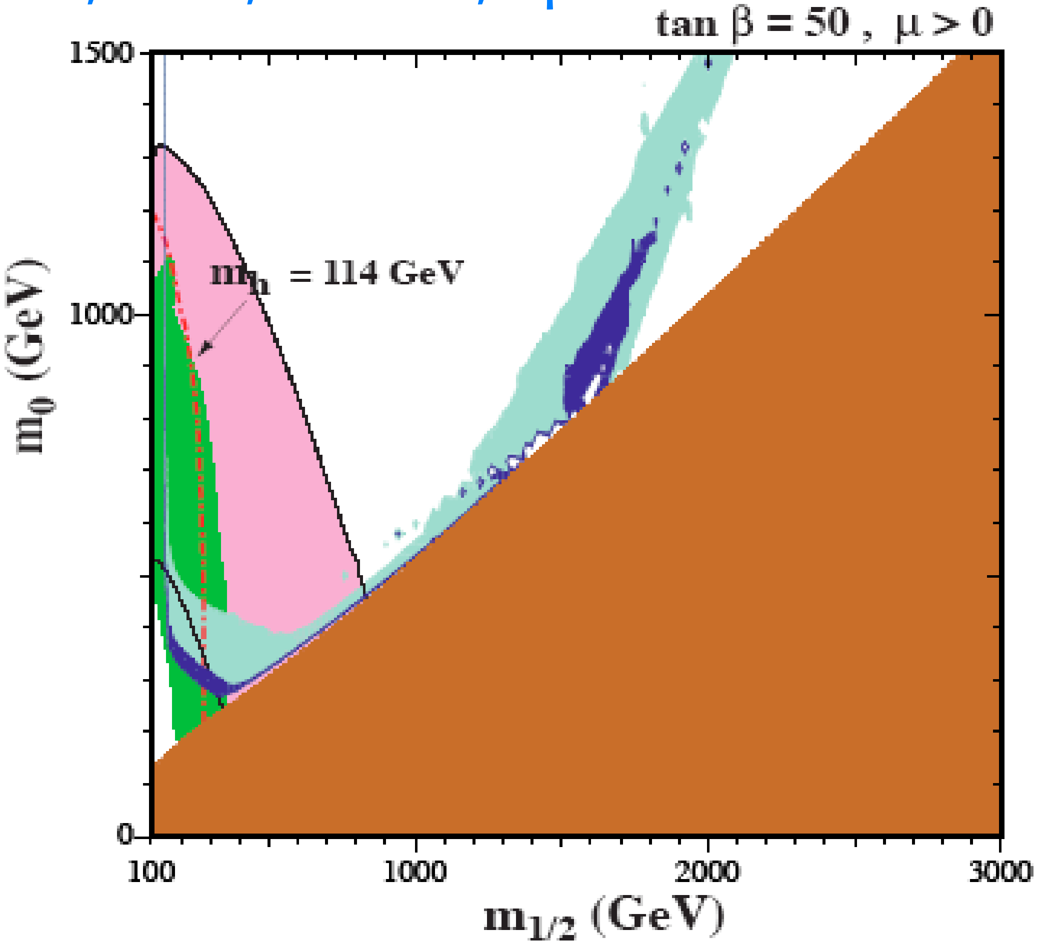


g-2

WMAP

$0.1<\Omega h^2<0.3$

Ellis, Olive, Santoso, Spanos



This is for the CMSSM
With less constraints, more space

Experimental hints for dark matter?

Annual modulations (DAMA/LIBRA)

e+/e- excess in cosmic rays detectors (PAMELA/ATIC)

γ excess (EGRET)

....

If really signals for DM those effect swould indicate more exotic forms of DM

Arkani-Hamed et al, ‘08
Cirelli et al, ‘08

Conceptual problems of the SM

Most clearly:

- No quantum gravity ($M_{Pl} \sim 10^{19}$ GeV)
- But a direct extrapolation of the SM leads directly to GUT's ($M_{GUT} \sim 10^{16}$ GeV)

M_{GUT} close to M_{Pl}

- suggests unification with gravity as in superstring theories
- poses the problem of the relation m_W vs M_{GUT}- M_{Pl}

Can the SM be valid up to M_{GUT}- M_{Pl}?? ← The “big” hierarchy problem

Not only it looks very unlikely, but the new physics must be near the weak scale!

With new physics at Λ the low energy theory is only an effective theory. After integration of the heavy d.o.f.:

$\mathcal{L}_i$: operator of dim i

$$\mathcal{L} = \underbrace{o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4}_{\text{Renorm.ble part}} \quad + \underbrace{o(1/\Lambda)\mathcal{L}_5 + o(1/\Lambda^2)\mathcal{L}_6 + \dots}_{\text{Non renorm.ble part}}$$

In absence of special symmetries or selection rules, by dimensions $c_i\mathcal{L}_i \sim o(\Lambda^{4-i})\mathcal{L}_i$

$\mathcal{L}_2$: Boson masses ϕ^2. In the SM the mass in the Higgs potential is unprotected: $c_2 \sim o(\Lambda^2)$

$\mathcal{L}_3$: Fermion masses $\psi\psi$. Protected by chiral symmetry and SU(2)xU(1): $\Lambda \to m\log\Lambda$

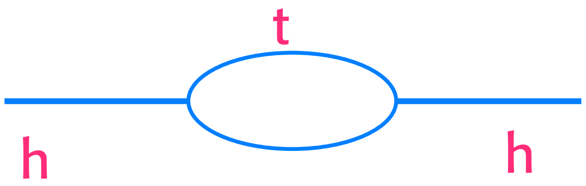
$\mathcal{L}_4$: Renorm.ble interactions, e.g. $\psi\gamma^\mu\psi A_\mu$

$\mathcal{L}_{i>4}$: Non renorm.ble: suppressed by $1/\Lambda^{i-4}$ e.g. $1/\Lambda^2\psi\gamma^\mu\psi\psi\gamma^\mu\psi$

For the low energy theory: 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

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

Λ: scale of new physics beyond the SM

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

Precision Flavour Physics

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

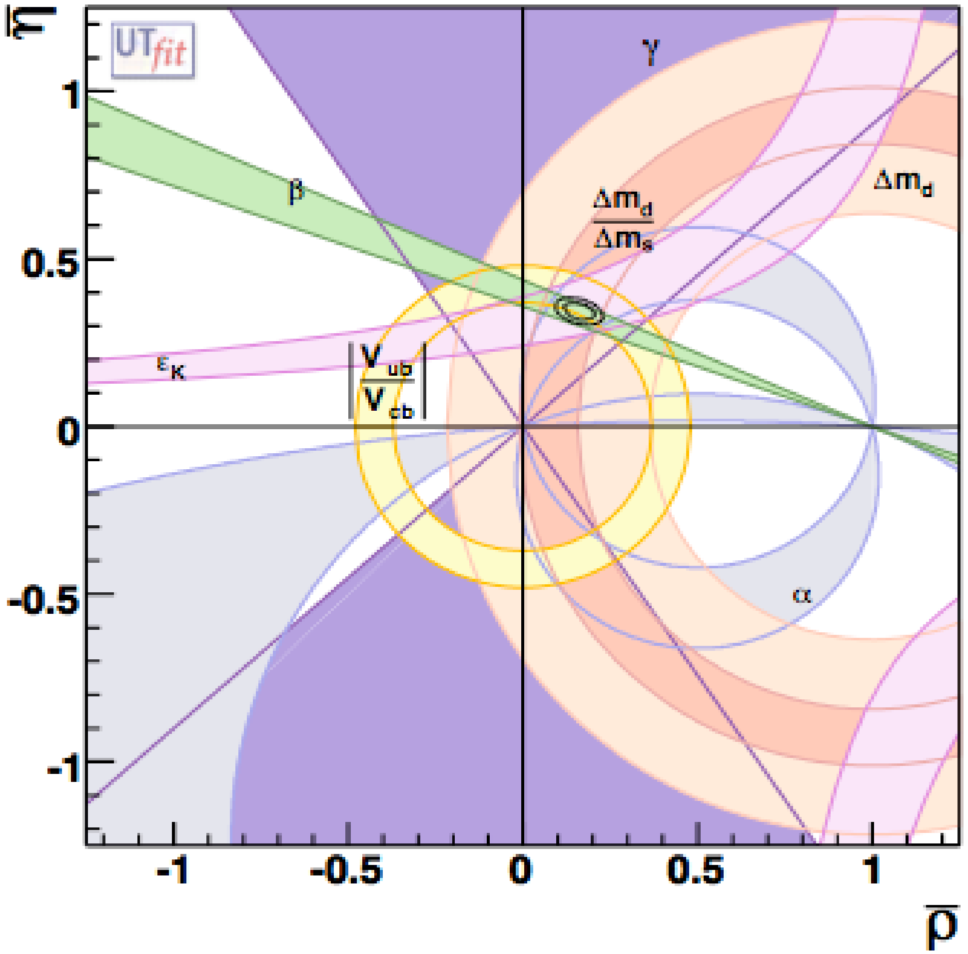
- Light Higgs -> New physics at ~ few TeV
- But all effective non rinorm. vertices for FCNC have bounds above a few TeV

Apparently the SM suppression of FCNC and the CKM mechanism for CP violation is only mildly modified by new physics:
an intriguing mystery and a major challenge for models of new physics

Not only one needs small NP contributions at the weak scale.
But also to control feedback from high scales thru RGE

In particular additional constraints on SUSY models
(universality or alignment at the GUT scale, R- parity cons.,....)

The study of B decays (BaBar, Belle, CDF...) has revealed no compelling signs of new physics



The CKM theory works (too) well!

The LHCb experiment
at the LHC
will go further in
this direction

Adding effective operators to SM generally leads to very large Λ

$$M(\mathrm{B_d}\text{-}\bar{\mathrm{B}}_\mathrm{d}) \sim \frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + \boxed{c_{\mathrm{NP}}\,\frac{1}{\Lambda^2}}$$

Isidori

$$c_{\mathrm{NP}} \to \begin{cases} \sim 1 \xrightarrow{\text{tree/strong + generic flavour}} \Lambda \gtrsim 2\times10^4 \text{ TeV [K]} \\ \sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavour}} \Lambda \gtrsim 2\times10^3 \text{ TeV [K]} \\ \sim (y_t V_{ti}{}^* V_{tj})^2 \xrightarrow{\text{tree/strong + MFV}} \Lambda \gtrsim 5 \text{ TeV [K \& B]} \\ \sim (y_t V_{ti}{}^* V_{tj})^2/(16\,\pi^2) \xrightarrow{\text{loop + MFV}} \Lambda \gtrsim 0.5 \text{ TeV [K \& B]} \end{cases}$$

But the hierarchy problem demands Λ in the few TeV range

only assuming $c_{\mathrm{NP}} \sim (y_t V_{tb}{}^* V_{td})^2$ (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): $\Lambda \sim m_{SUSY} - m_{ord}$ → 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

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

The anthropic route

The scale of the cosmological constant is a big mystery.

$\Omega_\Lambda \sim 0.65$ → $\rho_\Lambda \sim (2\ 10^{-3}\ \mathrm{eV})^4 \sim (0.1\mathrm{mm})^{-4}$ → Similar to m_ν!?

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

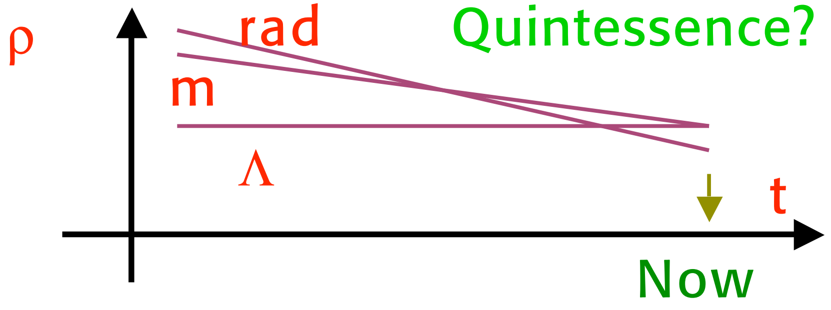
If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123}\,\rho_{obs}$

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?

I find applying the anthropic principle to the SM hierarchy problem excessive

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

Perhaps it is relevant for the residual fine tuning

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

An equal number of bosonic and fermionic degrees of freedom

Examples:

Electron field (4 components) → 2 charged scalar s-electron fields

Gluon (massless: 2 dof) → gluino: Majorana fermion

$$g = g^c$$

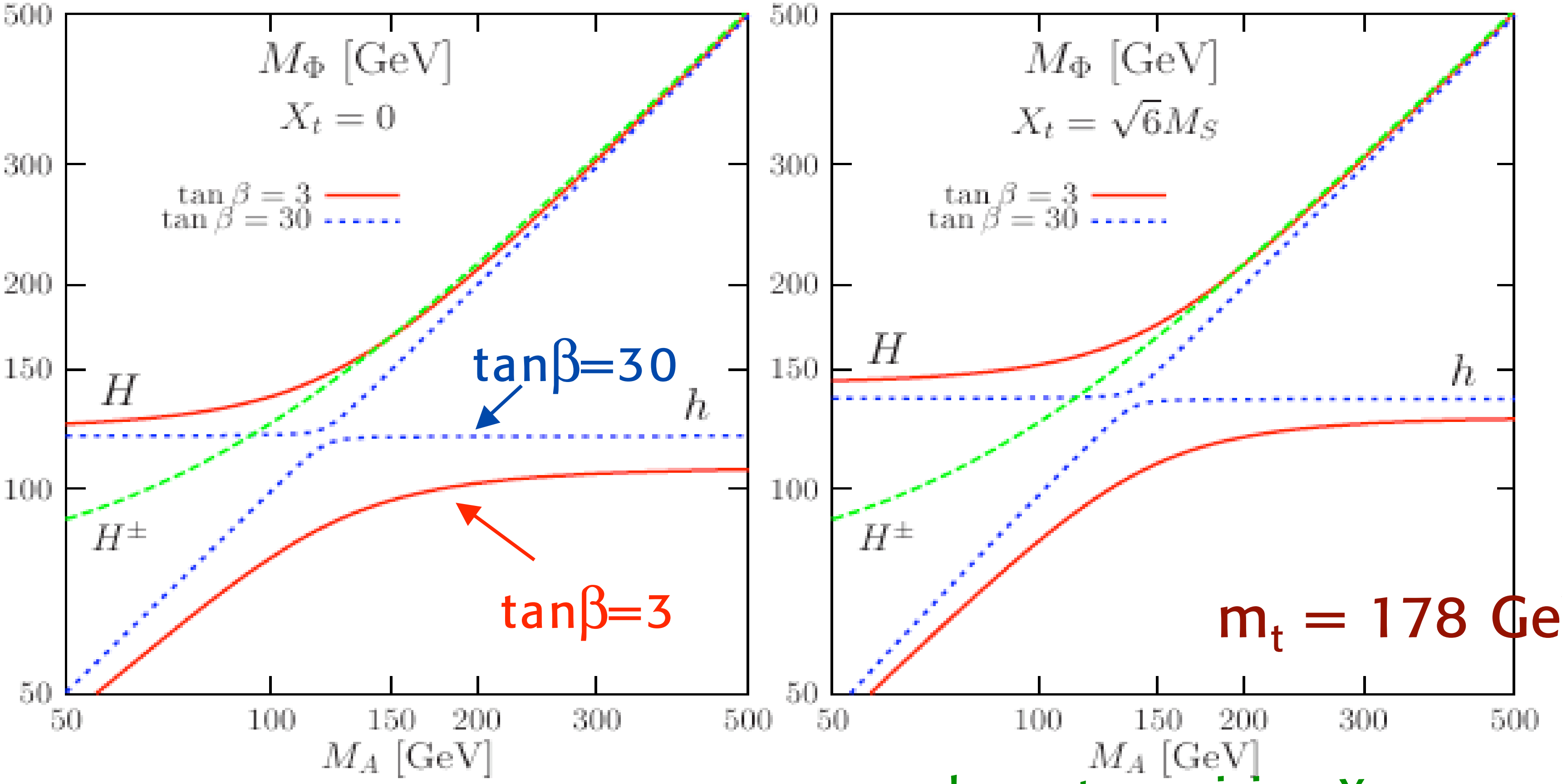
Why s-particles not yet seen? A clue:

Observed particles are those whose mass is forbidden by SU(2)xU(1)

When SUSY is broken but SU(2)xU(1) is unbroken s-particles get a mass, particles remain massless

In SUSY: 2 Higgs doublets, 5 in the phys. spectrum h, A, H, $H^{\pm}$

Djouadi



tanβ=30

tanβ=3

m_t = 178 GeV

no top mixing: X_t=0

large top mixing X_t

Now with m_t ~171 GeV:

m_h < ~125 GeV

SUSY fits with GUT's

From $\alpha_{QED}(m_Z)$, $\sin^2\theta_W$ measured at LEP predict $\alpha_s(m_Z)$ for unification (assuming desert)

EXP: $\alpha_s(m_Z)=0.119\pm0.003$
Present world average

- Coupling unification: Precise matching of gauge couplings at M_{GUT} fails in SM and is well compatible in SUSY

Non SUSY GUT's
$\alpha_s(m_Z)=0.073\pm0.002$
SUSY GUT's
$\alpha_s(m_Z)=0.130\pm0.010$

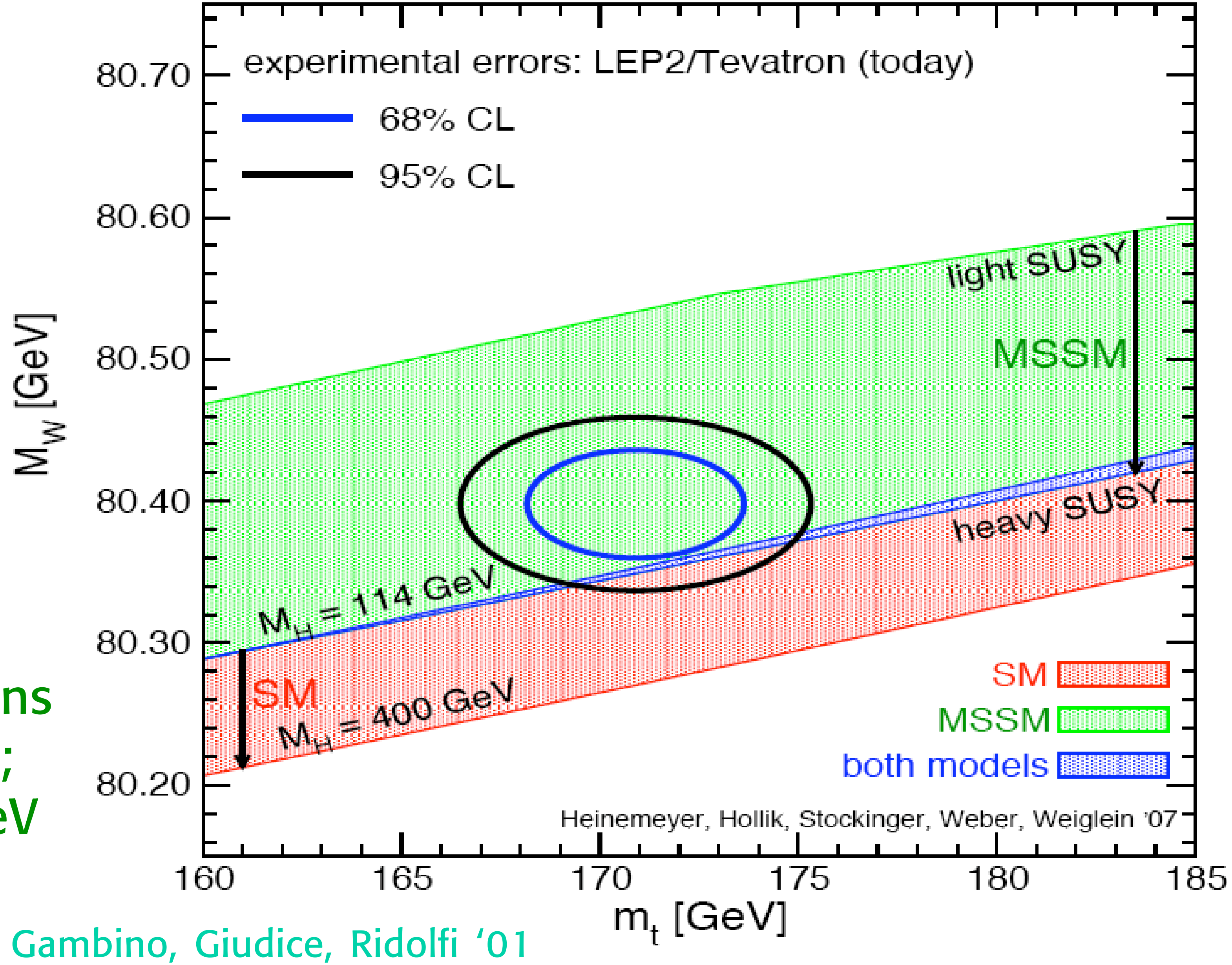
Langacker, Polonski

Dominant error:
thresholds near M_{GUT}

- Proton decay: Far too fast without SUSY
- $M_{GUT} \sim 10^{15}$GeV non SUSY ->10^{16}GeV SUSY
- Dominant decay: Higgsino exchange

While GUT's and SUSY very well match,
(best phenomenological hint for SUSY!)
in technicolor, extra dimensions,
little higgs etc., there is no ground for GUT's

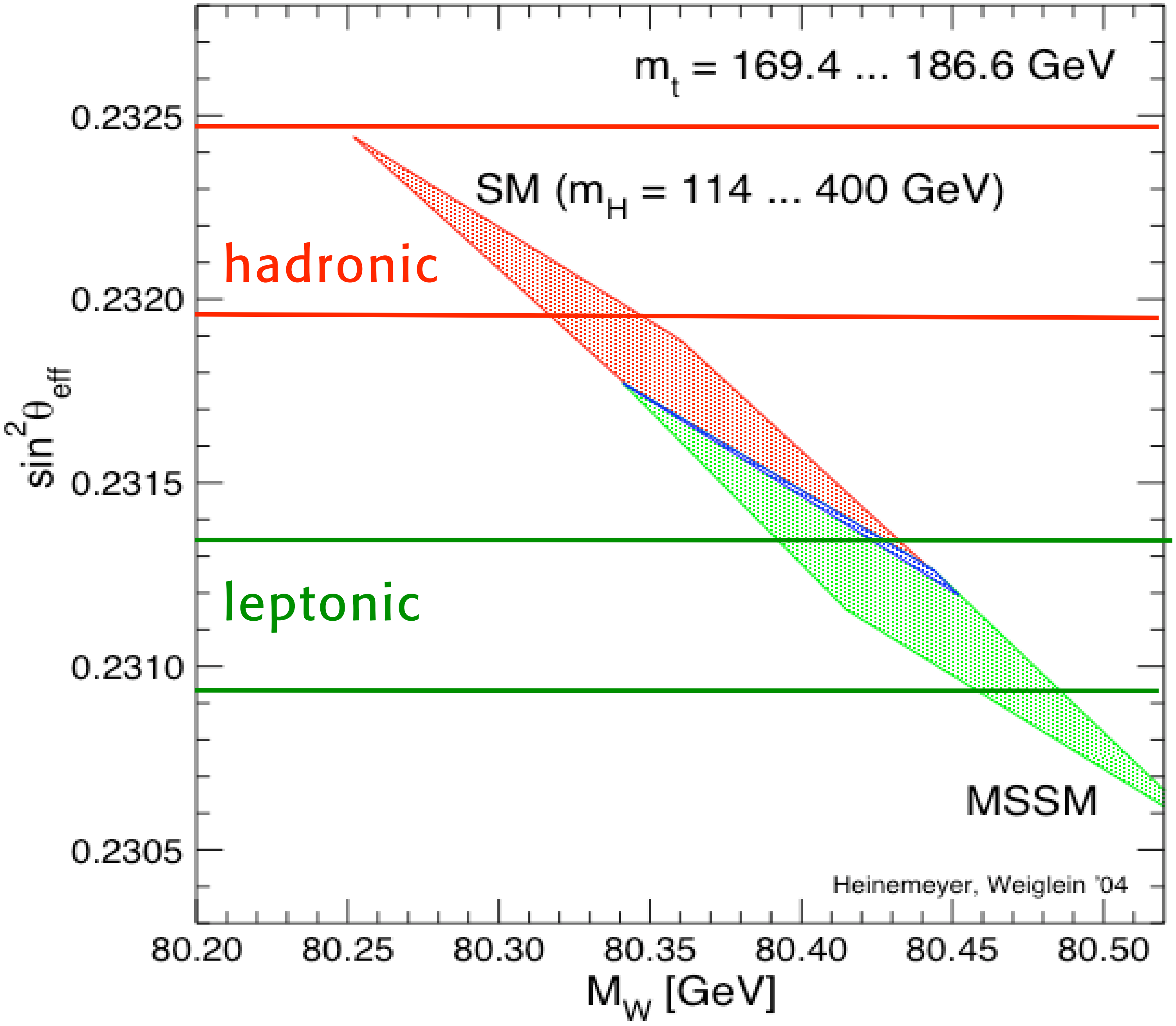
SUSY effects could modify the SM fit



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

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

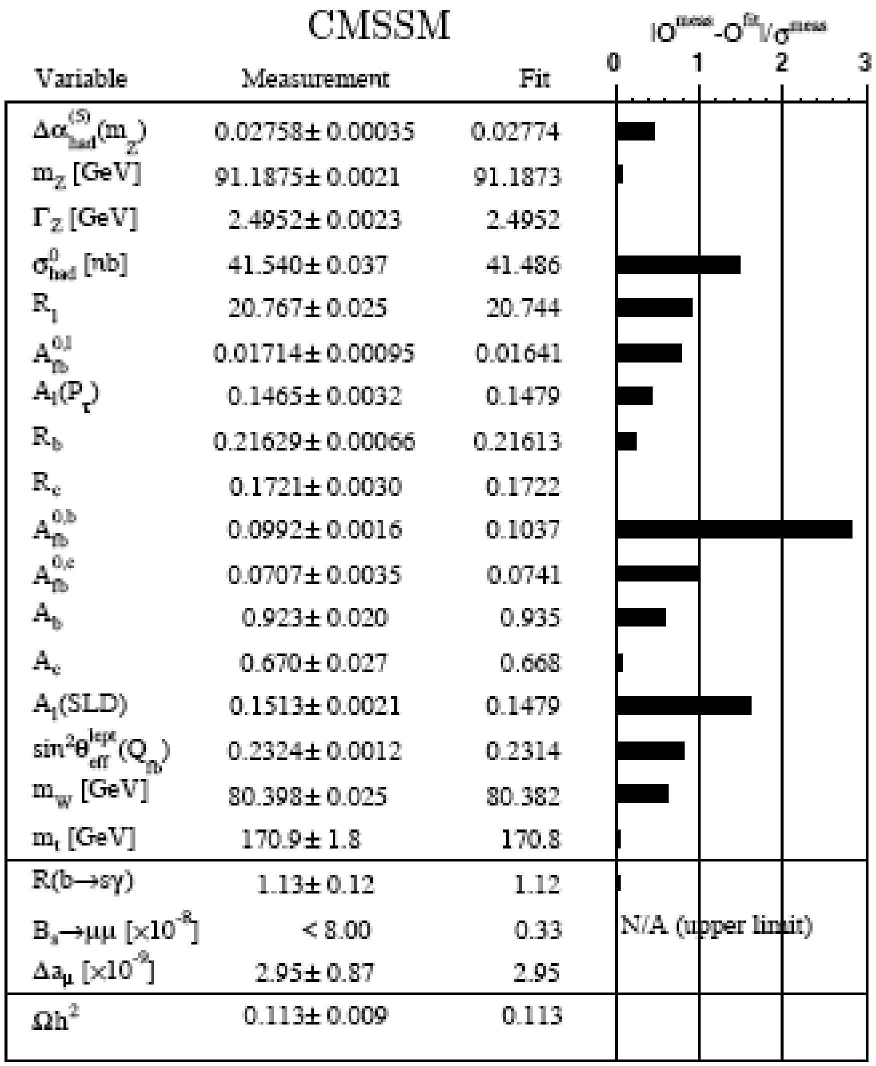
$\sin^2\theta$ is unfortunately ambiguous



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

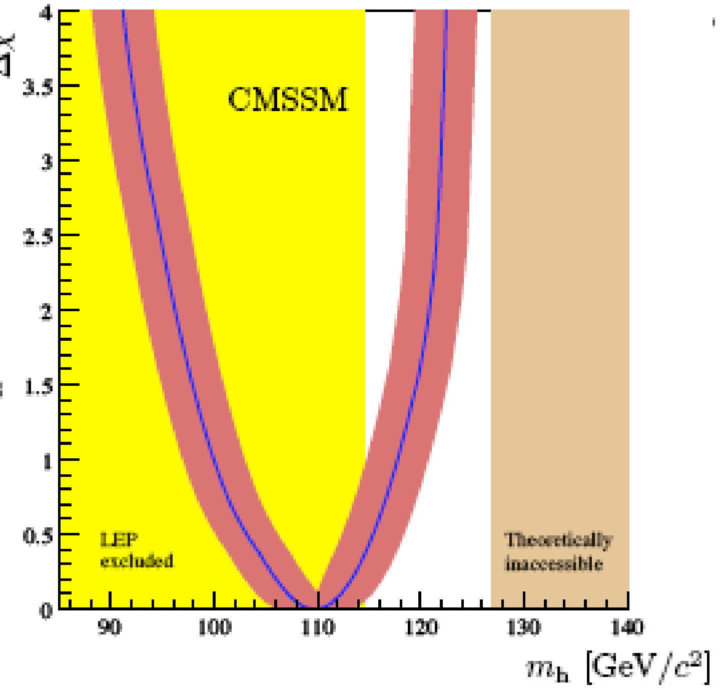
O. Buchmuller et al '07

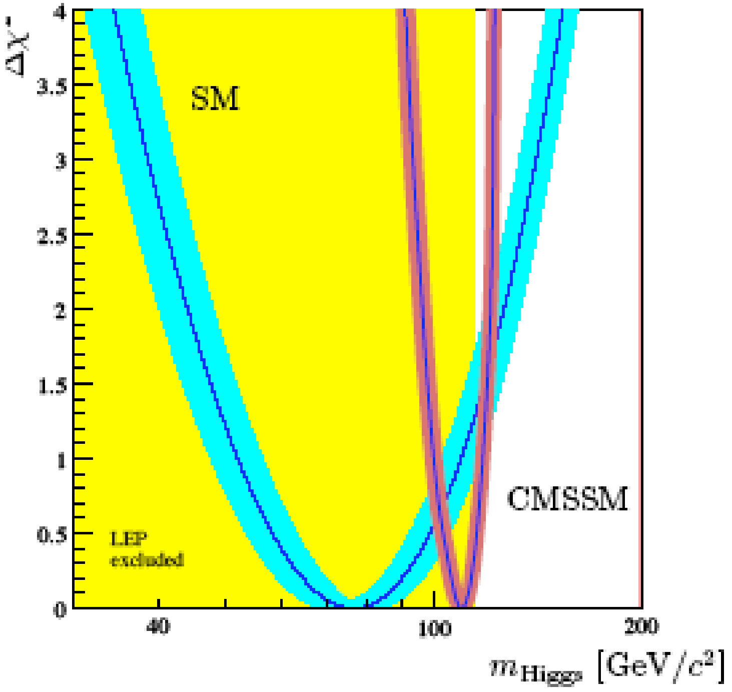
also:
J. Ellis et al '07



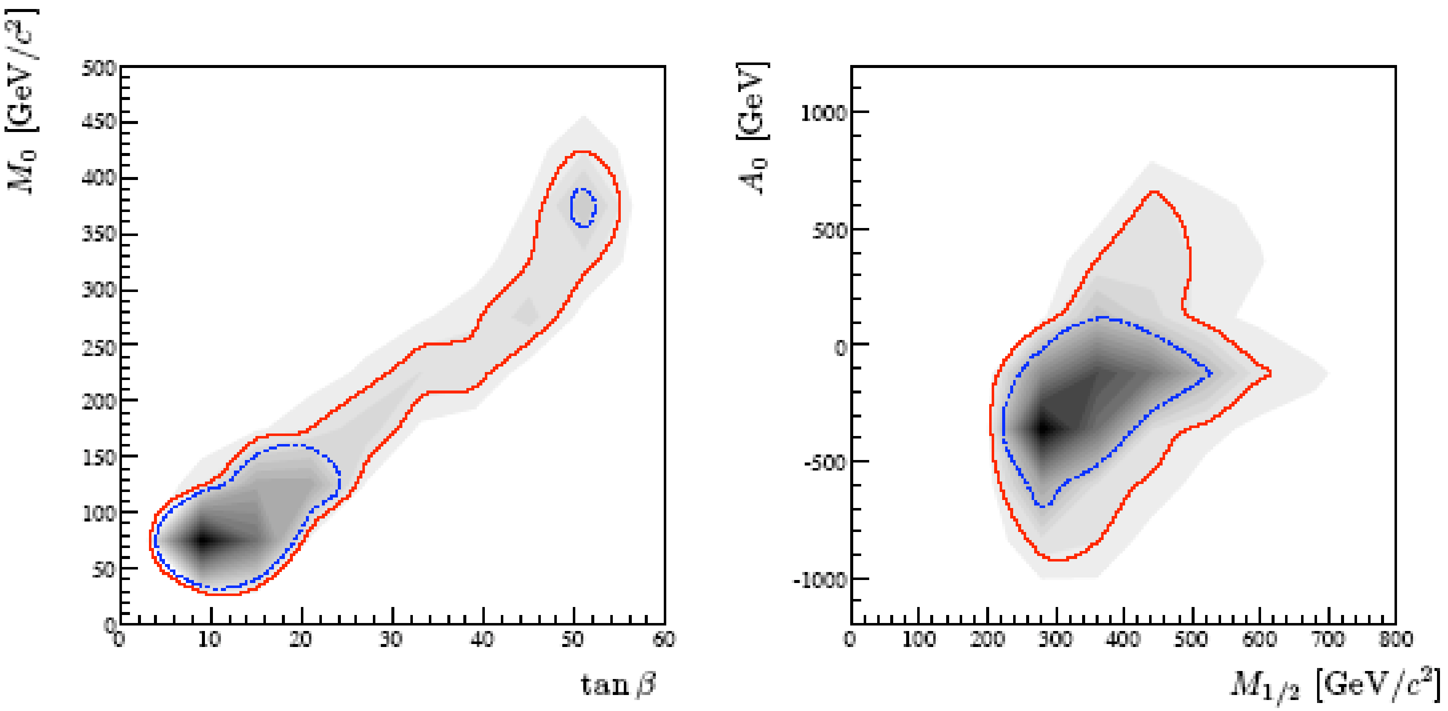
CMSSM

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	





O. Buchmuller et al '07

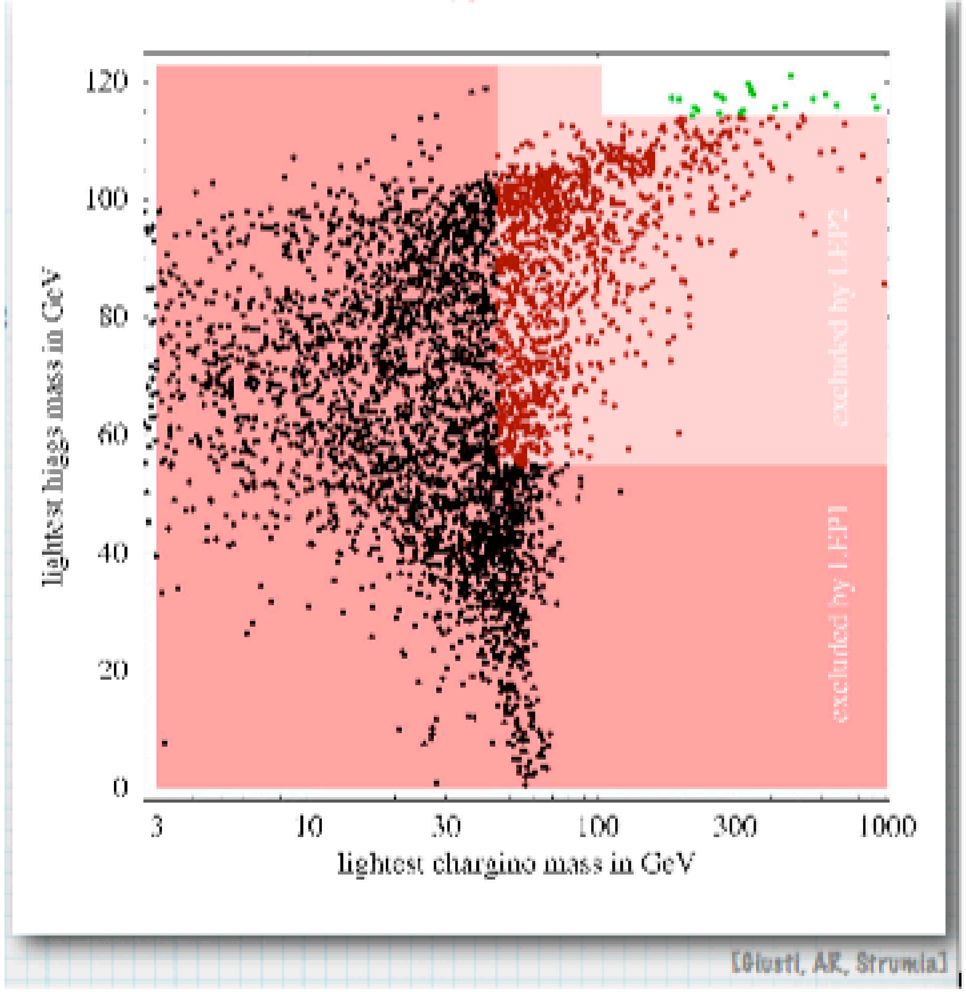


Evolution of SUSY fine tuning

A typical supergravity model is in trouble by now

After LEP-2 ➘

lightest
Higgs
mass
(GeV)



lightest chargino mass (GeV)

🡐 After LEP-1

Less fine tuning
in non minimal
models!

[Giusti-
Romanino-
Strumia,
hep-ph/9811386]

Summarising

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
(unique among NP models)
and has a good DM candidate: the neutralino
(actually more than one).

Remains the reference model for NP

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

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

$\Big\}$ ~1 TeV

⊕ 2 Higgs doublets ~0.2 TeV

Little Higgs:

One can make up a viable model.

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,.....

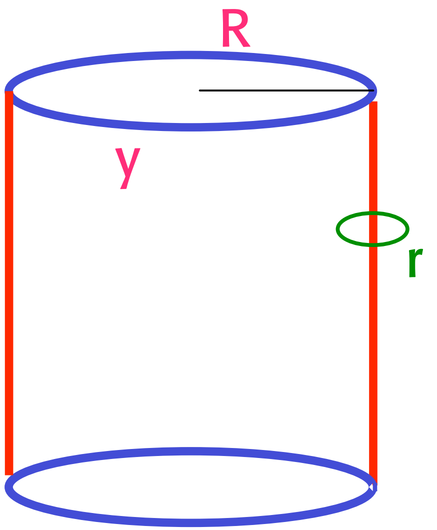
Extra Dimensions

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

Arkani-Hamed, Dimopoulos/ Dvali+Antoniadis

Early formulation: inspired by string theory, one assumed:

- Large compactified extra dimensions
- 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

- 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

The brane can itself have a thickness r:

$1/r \gtrsim 1\,\mathrm{TeV} \rightarrow r \lesssim 10^{-17}$ cm

→ KK recurrences of SM fields: W_n, Z_n etc

cfr:
- Gravity always on bulk

$1/R \gtrsim 10^{-3}$ eV $\rightarrow R \lesssim 0.1$ mm

- Factorized metric:

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

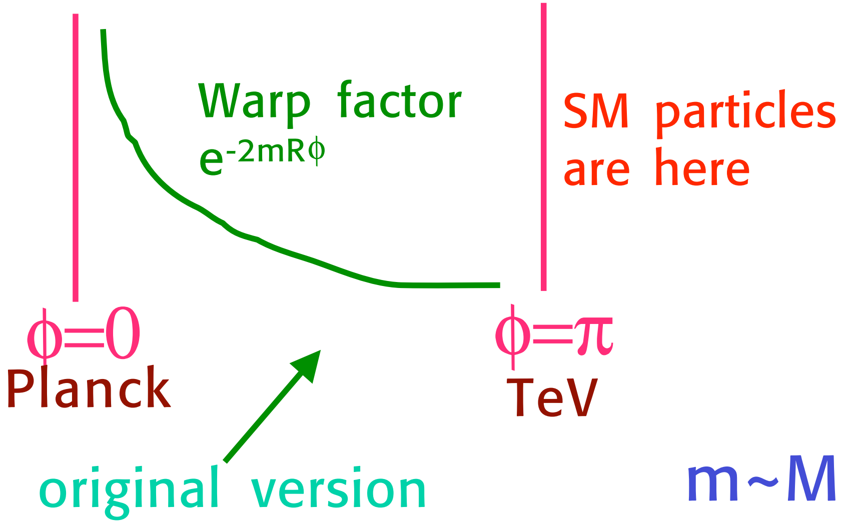
- Warped metric: Randall-Sundrum (R-S)

emerges as the most promising

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

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

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



Warp factor $e^{-2mR\phi}$

SM particles are here

$\phi=0$ Planck

$\phi=\pi$ TeV

original version

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

$m \sim M_{Pl}$ 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

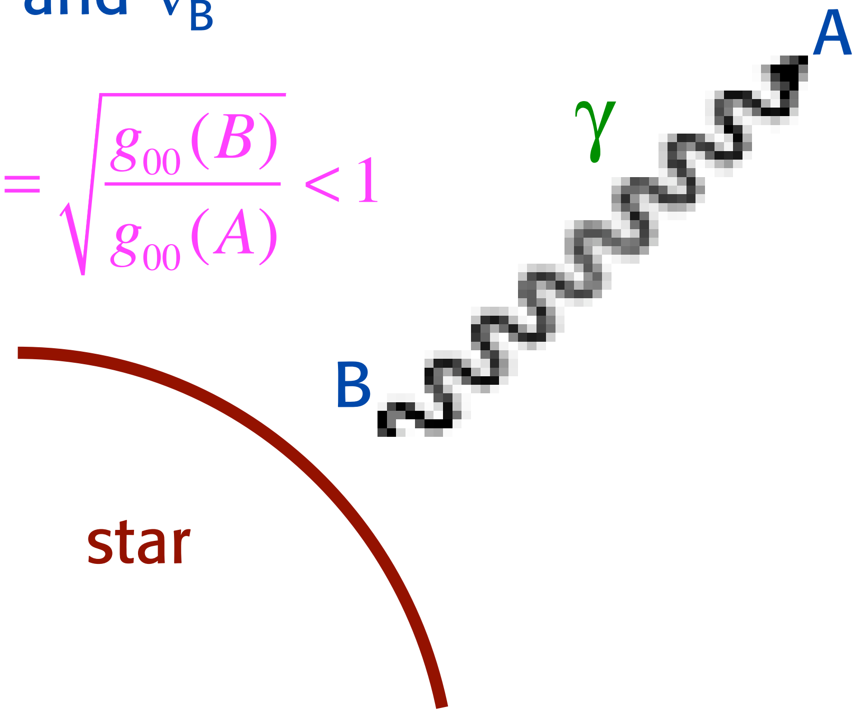
"radion"

Goldberger, Wise

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

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

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



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

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
- • • • • • • •

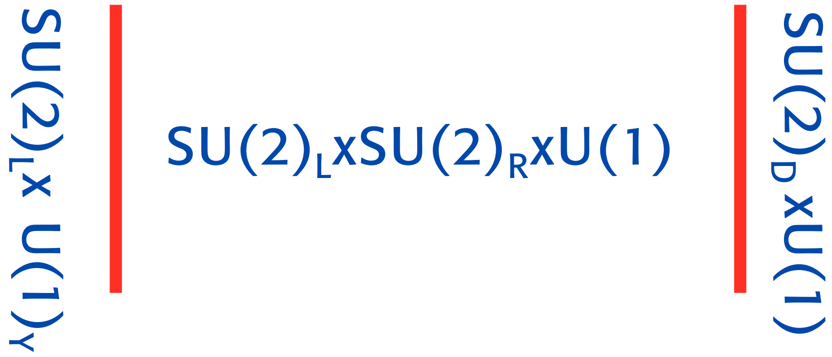
⊕ Model building based on RS explored in many directions

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

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

Csaki et al/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



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

$SU(2)_L xSU(2)_R xU(1)$

$SU(2)_D xU(1)$

M_{Pl}

TeV

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

$Z_k = k_{th}$ KK

Cancellation guaranteed
by sum rules implied
by 5-dim symmetry

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

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

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

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

corresponds to Higgs in the adjoint ($H=A_5$ 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

m_W fixes the KK gap and it is not sufficiently large

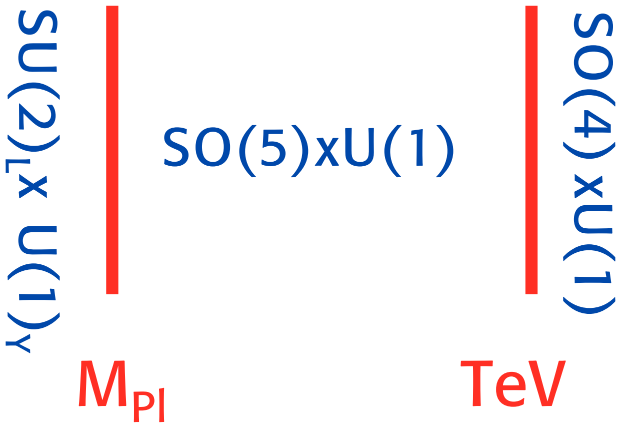
Substantial fine tuning required

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 AdS theory

Agashe, Contino, Pomarol



$SU(2)_L \times U(1)_Y$

$SO(5) \times U(1)$

$SO(4) \times U(1)$

M_{Pl} TeV

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 near the TeV brane)

As in Little Higgs models

The Higgs is a PGB and EW symmetry breaking is triggered by top-loop 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

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

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”