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Introduction to the Terascale

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The first collisions at the LHC are expected at the end of '07.
The physics run at 14 Tev will start in spring '08.

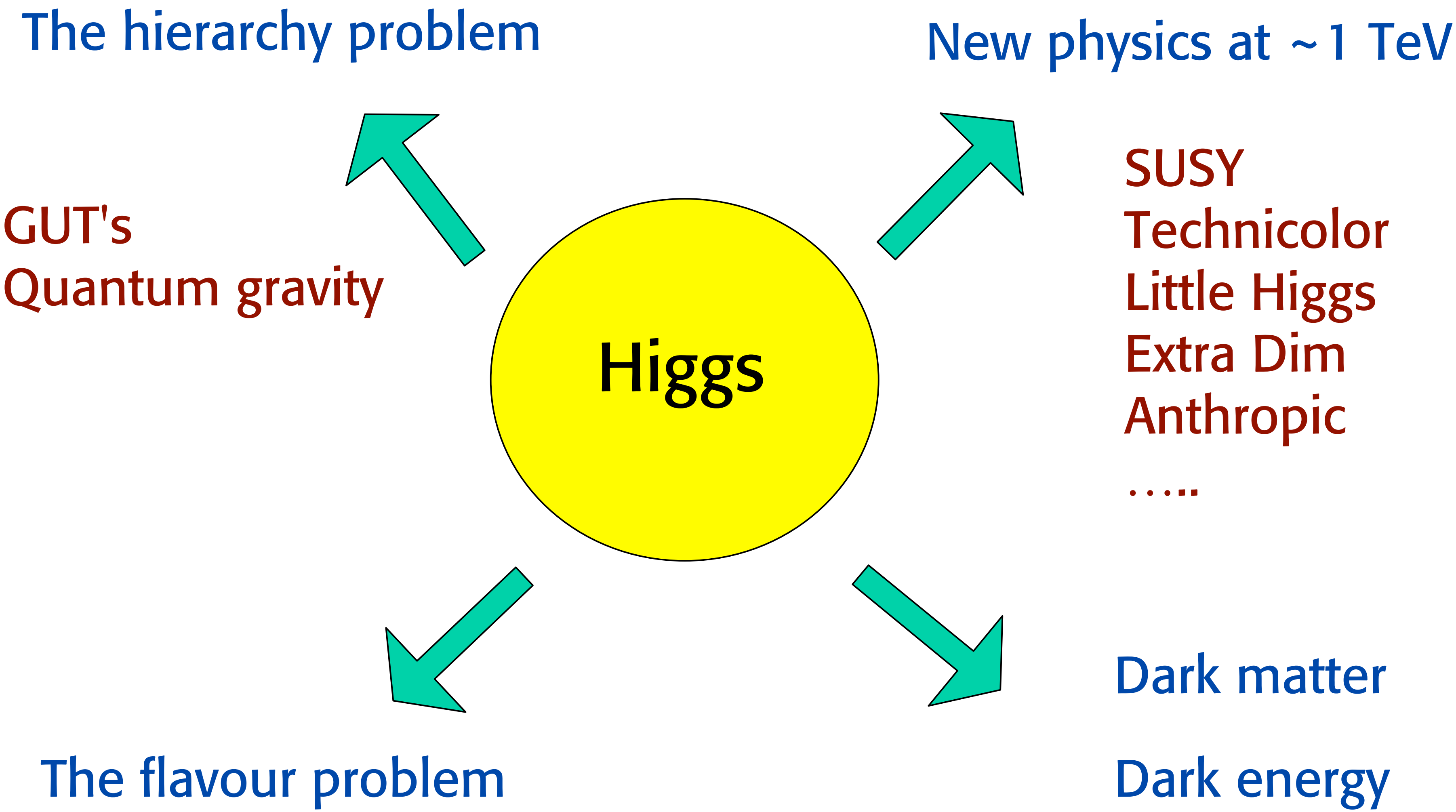
Physics top priorities at the LHC:

- Clarify the Higgs 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

The Higgs problem is central in particle physics today



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

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

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

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

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

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

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

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

All we know from experiment about the SM Higgs:

Rad. corr's -> $m_H < 207$ GeV (95%cl, incl. direct search bound)
but no Higgs seen -> $m_H > 114.4$ GeV (95%cl);

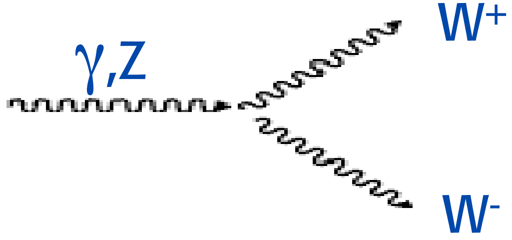
Only hint $m_W = m_Z \cos\theta_W$ ⟶ doublet Higgs

Experiments prove that all couplings are symmetric

Basic tree level relations: (accuracy few per mil)

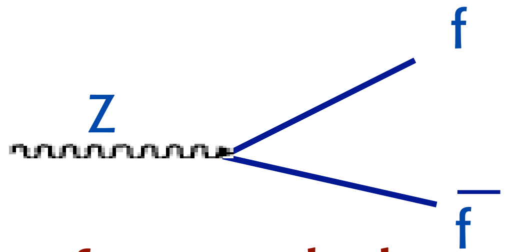
[All corrected by small, computable $f(m_t^2, \log m_H)$ radiative effects]

- $g \sin\theta_W = e$;
- $g'/g = tg\theta_W$;
- $\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2}$;
- $\frac{g_{WW\gamma}}{g_{WWZ}} = tg\theta_W$



- $\frac{g}{2\cos\theta_W}\bar{\psi}\gamma_\mu(g_V^f - g_A^f\gamma_5)\psi Z^\mu$

$$\begin{cases} g_A^f = \pm\frac{1}{2} \\ g_V^f/g_A^f = 1 - 4|Q^f|\sin^2\theta_W \end{cases}$$



f=u,c,t, d,s,b, e,μ, τ, ν's

Yet the symmetry is badly broken in the mass spectrum!

Gauge symmetry predicts: All gauge bosons, All fermions } Massless

But $m_W, m_Z >> 0$

$m_Z \sim M_{\text{molybdenum atom}} \sim$ 97 nucleons

In spectrum:
no remnant of even
global SU(2) symmetry!

Also, for example, $m_t \neq m_b \neq 0$ (175, 4.5 GeV)

Spontaneous symmetry breaking

Currents, charges symmetric. Spectrum totally non symmetric

SSB in gauge theories → Higgs mechanism

That some sort of Higgs mechanism is at work has already been established

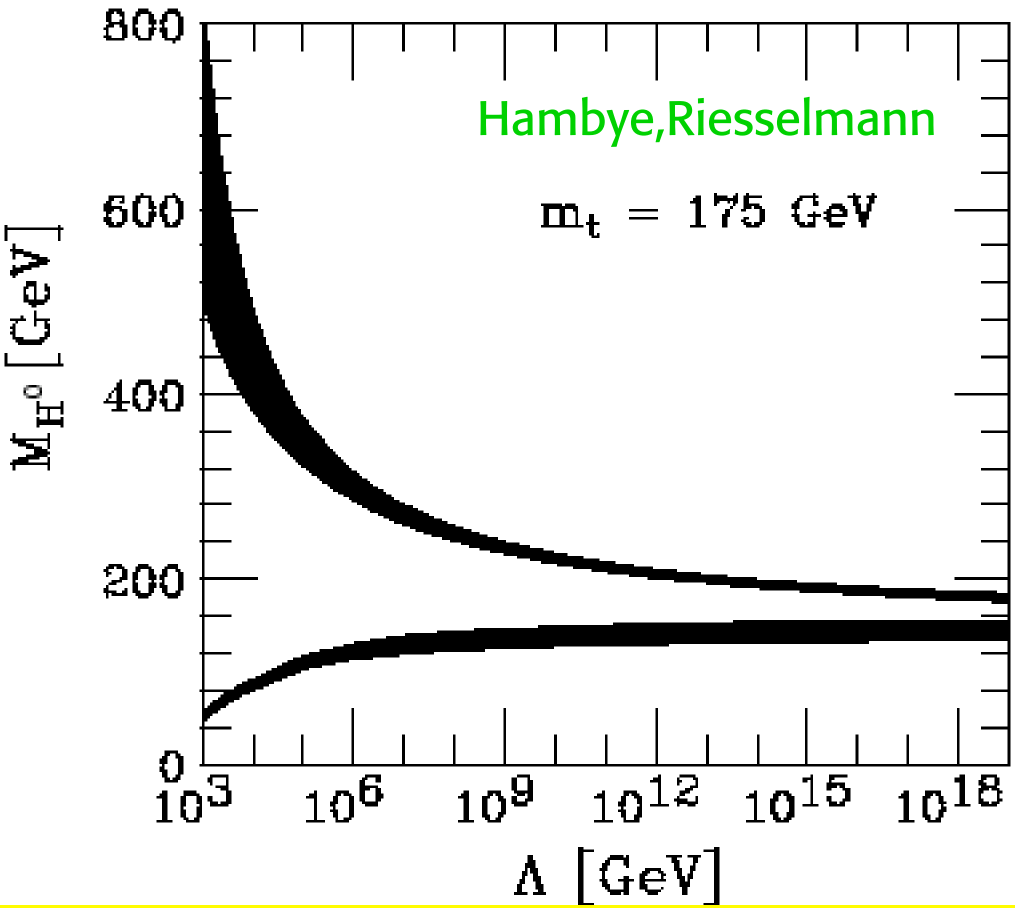
The questions are about the nature of the Higgs particle(s)

- 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 large extra dimensions (fifth comp. of a gauge boson, an effect of orbifolding or of boundary conditions....)
- Some combination of the above

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



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

Higgs potential

"Wrong" sign

Classic: $V[\phi] = -\mu^2\phi^2 + \lambda\phi^4$ $\mu^2>0$, $\lambda>0$

$$\phi \Rightarrow v + \frac{H}{\sqrt{2}} \quad \Rightarrow \quad v^2 = \frac{\mu^2}{2\lambda} = \frac{m_H^2}{4\lambda}$$

Quantum loops: $\lambda\phi^4 \Rightarrow \lambda\phi^4\left(1 + \gamma \ln\frac{\phi^2}{\Lambda^2} + \ldots\right) \xrightarrow{RG} \lambda(\Lambda)\phi'^4(\Lambda)$

(Ren. group improved pert. th)

$$\phi' = [\exp\int\gamma(t)dt]\phi$$

Running coupling

$t = \ln\Lambda/v$ h_t=top Yukawa

$$\frac{d\lambda(t)}{dt} = \beta_\lambda(t) = const[\lambda^2 + 3\lambda h_t^2 - 9h_t^4 + small]$$

Initial conditions (at Λ=v) $\lambda_0 = \frac{m_H^2}{4v^2}$ and $h_{0t} = \frac{m_t}{v}$

Running coupling $t = \ln\Lambda/v$ h_t=top Yukawa

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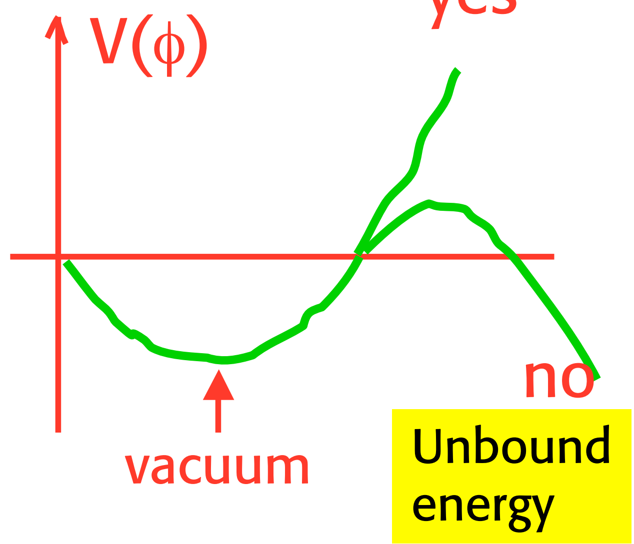
Initial conditions (at $\Lambda = v$) $\lambda_0 = \frac{m_H^2}{4v^2}$ and $h_{0t} = \frac{m_t}{v}$

Too small m_H? h_t wins, $\lambda(t)$ decreases. But $\lambda(t)$ must be >0 below Λ for the vacuum to be stable

⇒ $m_H \geq \sim 135$ GeV if $\Lambda \sim M_{GUT}$

(or at least metastable with lifetime $\tau > \tau_{Universe}$)

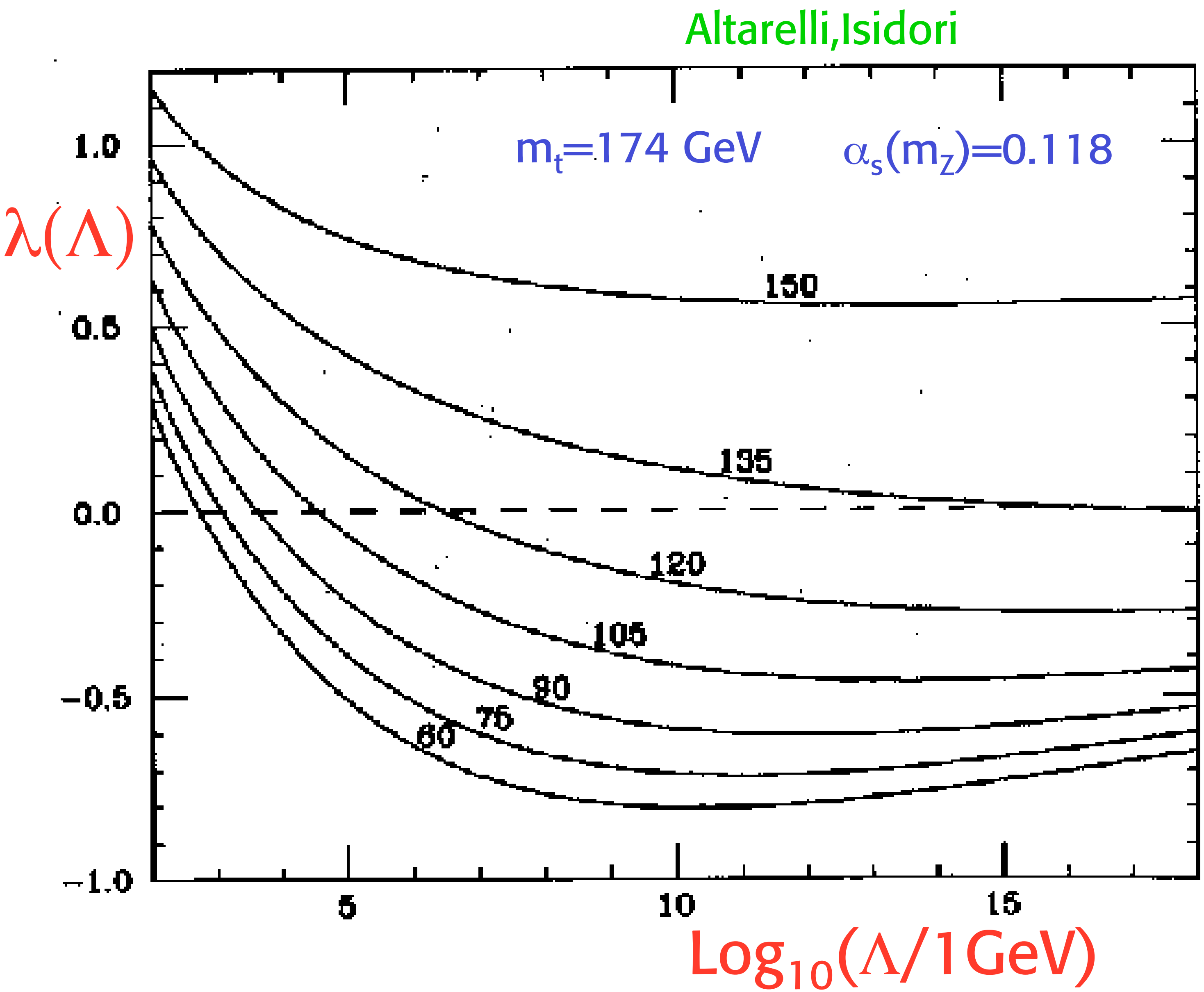


Cabibbo et al, Sher, Altarelli, Isidori

stability $$m_H(\text{GeV}) > 133 + 2.0\,[m_t(\text{GeV}) - (175 \pm 2)] - 1.6\left[\frac{\alpha_s(m_Z) - 0.118}{0.002}\right]$$

metastability $$m_H(\text{GeV}) > 117 + 2.9\,[m_t(\text{GeV}) - (175 \pm 2)] - 2.5\left[\frac{\alpha_s(m_Z) - 0.118}{0.002}\right]$$

Isidori, Ridolfi, Strumia



Altarelli,Isidori
m_t=174 GeV
$\alpha_s(m_Z)$=0.118
$\lambda(\Lambda)$
1.0
0.5
0.0
−0.5
−1.0
150
135
120
105
90
75
60
5
10
15
$Log_{10}(\Lambda/1GeV)$

Running coupling $t = \ln\Lambda/v$ h_t=top Yukawa

$$\frac{d\lambda(t)}{dt} = \beta_\lambda(t) = const[\lambda^2 + 3\lambda h_t^2 - 9h_t^4 + small]$$

b

Initial conditions (at Λ=v) $\lambda_0 = \frac{m_H^2}{4v^2}$ and $h_{0t} = \frac{m_t}{v}$

Too large m_H? λ^2 wins, $\lambda(t)$ increases.

$$\lambda(t) \sim \frac{\lambda_0}{1 - b\lambda_0 t}$$

Landau pole

The upper limit on m_H is obtained by requiring that no Landau pole occurs below Λ

$m_H \leq$ ~180 GeV if $\Lambda \sim M_{GUT}$
~ 600-800 GeV if $\Lambda \sim$ o(TeV)

Rather than a bound says where non pert effects are important

Caution: near the pole pert. theory inadequate.
Simulations on the lattice appear to confirm the bound
Kuti et al, Hasenfratz et al, Heller et al

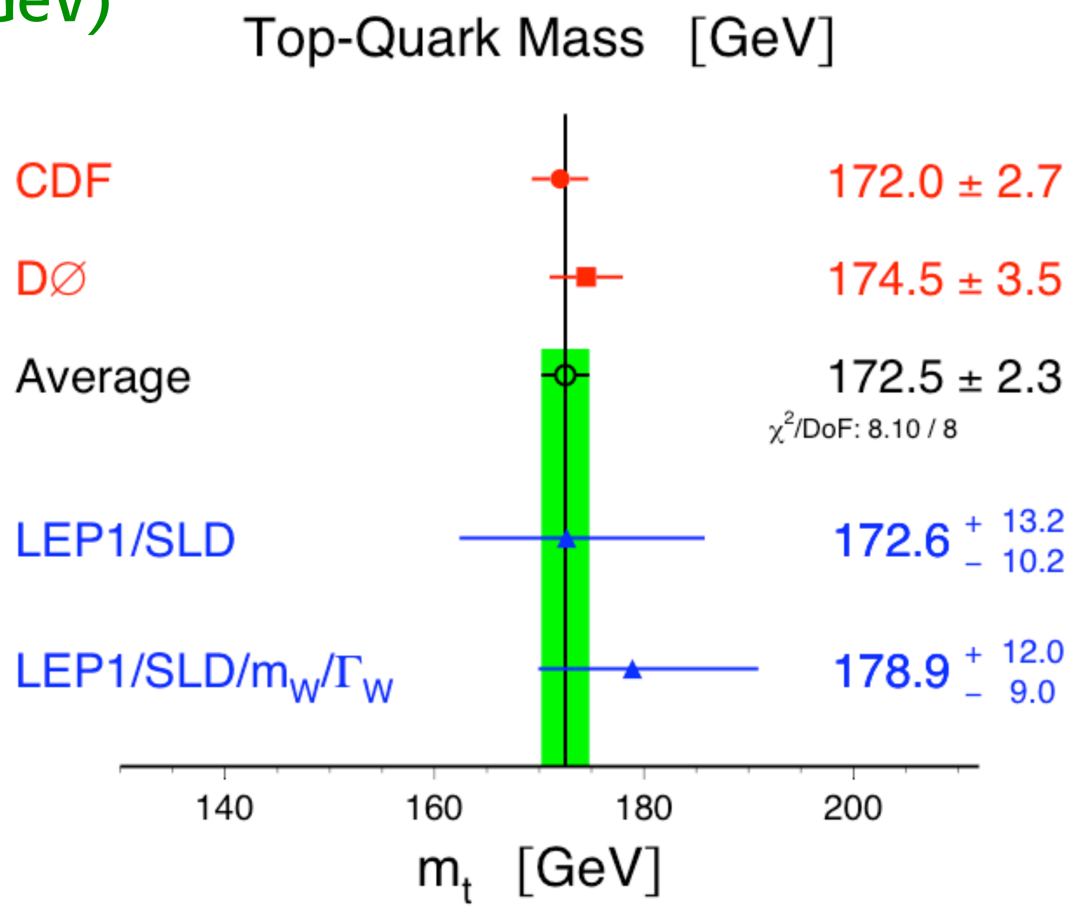
Precision Tests of SM

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 '06



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

m_t ⇓ m_H ⇓

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

The χ^2 is reasonable:

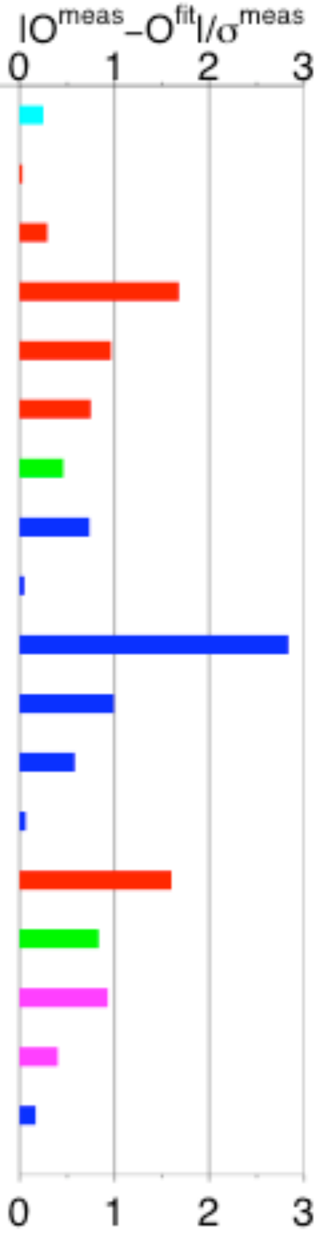
χ^2/ndof~17.5/13 (~17.7%)

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

a ~2.5σ deviation?

Winter 2006

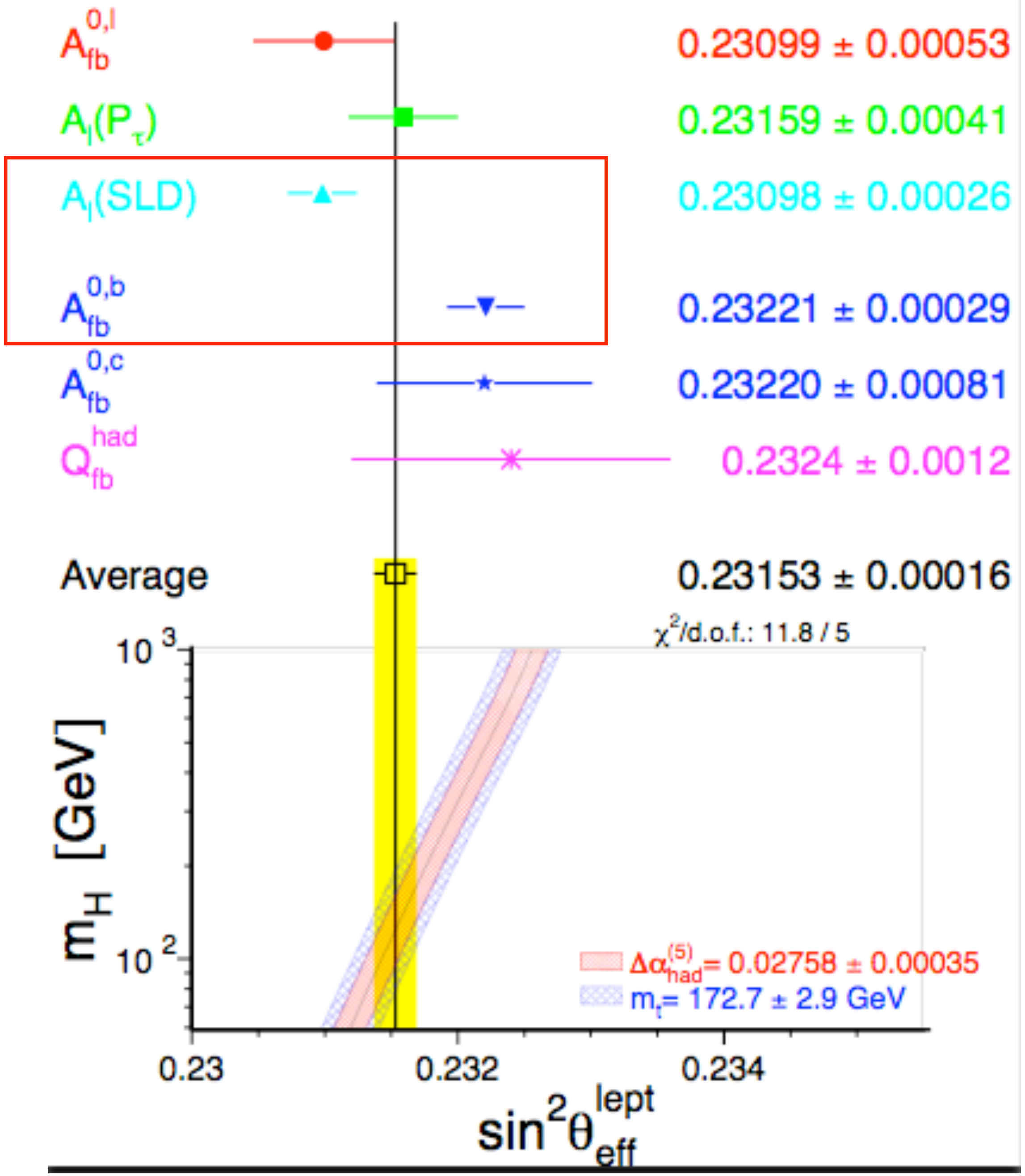
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
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	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.404 ± 0.030	80.376
Γ_W [GeV]	2.115 ± 0.058	2.092
m_t [GeV]	172.5 ± 2.3	172.9



$\sin^2\theta_W$

The two most precise measurements
do not really match!

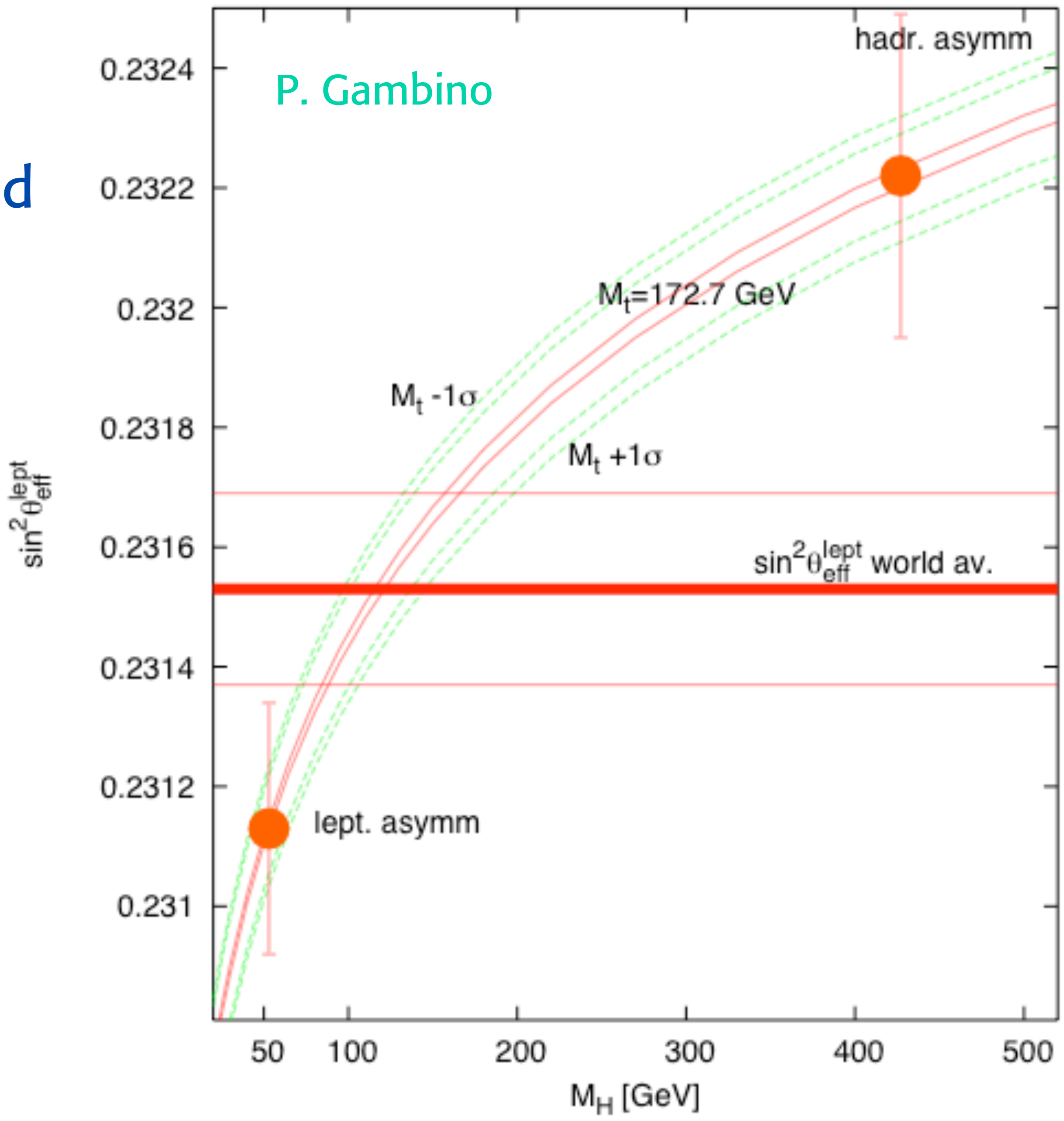
This unfortunate fact makes the interpretation of precision tests less sharp.



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



- The measured value of m_W is a bit high (given m_t)

(now came a little bit down from 80.420 -> 80.404)

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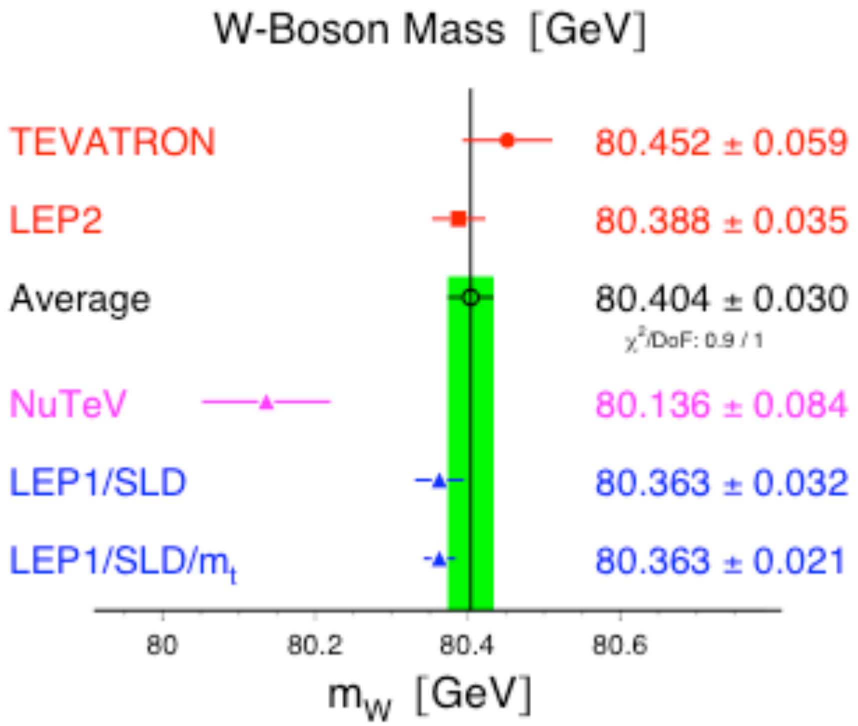
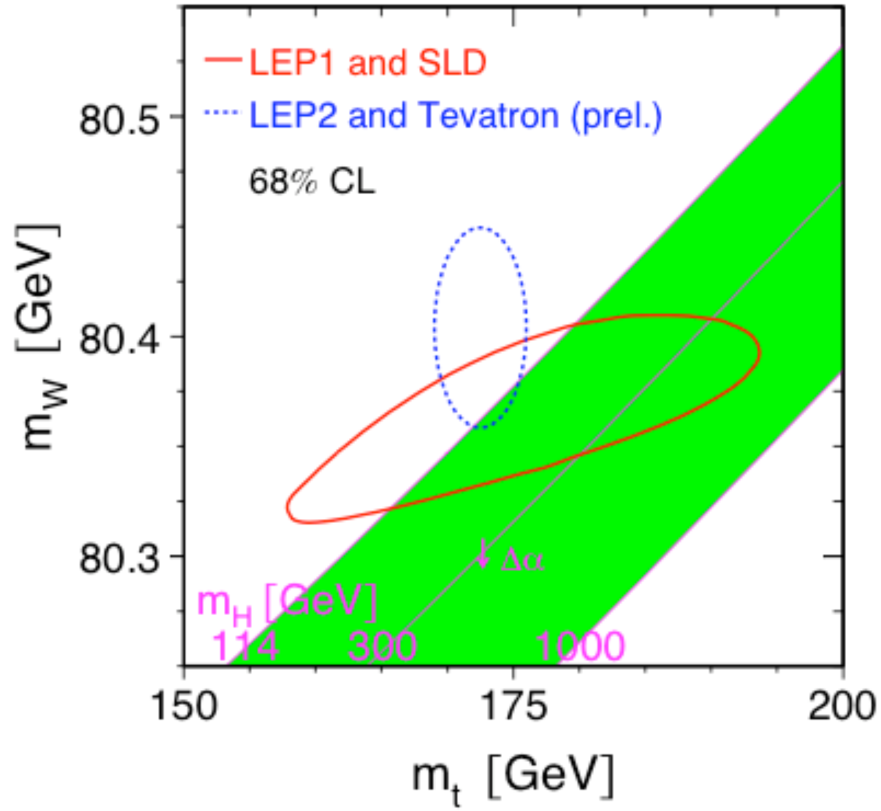
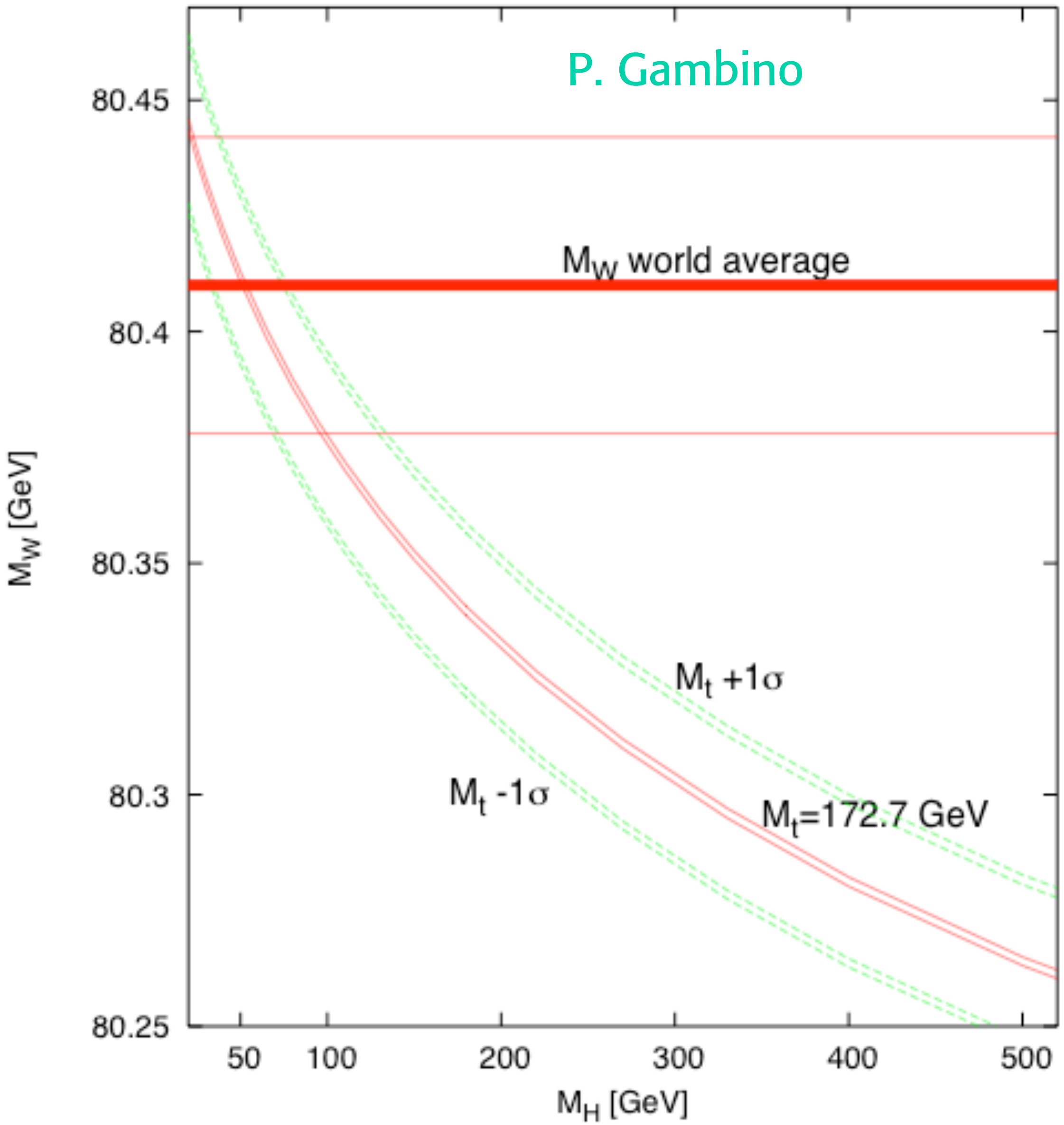




Plot m_W vs m_H

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

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	m_W	m_t	m_W, m_t
m_t(GeV)	178.9+12-9	172.5±2.3	172.9±2.2
m_H(GeV)	145+242-81	110+59-40	89+42-30
log[m_H(GeV)]	2.16±0.40	2.04 ± 0.19	1.95± 0.17
$\alpha_s(m_Z)$	0.1190(28)	0.1190 (27)	0.1186 (27)
χ^2/dof	17.1/12	16.0/11	17.5/13
m_W(MeV)	80385(21)	80363(21)	80376(16)

WA: m_W=80425(34)

Rad. corr.'s predict m_t and m_W very well. Probably also m_H!

Status of the SM Higgs fit

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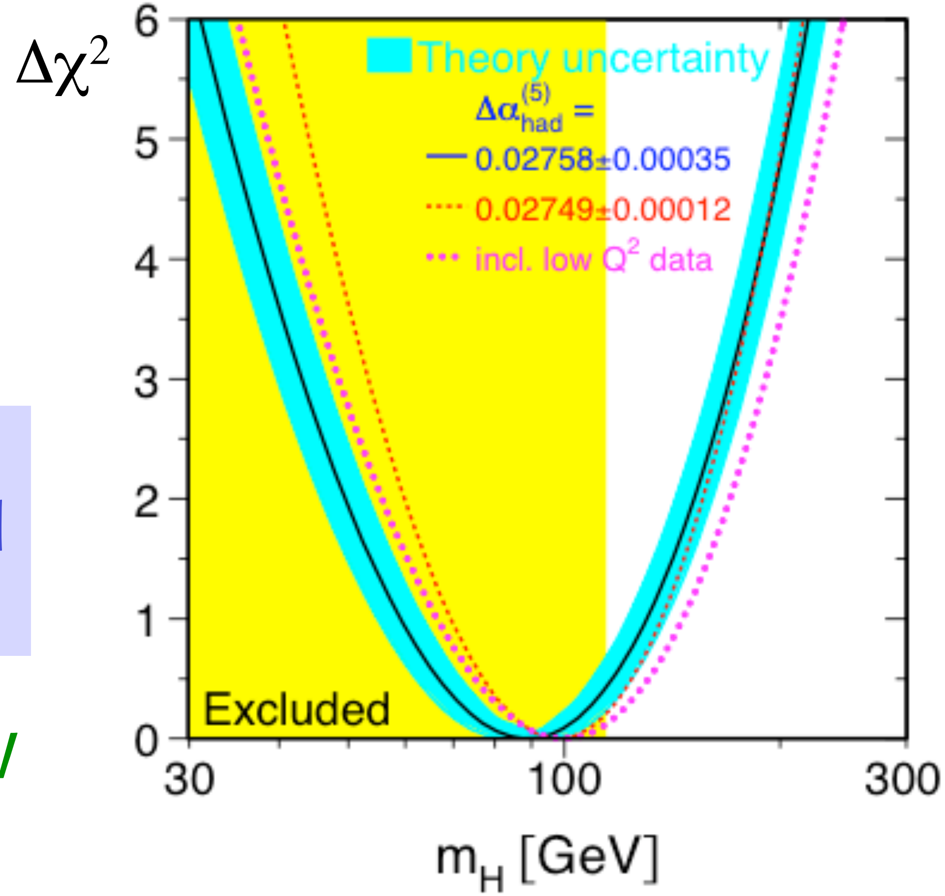
Rad Corr.s -> ← Sensitive to log m_H

$\log_{10} m_H(\text{GeV}) = 1.95 \pm 0.18$

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

Direct search: $m_H > 114.4$ GeV



At 95% cl

$m_H < 175$ GeV (rad corr.'s)

$m_H < 207$ GeV (incl. direct search bound)

$\log_{10} m_H \sim 2$ is a very important result!!

Drop H from SM -> renorm. lost -> divergences -> cut-off Λ

$$\log m_H \rightarrow \log\Lambda + \text{const}$$

Any alternative mechanism amounts to identify the physics of Λ and the prediction of finite terms.

The most sensitive to $\log m_H$ are $\varepsilon_1 \sim \Delta\rho$ and ε_3 (or T&S):

$\log_{10} m_H \sim 2$ means that $f_{1,3}$ are compatible with the SM prediction

$$\varepsilon_1 = -\underbrace{\frac{3 G_F m_W^2}{4\pi^2\sqrt{2}}}_{-1.2\ 10^{-3}} \mathrm{tg}^2\theta_W \left[\log\frac{m_H}{m_Z} + f_1\right]$$

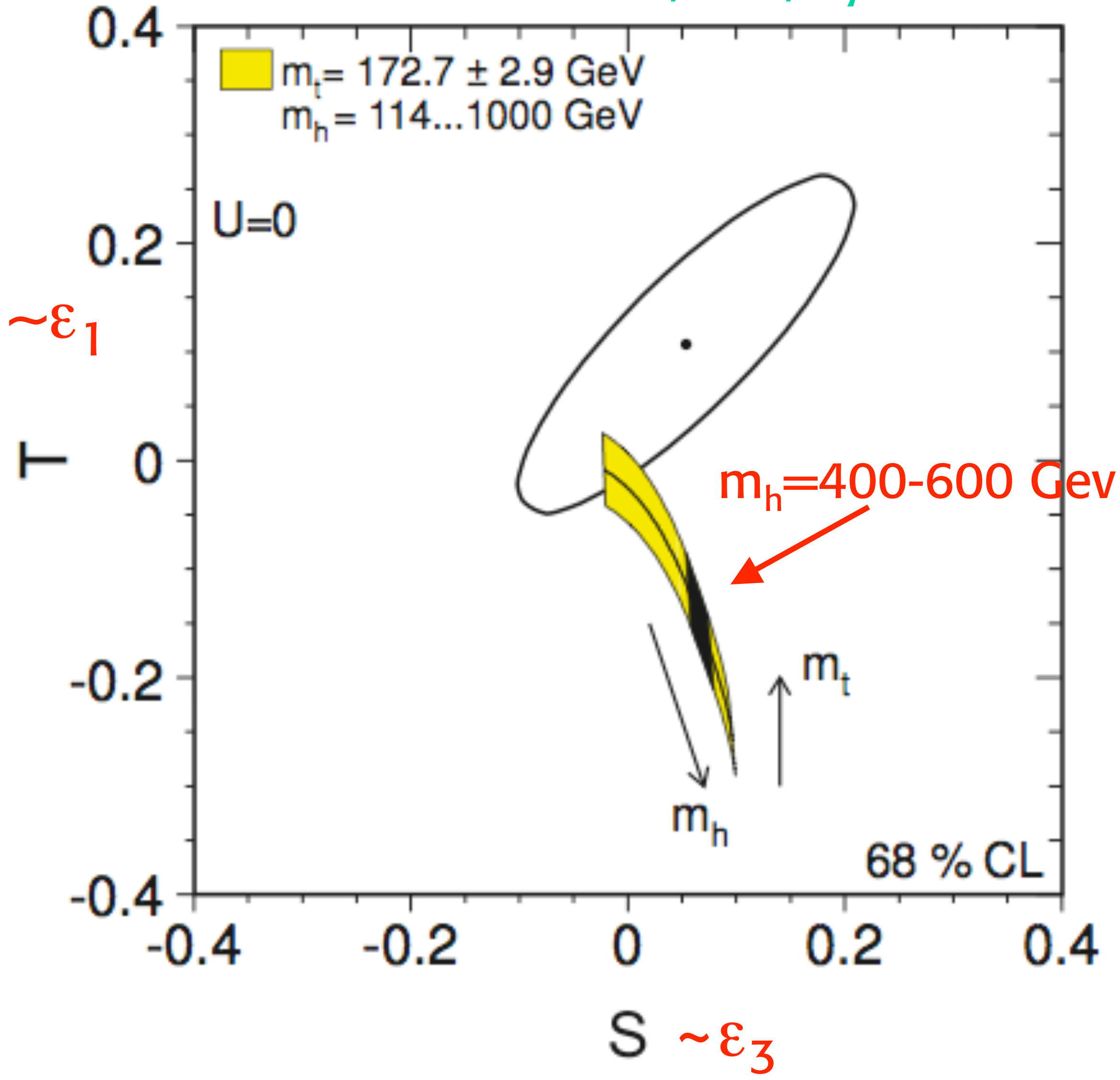
$$\varepsilon_3 = \underbrace{\frac{G_F m_W^2}{12\pi^2\sqrt{2}}}_{0.45\ 10^{-3}} \left[\log\frac{m_H}{m_Z} + f_3\right]$$

New physics can change the bound on m_H (different $f_{1,2}$): well possible!

Some conspiracy is needed to simulate a light Higgs

Barbieri, Hall, Rychkov

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



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

Looks pretty unlikely!!

The LHC 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 perfect 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
- •••••

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

Conceptual problems of the SM

Most clearly:

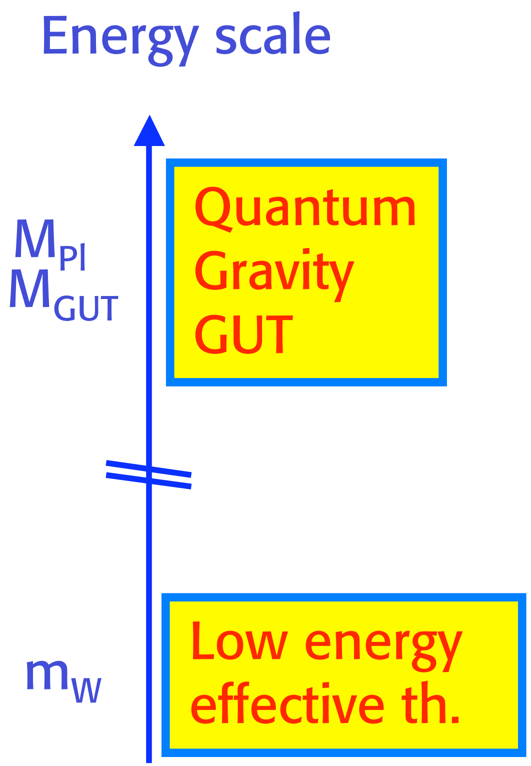
- No quantum gravity (M_{Pl} ~ 10^{19} GeV)
- But a direct extrapolation of the SM leads directly to GUT's (M_{GUT} ~ 10^{16} GeV)

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!



The hierarchy problem

Assume:

- A TOE at $\Lambda \sim M_{GUT} \sim M_{Pl}$
- A low en. th at o(TeV)
- A "desert" in between

The low en. th must be renormalisable as a necessary condition for insensitivity to physics at Λ.

[the cutoff can be seen as a parametrisation of our ignorance of physics at Λ]

But, as Λ is so large, in addition the dep. of ren. masses and couplings on Λ must be reasonable:
e.g. a mass of order m_W cannot be linear in Λ if $\Lambda \sim M_{GUT}, M_{Pl}$.

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

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

$$\mathcal{L} = o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4 \quad + o(1/\Lambda)\mathcal{L}_5 + o(1/\Lambda^2)\mathcal{L}_6 + \ldots$$

Renorm.ble part — 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 $\bar{\psi}\psi$. Protected by chiral symmetry and SU(2)xU(1): $\Lambda \to m\log\Lambda$

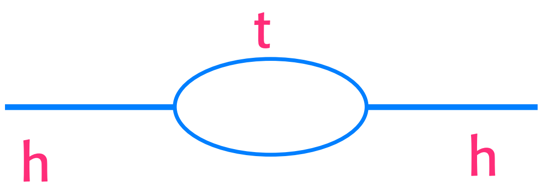
$\mathcal{L}_4$: Renorm.ble interactions, e.g. $\bar{\psi}\gamma^\mu\psi A_\mu$

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

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 are not directly visible

An additional "inert" Higgs doublet could somewhat ease the problem (Barbieri, Hall, Rychkov)

Precision Flavour Physics

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

- Light Higgs -> New physics at ~ 1 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

New CDF&D0 results on Δm_s

Gomez-Ceballos

B^0/B_s^0 mix through box diagram:

$$\Delta m_q \propto m_{B_q} \hat{B}_{B_q} f_{B_q}^2 \left| V_{tb} V_{tq}^* \right|^2$$

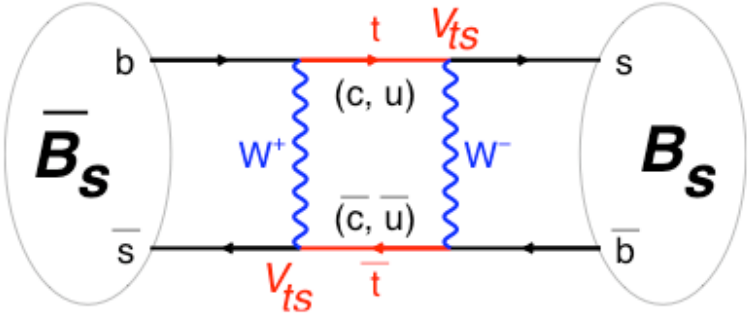
$$q = s, d$$

Uncertainties cancel in ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

with $\xi = 1.21 \,^{+0.047}_{-0.035}$

(Okamoto, Lattice 2005)



CDF: $\Delta m_s = 17.33^{+0.42}_{-0.21}(stat.) \pm 0.07(syst.) ps^{-1}$

$$|V_{td}|/|V_{ts}| = 0.208 \,^{+0.008}_{-0.007}$$

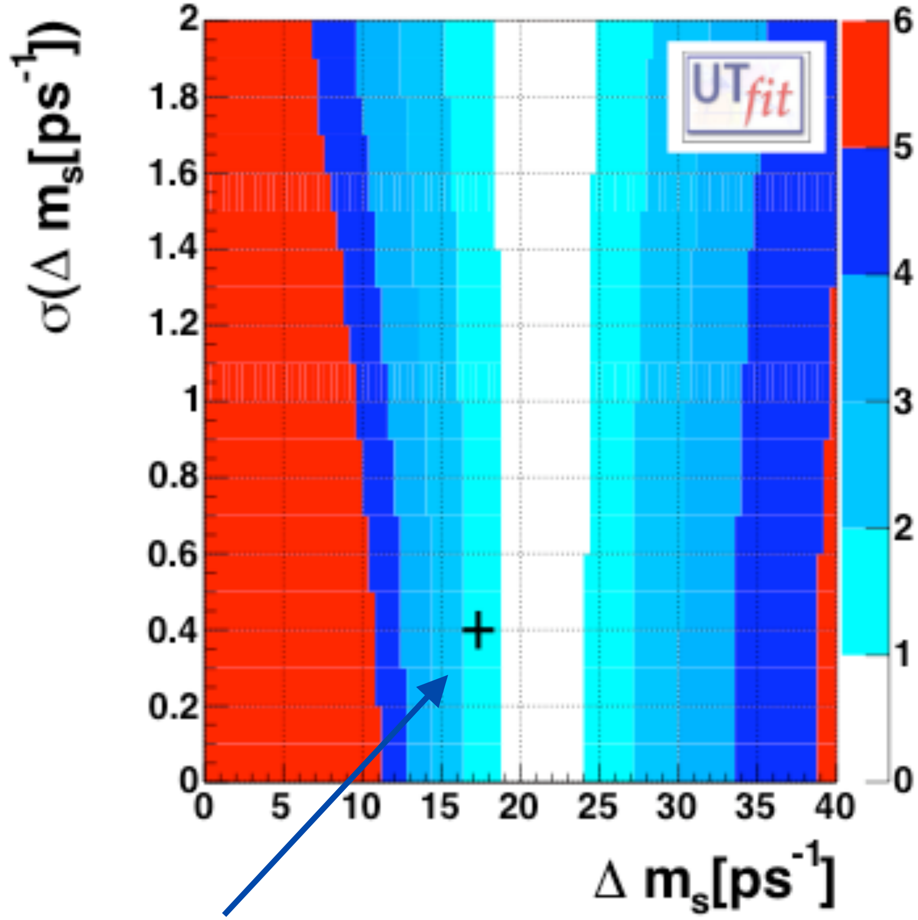
D0: $\Delta m_s = 17\text{-}21\ ps^{-1}$ at 90%

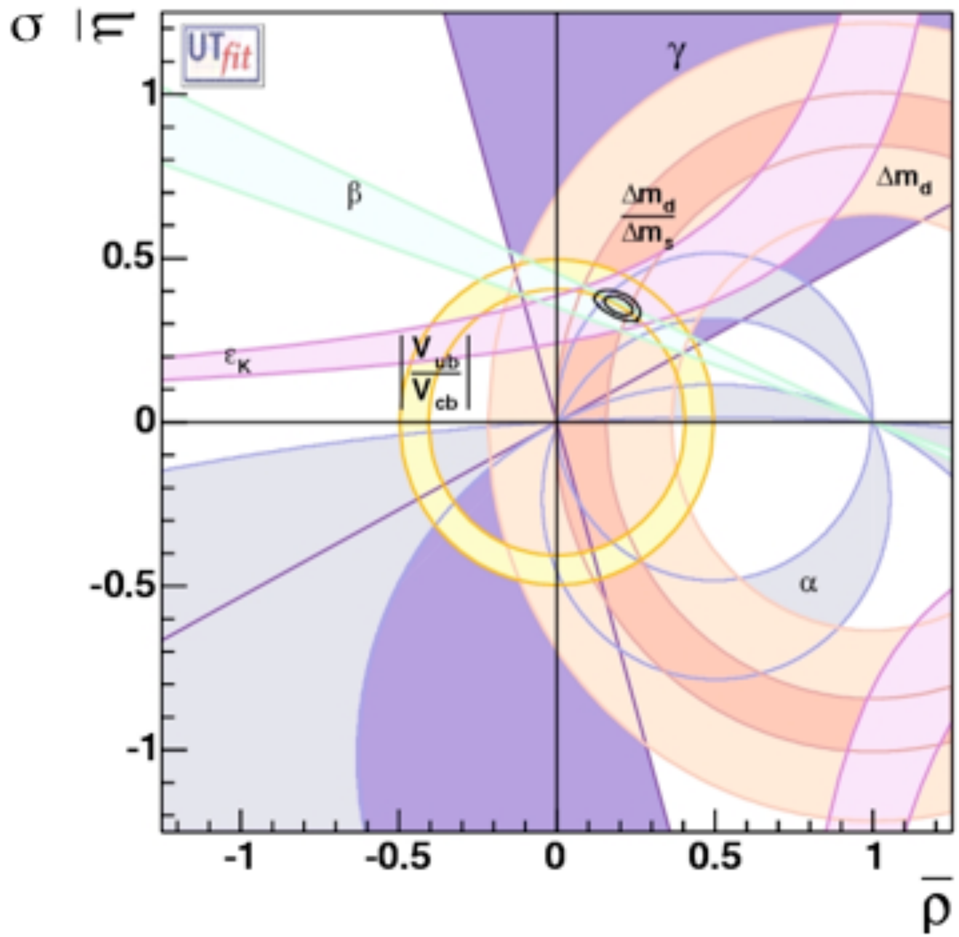
CKM fits (excluding Δm_s) $18.3+6.5-1.5\ ps^{-1}$ CKM fitter

$21.5 \pm 2.6\ ps^{-1}$ UTfit

$$|V_{td}/V_{ts}| = \lambda\sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}$$

(recall: $V_{ts} = -A\lambda^2$)





+ -> 17.35±0.25 combined

Recently α & γ measured compatible with the tip of the UT

B-factories, CDF, D0..... have severely tested the CKM picture (in the particularly dangerous 3rd generation sector).

The CKM picture is confirmed as the main source of CPV

$$H_{NP} < 20\% \; H_{SM}$$

This poses strong constraints for models BSM

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.

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  exact (unrealistic): cancellation of $\delta\mu^2$

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

- Large 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

Back to the "little" hierarchy problem:

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

In broken SUSY Λ^2 is replaced by $m_{stop}^2 - m_t^2$

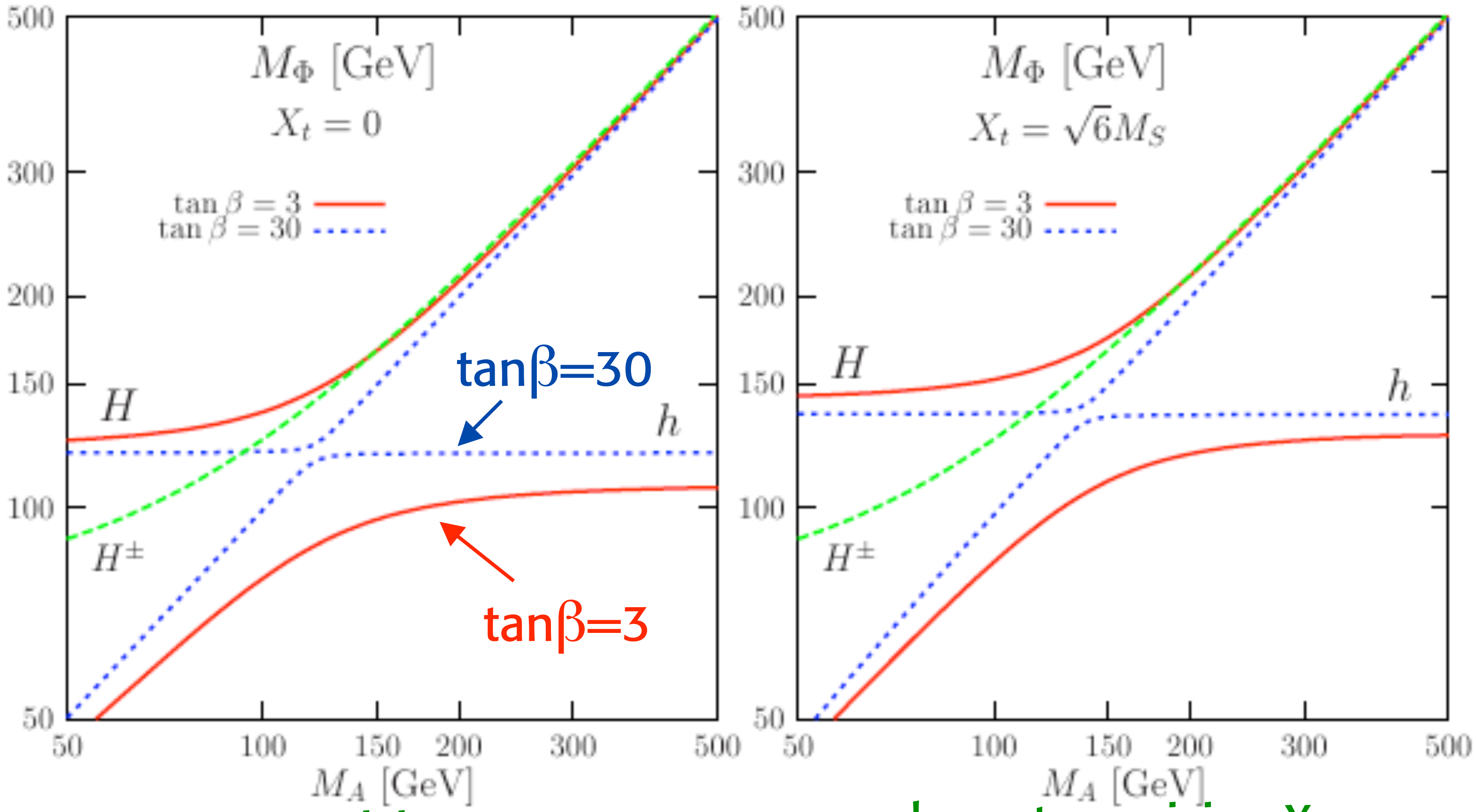
$m_H > 114.4$ GeV, $m_{\chi+} > 100$ GeV, EW precision tests, success of CKM, absence of FCNC, all together, impose sizable Fine Tuning (FT) on minimal realizations (MSSM, CMSSM…).

Still 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 (actually more than one).

Remains the reference model for NP

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

Djouadi



no top mixing: X_t=0

large top mixing X_t

m_t = 178 GeV (conservative: smaller m_t, smaller m_{hmax})

$m_h < \sim 135$ GeV

But: Lack of SUSY signals at LEP + lower limit on m_H
→ problems for minimal SUSY

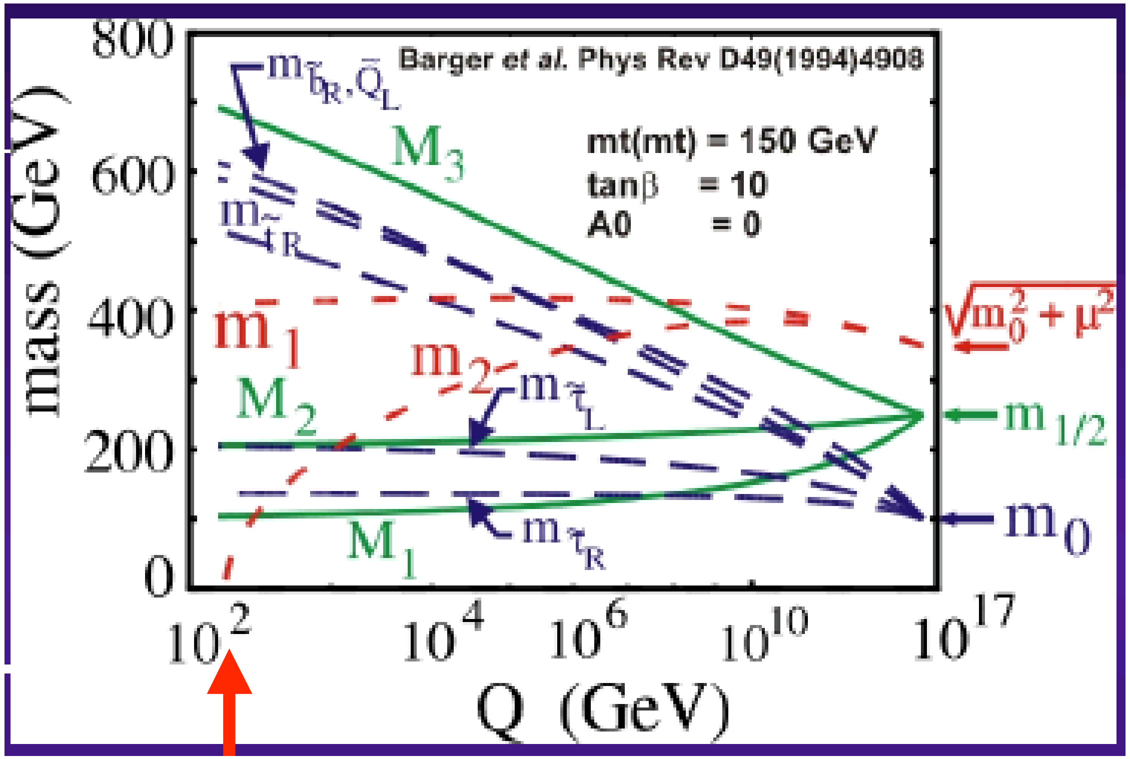
- In MSSM: $$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3\alpha_w m_t^4}{4\pi m_W^2 \sin^2\beta} \ln \frac{\tilde{m}_t^4}{m_t^4} < \sim 130 \text{ GeV}$$

So $m_H > 114$ GeV considerably reduces available parameter space.

m_{stop} large tends to clash with $\delta m_h^2 \sim m_{stop}^2$

- In SUSY EW symm. breaking is induced by H_u running

Exact location implies constraints →



m_Z can be expressed in terms of SUSY parameters

For example, assuming universal masses at M_{GUT} for scalars and for gauginos

$$m_Z^2 \approx c_{1/2} m_{1/2}^2 + c_0 m_0^2 + c_t A_t^2 + c_\mu \mu^2$$

$c_a = c_a(m_t, \alpha_i, \ldots)$

Clearly if $m_{1/2}, m_0, \ldots >> m_Z$: Fine tuning!

LEP results (e.g. $m_{\chi+}$ >~100 GeV) exclude gaugino universality if no FT by > ~20 times is allowed

Without gaugino univ. the constraint only remains on m_{gluino} and is not incompatible

$$m_Z^2 \approx 0.7 m_{gluino}^2 + \ldots$$

Barbieri, Giudice; de Carlos, Casas; Barbieri, Strumia; Kane, King; Kane, Lykken, Nelson, Wang......

[Exp. : m_{gluino} >~200GeV]

Residual FT could be considerably reduced by going to a non minimal model e.g adding an extra Higgs singlet (NMSSM)

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 particle with m ~ 10^1-10^3 GeV

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

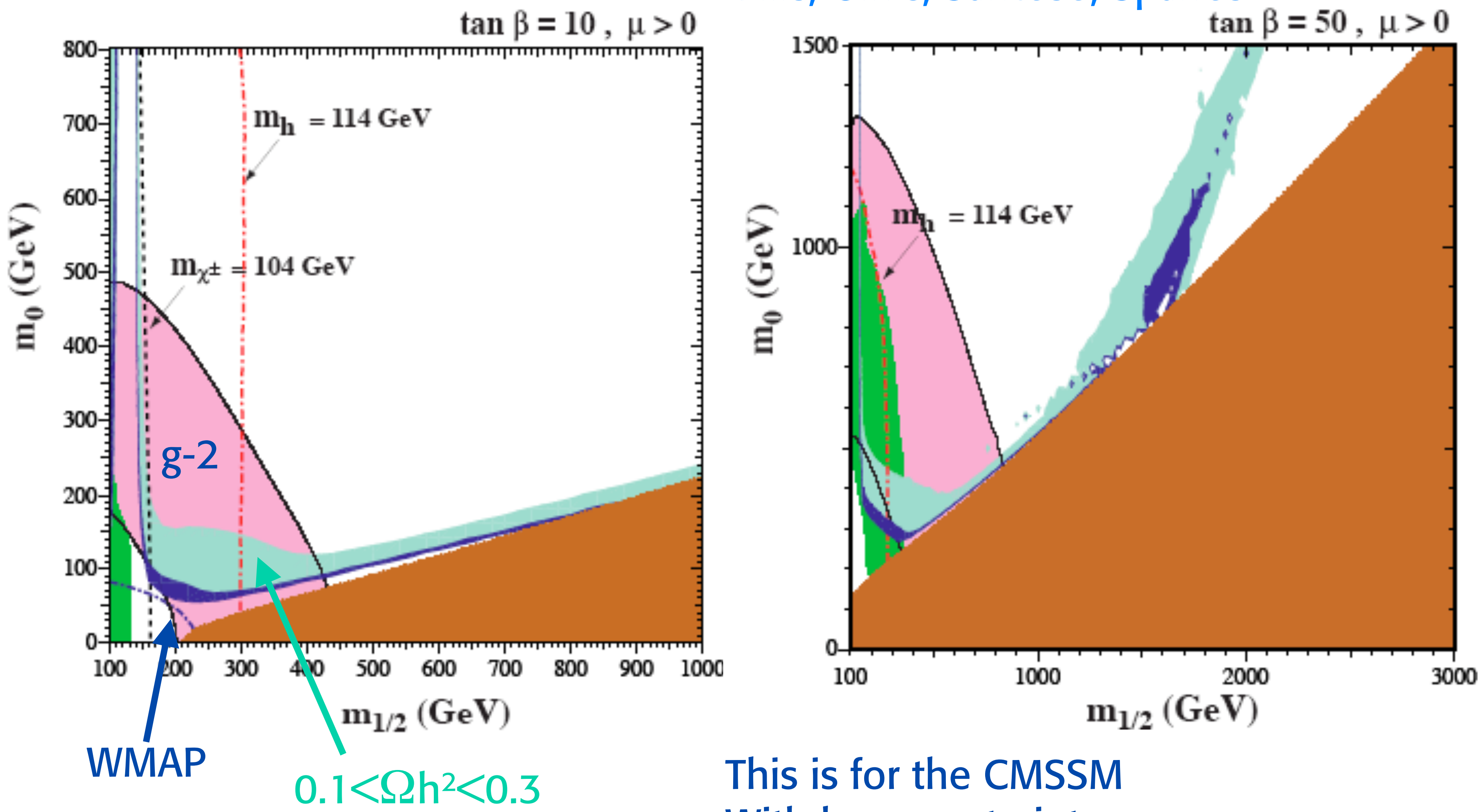
$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle}$$

can work for typical weak cross-sections!!!

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

SUSY Dark Matter: we hope it is the neutralino

Ellis, Olive, Santoso, Spanos



This is for the CMSSM
With less constraints, more space

No signals of SUSY sofar (not in EW tests, not in flavour)-->
--> fine tuning is needed at the level of a few percent

Possibly some tricks could help:

- Only 3rd generation spartners light
- A more complicated Higgs sector (NMSSM)
- ....

But a new wave of model building was started

Sofar no model has emerged which needs less fine tuning than SUSY.
The need of fine tuning appears to be imposed on us by the data!

Pessimist views:
If you must tolerate % fine tuning, why not $^0/_{00}$ and we see no new physics at the LHC? Even worse:
perhaps naturalness not a good criterium --> anthropic

Principles tried to ensure a light Higgs:

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

Little Higgs

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

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

Extra dimensions

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)

cut off Λ ~10 TeV

Λ^2 divergences canceled by:

$\delta m^2_{H\|top}$	new coloured fermion χ with Q=2/3	~1 TeV
$\delta m^2_{H\|gauge}$	W', Z', γ'	
$\delta m^2_{H\|Higgs}$	new scalars	
	2 Higgs doublets	~0.2 TeV

E-W Precision Tests? Problems. Needs epicycles: T-parity, mirror fermions…. Cheng, Low

Just a postponement: UV completion? GUT's?

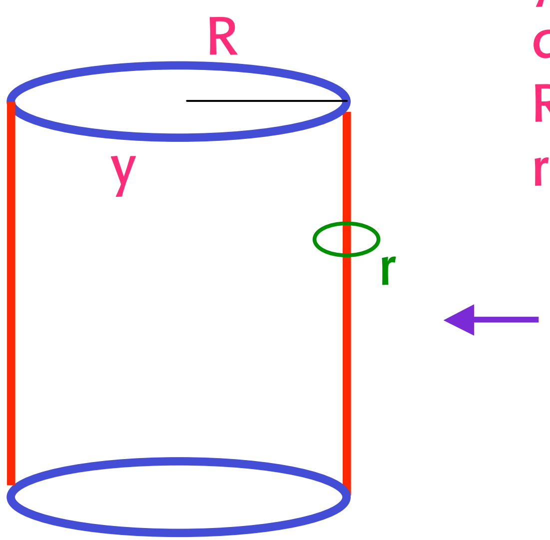
Large Extra Dimensions

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

Arkani-Hamed, Dimopoulos/ Dvali+Antoniadis/ Randall,Sundrun…..

Inspired by string theory, one assumes:

- Large compactified extra dimensions (either flat or warped)
- 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:
compact dim. → Kaluza-Klein (KK) modes

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

Many possibilities:

- SM fields on a brane

The brane can itself have a thickness r:
$1/r >\sim 1\,\text{TeV}$ → $r <\sim 10^{-17}$ cm

→ KK recurrences of SM fields: W_n, Z_n etc

cfr: • Gravity on bulk
$1/R >\sim 10^{-3}$ eV → $R <\sim 0.1$ 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 →

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

↪ $m = M_{Pl} \exp(-2mR\pi)$ → $Rm \sim 10$

- Large Extra Dimensions is a very 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)?

    R-S best in this respect

    Goldberger,Wise

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

$$m = M_{Pl} \exp(-2mR\pi) \quad \text{warped}$$

  * $\Lambda \sim 1/R$ 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

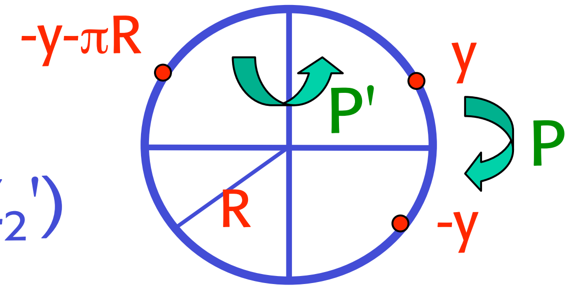
- But could be part of the truth!

- Interesting directions explored

Symmetry breaking by orbifolding

An example: for $1/R \sim M_{GUT}$

$S/(Z_2 x Z_2')$



GUT's in ED: very appealing

SUSY-SU(5), -SO(10) in 5 or 6 dimensions

Kawamura/GA, Feruglio/ Hall, Nomura;
Hebecker, March-Russell;
Hall, March-Russell, Okui, Smith
Asaka, Buchmuller, Covi
....

Z_2-> P: y ⇔ -y

Z_2'-> P': y' ⇔ -y'

$y' = y + \pi R/2$

or y ⇔ -y- πR

- No baroque Higgs system
- Natural doublet-triplet splitting
- Coupling unification can be maintained

• • • •

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

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

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

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

P breaks N=2 SUSY down to N=1 SUSY
but conserves SU(5): on 5 of SU(5) P=(+,+,+,+,+)

P' breaks SU(5) P'=(-,-,-,+,+) $P'T^aP'=T^a$, $P'T^\alpha P'= -T^\alpha$
(T^a: span 3x2x1, T^α : all other SU(5) gen.'s)

P P'	bulk field		mass
++	$A^a_\mu, \lambda^a_2, H^D_u, H^D_d$	← Doublet	2n/R
+ -	$A^\alpha_\mu, \lambda^\alpha_2, H^T_u, H^T_d$	← Triplet	(2n+1)/R
- +	$A^\alpha_5, \Sigma^\alpha, \lambda^\alpha_1, H'^T_u, H'^T_d$		(2n+1)/R
- -	$A^a_5, \Sigma^a, \lambda^a_1, H'^D_u, H'^D_d$		(2n+2)/R

Note: $\partial_5 = (-,-)$

Gauge parameters are also y dep.

$$U = \exp[i\xi^a(x_\mu, y)T^a + i\xi^\alpha(x_\mu, y)T^\alpha]$$

$$\xi^a(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum \xi^a(x_\mu)\cos\frac{2ny}{R}$$

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

} both≠not zero at y=0

$$U = \exp[i\xi^a(x_\mu, y)T^a + i\xi^\alpha(x_\mu, y)T^\alpha]$$

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

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

At y=0 both ξ^a and ξ^α not 0: so full SU(5) gauge transf.s, while at y=πR/2 only SU(3)xSU(2)xU(1).

Virtues:

- No baroque 24 Higgs to break SU(5)
- $A^{a(0)}_\mu$, $\lambda^{a(0)}_2$ massless N=1 multiplet
- $A^{a(2n)}_\mu$ eat $\partial_5 A^{a(2n)}_5$ and become massive (n>0)
- Doublet-Triplet splitting automatic and natural:
  $H^{D(0)}_{u,d}$ massless, $H^{T(0)}_{u,d}$ m~1/R~m_{GUT}
- Proton decay can be suppressed or forbidden.

Symmetry breaking at the weak scale

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

- SUSY Breaking

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

5D SUSY-SM compactified on $S/(Z_2\text{-}Z_2')$

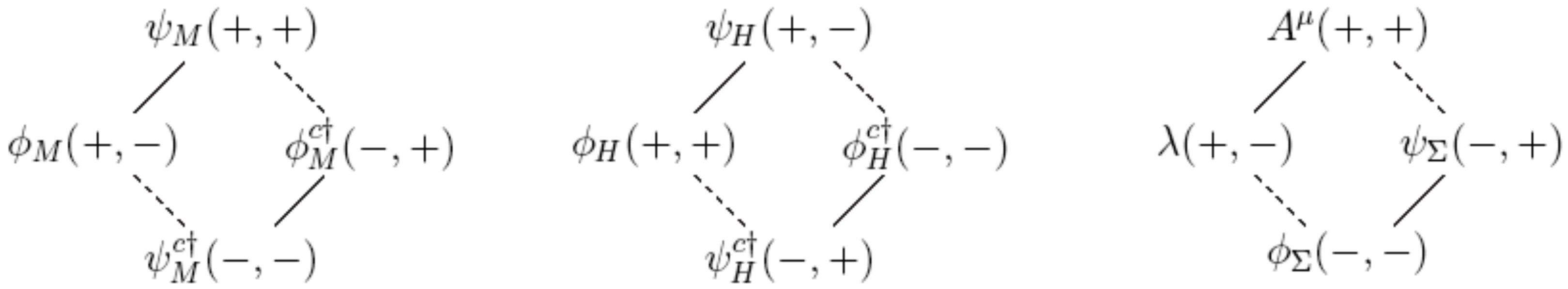
•Z breaks N=2 SUSY, Z′ N=1 SUSY (Scherk-Schwarz)

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

- Higgs boson mass in principle computable

no invariant Higgs mass operator in 5-dim

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



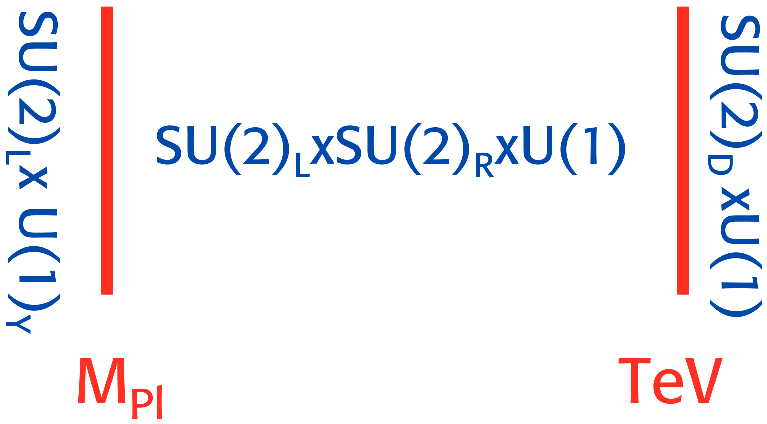
matter Higgs (only 1!) gauge

all are in the bulk

• 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



Warped R-S background

Symmetries broken by Boundary Conditions (BC) on the branes

Altogether only $U(1)_Q$ unbroken

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

y-Boundary Conditions

A scalar example

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

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

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

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

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

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

$V^{ab} = v t^a t^b v$ can arise from a Higgs H localised on the brane: $D_M H D^M H$, $D_M = \ldots + t^a A_M^a$, $\langle H \rangle = v$

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

We set: $A = A_0 \cos My$

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

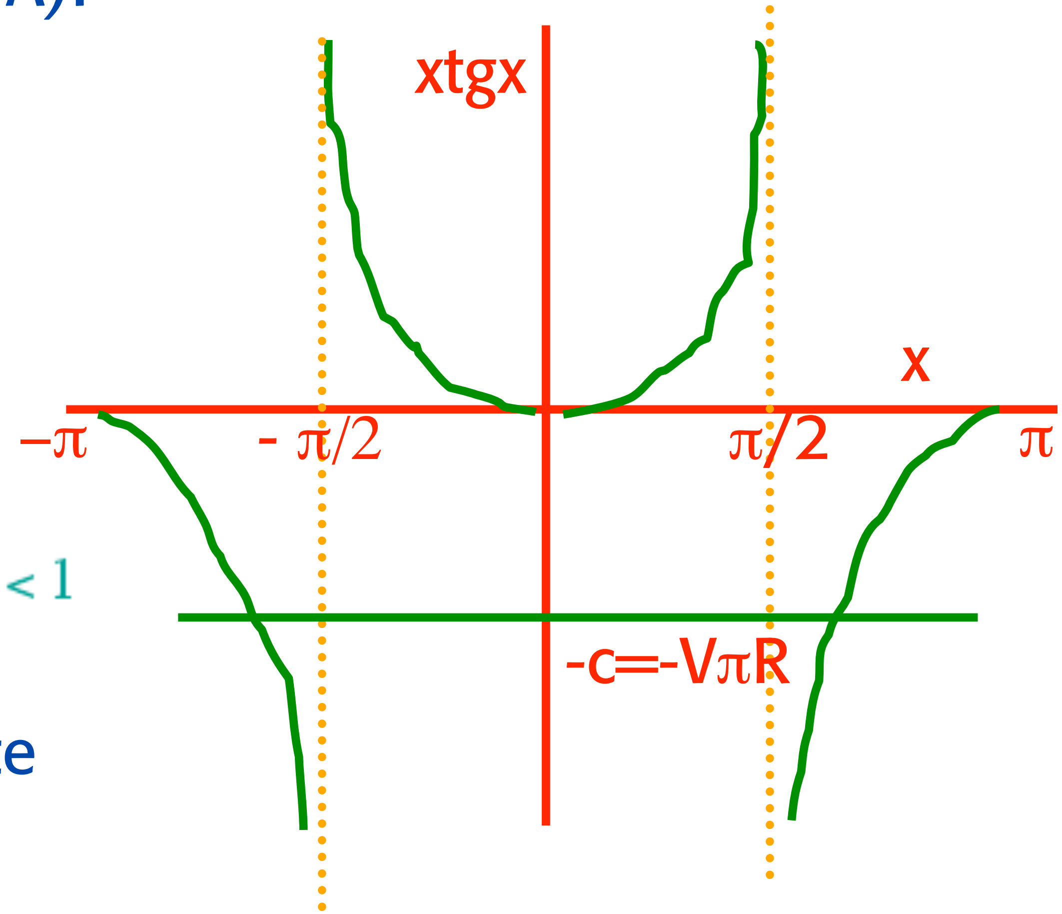
We find M (mass of boson A):

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

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

$$x\,tgx = -c$$

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



Note that MR remains finite
for V-> infinity

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 restaured 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

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

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

Boundary conditions allow a general breaking pattern
(for example, can lower the rank of the group)
equivalent to have generic Higgses on the brane

Breaking by orbifolding is more rigid
(the rank remains fixed)
corresponds to Higgs in the adjoint (A_5 the 5th A_M)

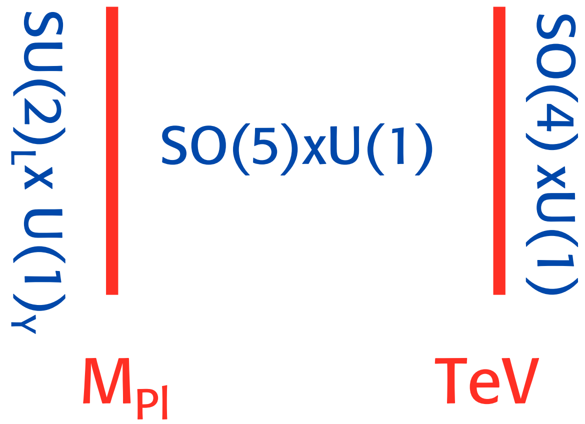
No convincing, realistic Higgsless model for EW symmetry breaking emerged so far:

Serious problems with EW precision tests
e.g. Barbieri, Pomarol, Rattazzi,Strumia, Chivukula et al
also with Z->bb
Substantial fine tuning required

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



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

Warped R-S background

As in Little Higgs models

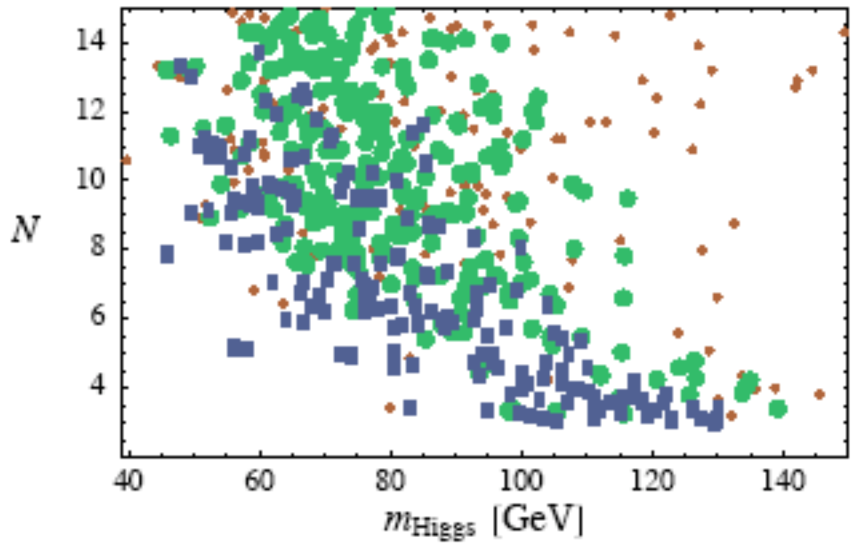
The Higgs is a PGB and EW symmetry breaking is triggered by top-loop effects. In 4-dim the bulk appears as a strong sector

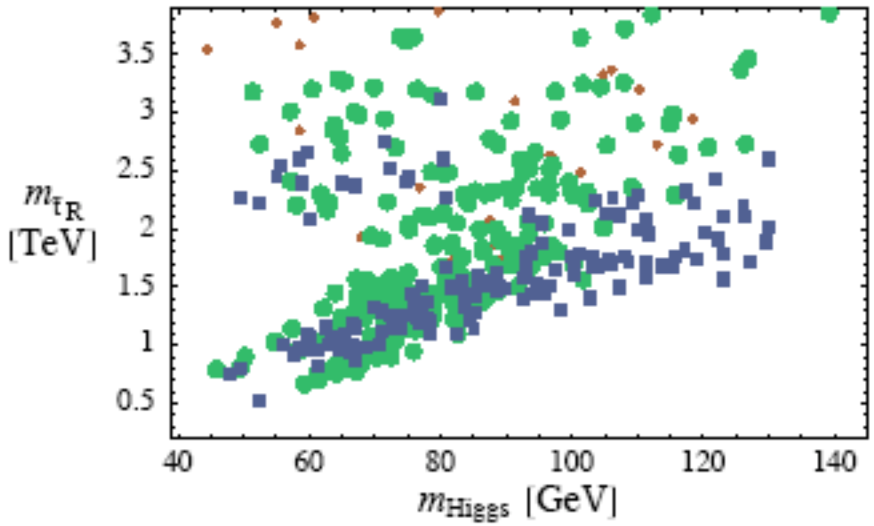
The 5-dim theory is weakly coupled so that the Higgs potential and EW observables can be computed

The Higgs is light: $m_H < 140$ GeV

The Higgs is (too?) light
in this model

Problems with EW precision
tests and Zbb





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

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

The anthropic route: is naturalness relevant?

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: $\rho_\Lambda \sim (\Lambda_{cutoff})^4$

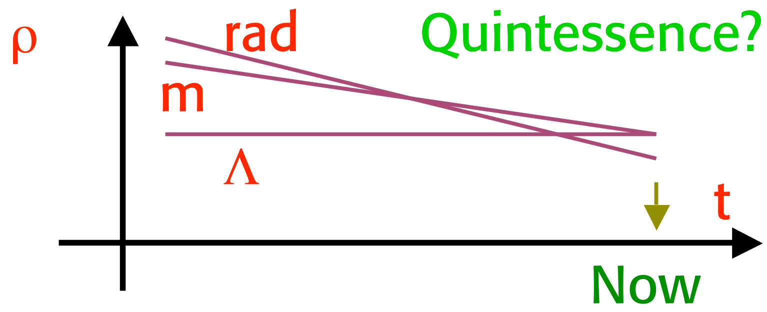
If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123}\ \rho_{obs}$

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?

The scale of vacuum energy poses a large naturalness problem!

So far no clear way out:

- A modification of gravity? (extra dim.)
- Leak of vac. energy to other universes (wormholes)?
- • • • •

Perhaps naturality irrelevant

- Anthropic principle: just right for galaxy formation

(Weinberg)

Perhaps naturality irrelevant also for Higgs: Arkani-Hamed, Dimopoulos; Giudice, Romanino '04, String Th. Landascapes '05

Split SUSY: a fine tuned light Higgs + light gauginos and higgsinos. All other s-partners heavy (a new scale) Preserves coupling unification and dark matter

But then also a two-scale non-SUSY GUT with axions as DM

Normal SUSY, no SUSY, split SUSY? LHC will tell

I find applying the anthropic principle to the "big" 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 "little" hierarchy

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….)

Summarizing

- SUSY remains the Standard Way beyond the SM
- What is unique of SUSY is that it works up to GUT's .

  GUT's are part of our culture!
  Coupling unification, neutrino masses, dark matter, ...
  give important support to SUSY

- It is true that one expected SUSY discovery at LEP

(this is why there is a revival of alternative model building and of anthropic conjectures)

- No compelling, realistic alternative so far developed

(not an argument! Interesting models explored)

- Extra dim.s is a complex, rich, attractive, exciting possibility.
- Little Higgs models look as just a postponement

(both interesting to pursue)

Get the LHC ready fast; we badly need exp input!!!