②

KIT, 6-10 February '12

Beyond the Standard Model

Guido Altarelli

Universita' di Roma Tre
CERN

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

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

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

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

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

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

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

After LEP all we knew from experiment about the SM Higgs:

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

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

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

The Higgs problem is central in particle physics today

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

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

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

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

Precision EW Tests of SM

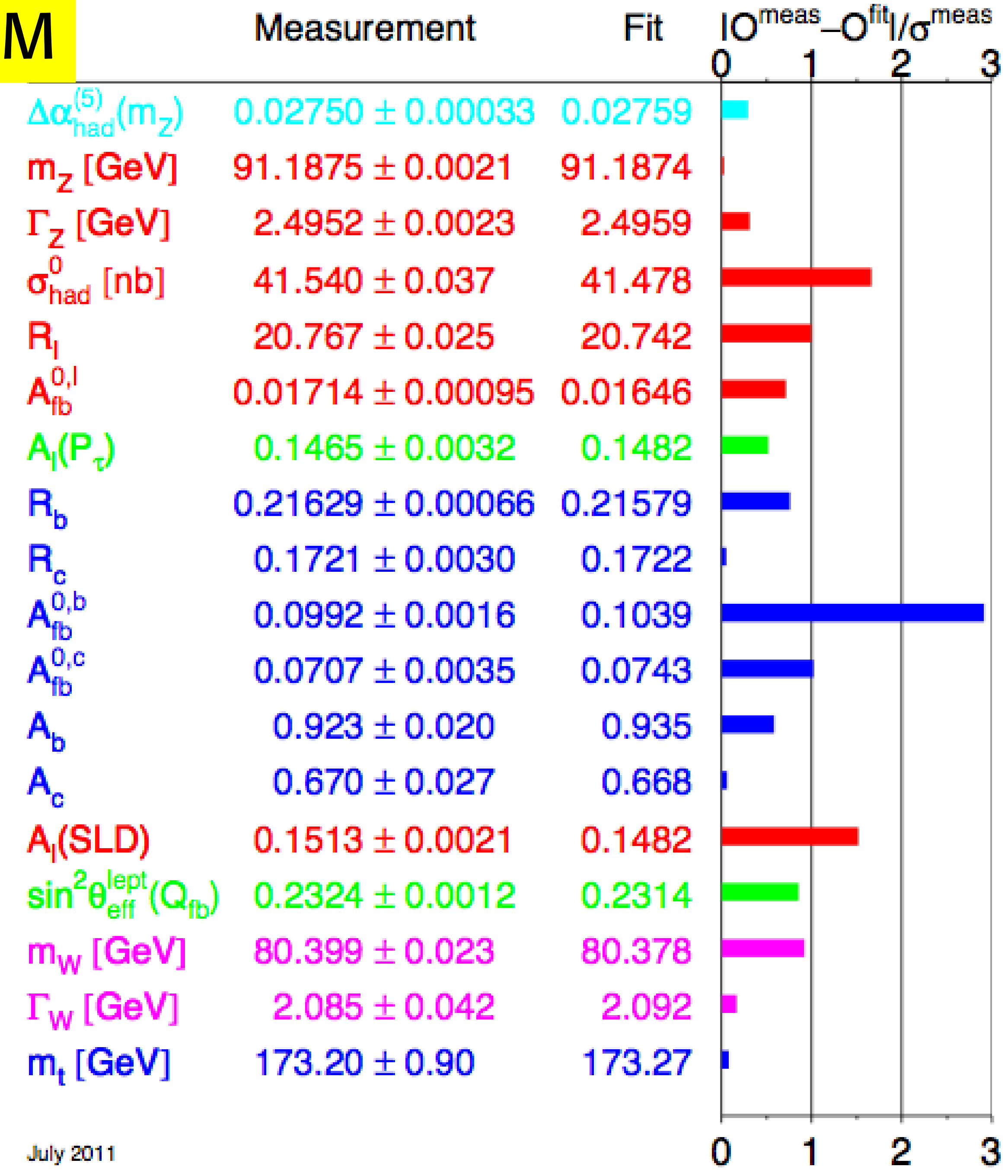
Overall they support the SM and a light Higgs.

The χ^2 is reasonable:

χ^2/ndof~17.5/13 (~18%)

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

a_μ ~ 3.6σ deviation?



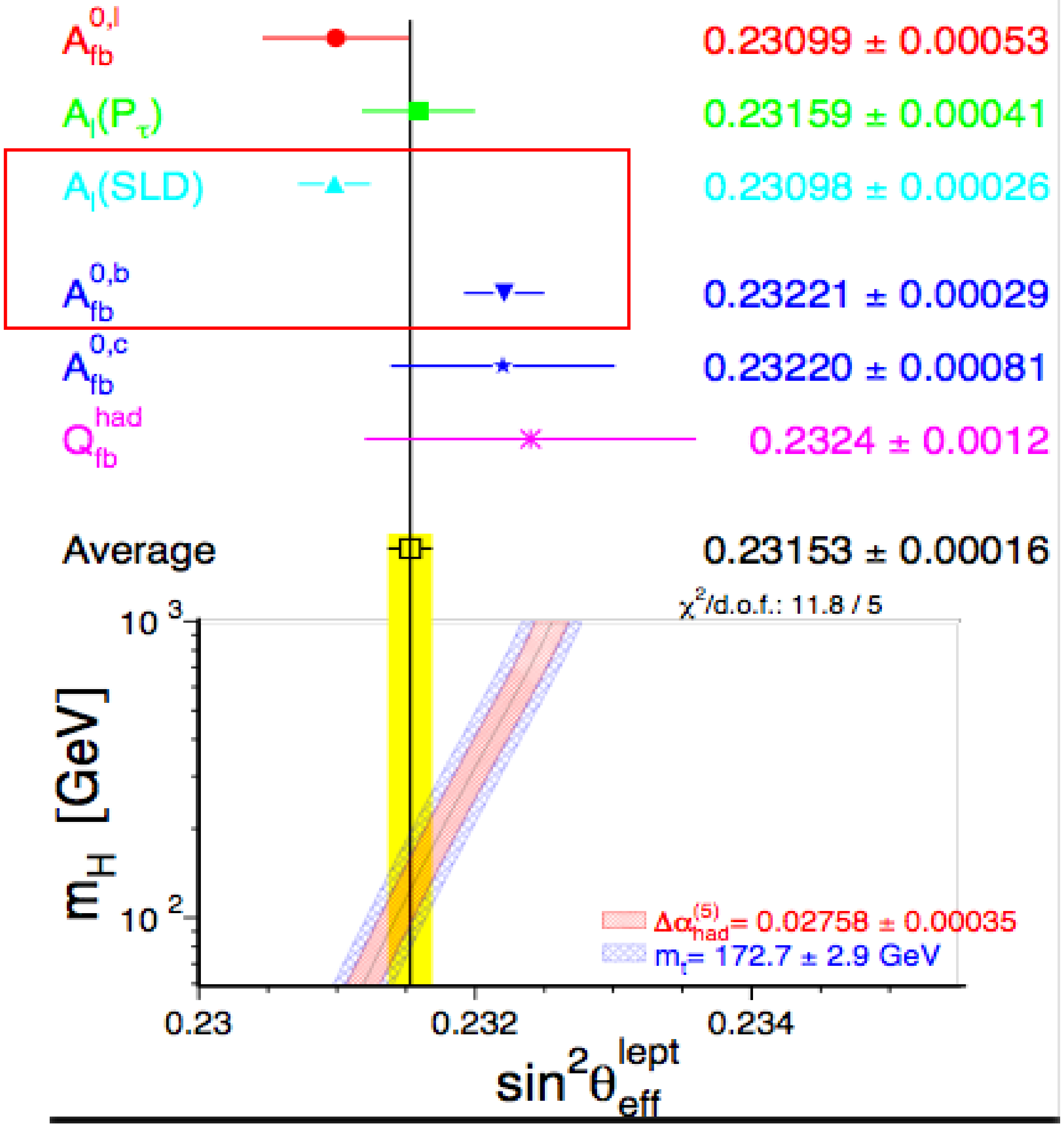
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1039
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27

July 2011

$\sin^2\theta_W$

The two most precise measurements
do not really match!

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

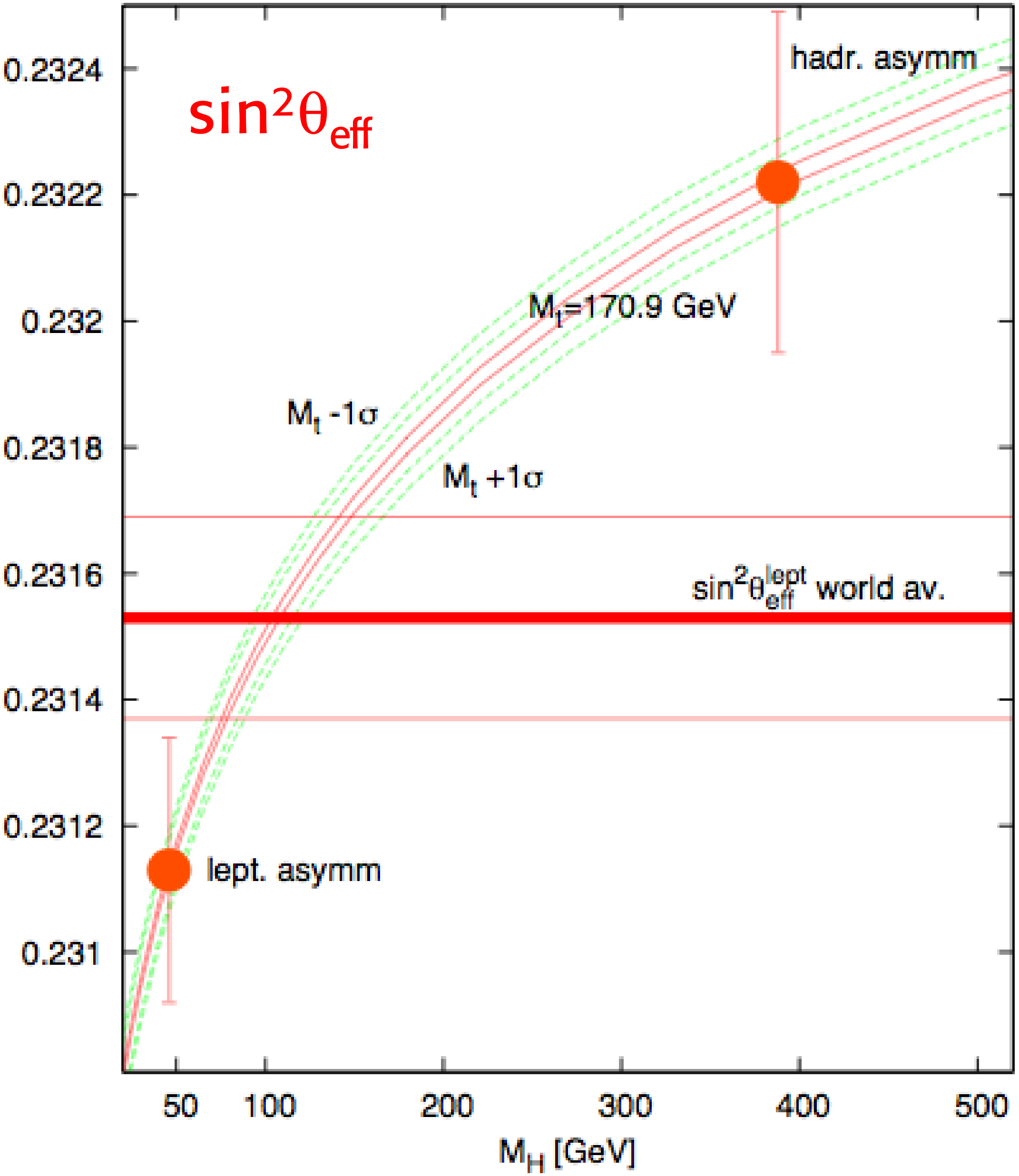


P. Gambino

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

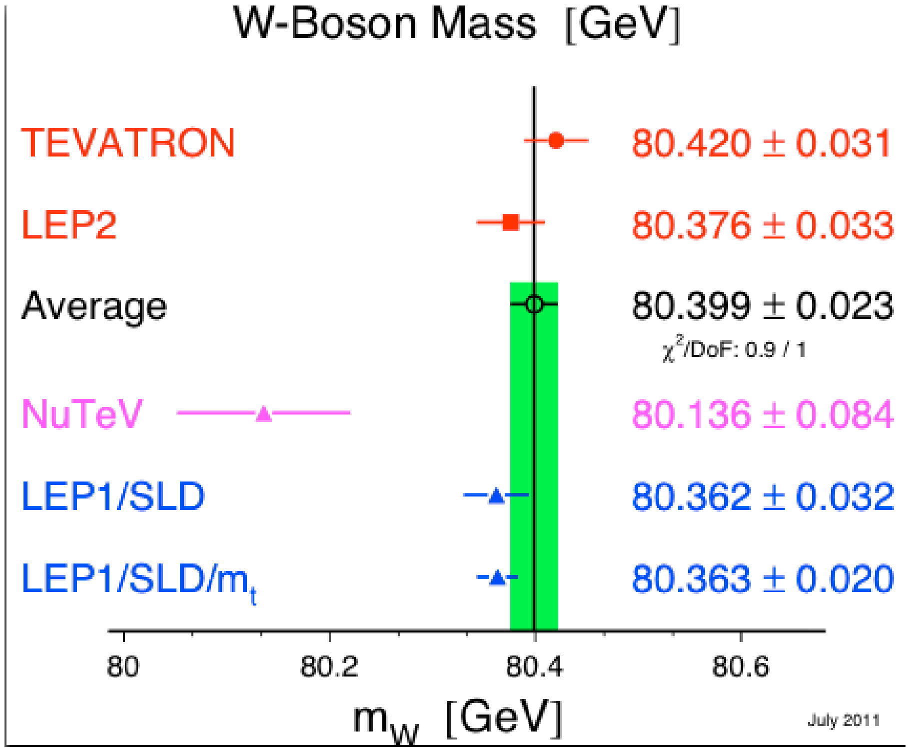
Exp. values are plotted at the m_H point that better fits given m_{texp}

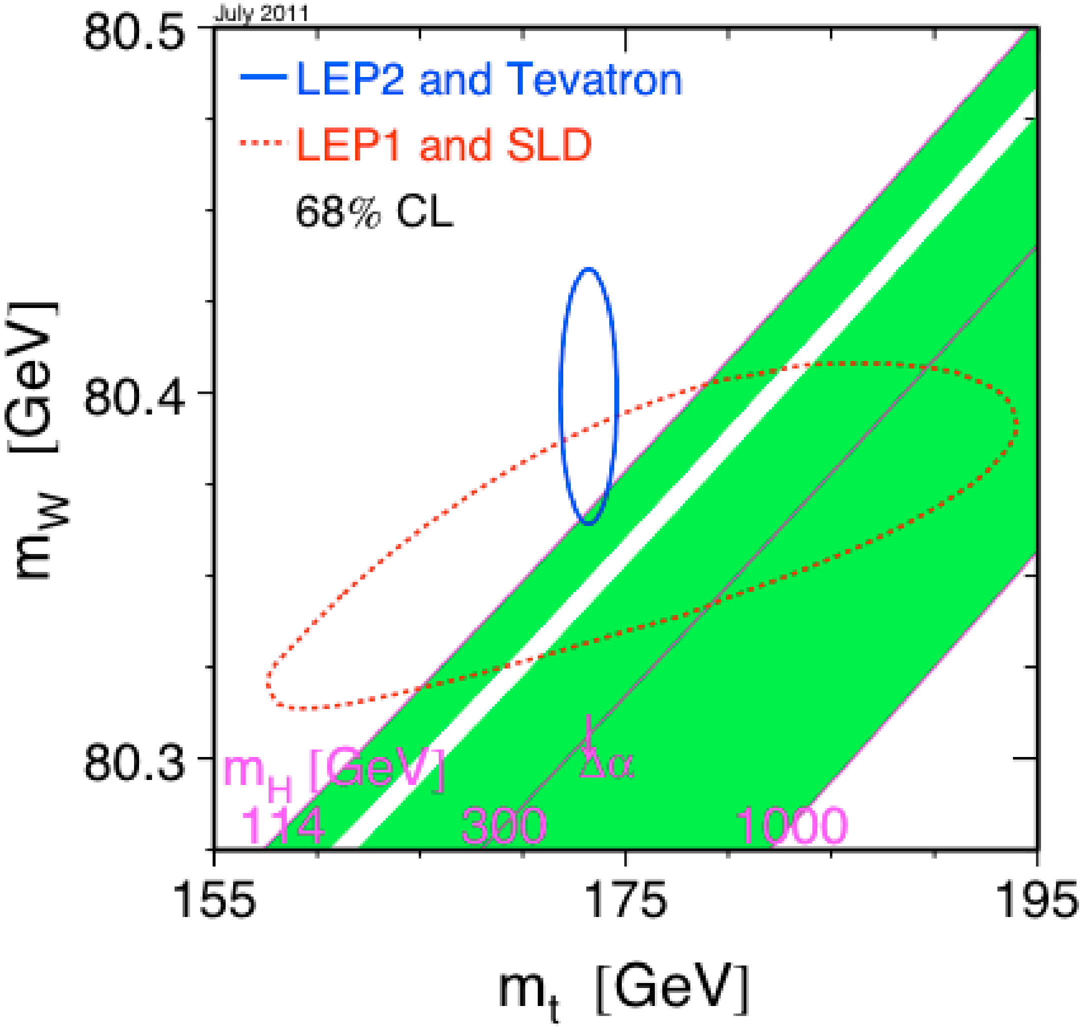
Clearly leptonic and hadronic asymm.s push m_H towards different values



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

Summer '11



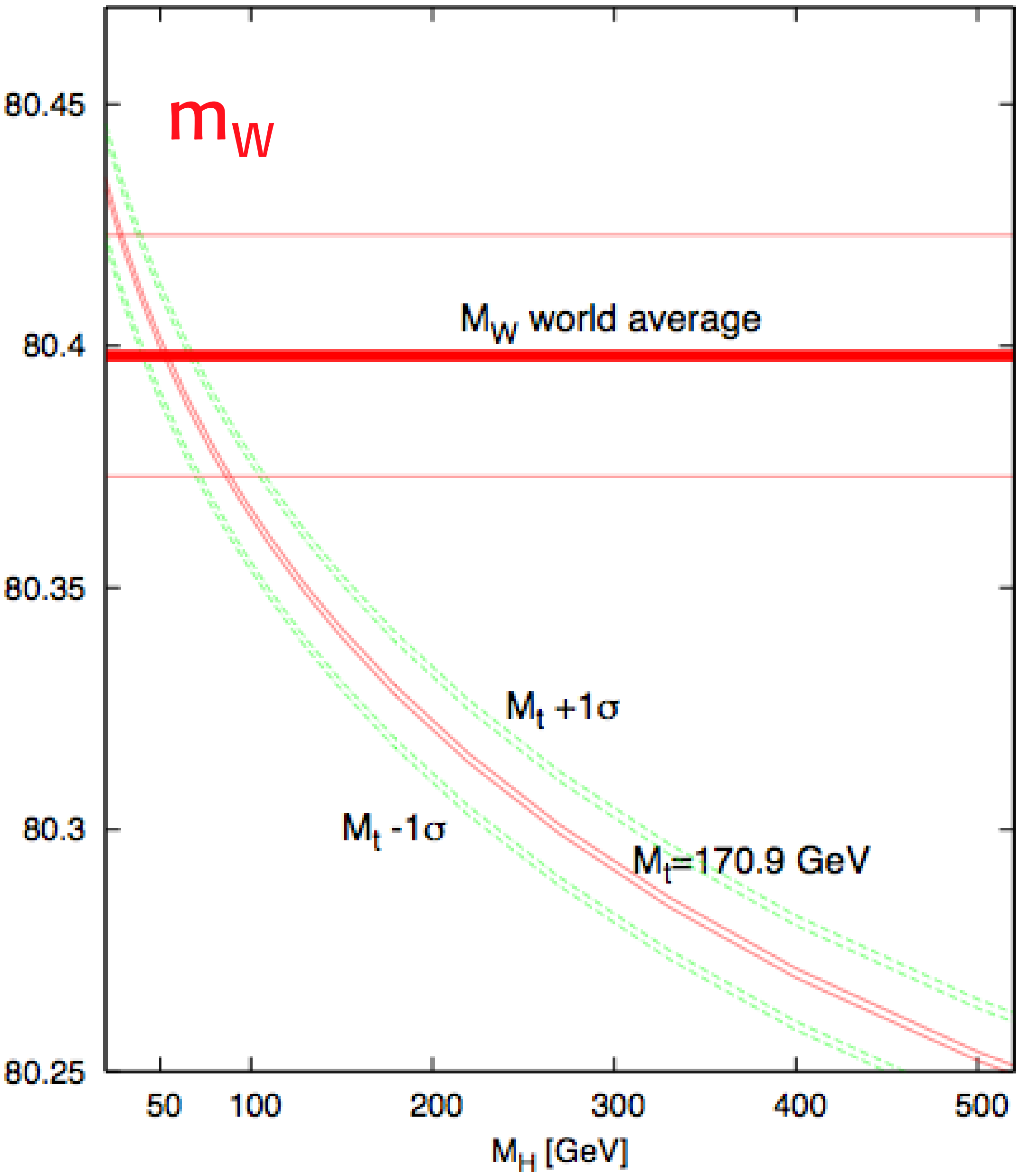


Plot m_W vs m_H

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

Summer '11

	only m_W	only m_t	m_W, m_t
m_t(GeV)	179.7+12-9	173.2±0.9	173.27±0.89
m_H(GeV)	158+260-88	122+59-41	91+34-26
log[m_H(GeV)]	2.20±0.39	2.09 ± 0.17	1.96± 0.14
$\alpha_s(m_Z)$	0.1190(28)	0.1191 (27)	0.1185 (26)
χ^2/dof	17.0/12	16.0/11	17.5/13
m_W(MeV)	80386(18)	80365(20)	80378(14)

WA: m_W=80399(23)

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

Radiative corr's indicate a light H

Sensitive to log m_H

Rad Corr.s ->

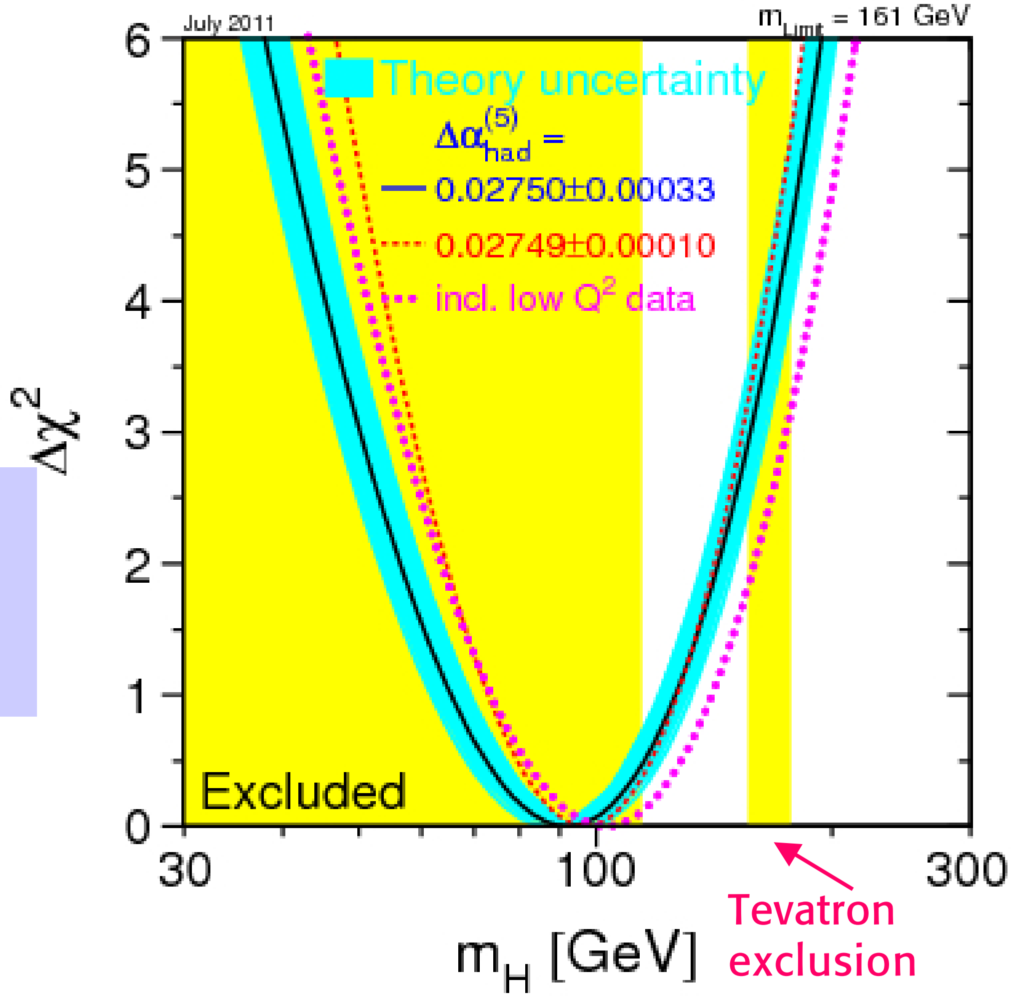
$\log_{10} m_H(\mathrm{GeV}) = 1.96 \pm 0.14$

$m_H = 91 + 34 - 26$ GeV

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

Direct search: $m_H > 114.4$ GeV

July'11 Before LHC data



Tevatron exclusion

At 95 % cl

$m_H < 161$ GeV (rad corr.'s)

$m_H < 185$ 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

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

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

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

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

Some conspiracy is needed to simulate a light Higgs

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

Can we do without the Higgs?

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

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

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

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

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

Thus something must happen at the few TeV scale!!

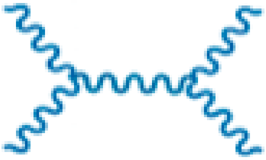
With no Higgs unitarity violations for E_{CM} ~ 1-3 TeV

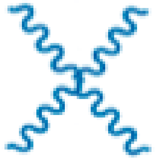
Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy s

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

Zwirner

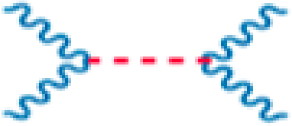
An example: $\mathcal{A}(W_L^+ \, W_L^- \longrightarrow Z_L \, Z_L) \quad (s \gg m_W^2)$





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

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



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

If no Higgs then something must happen!

A crucial question for the LHC

What saves unitarity?

- the Higgs
- some new vector boson

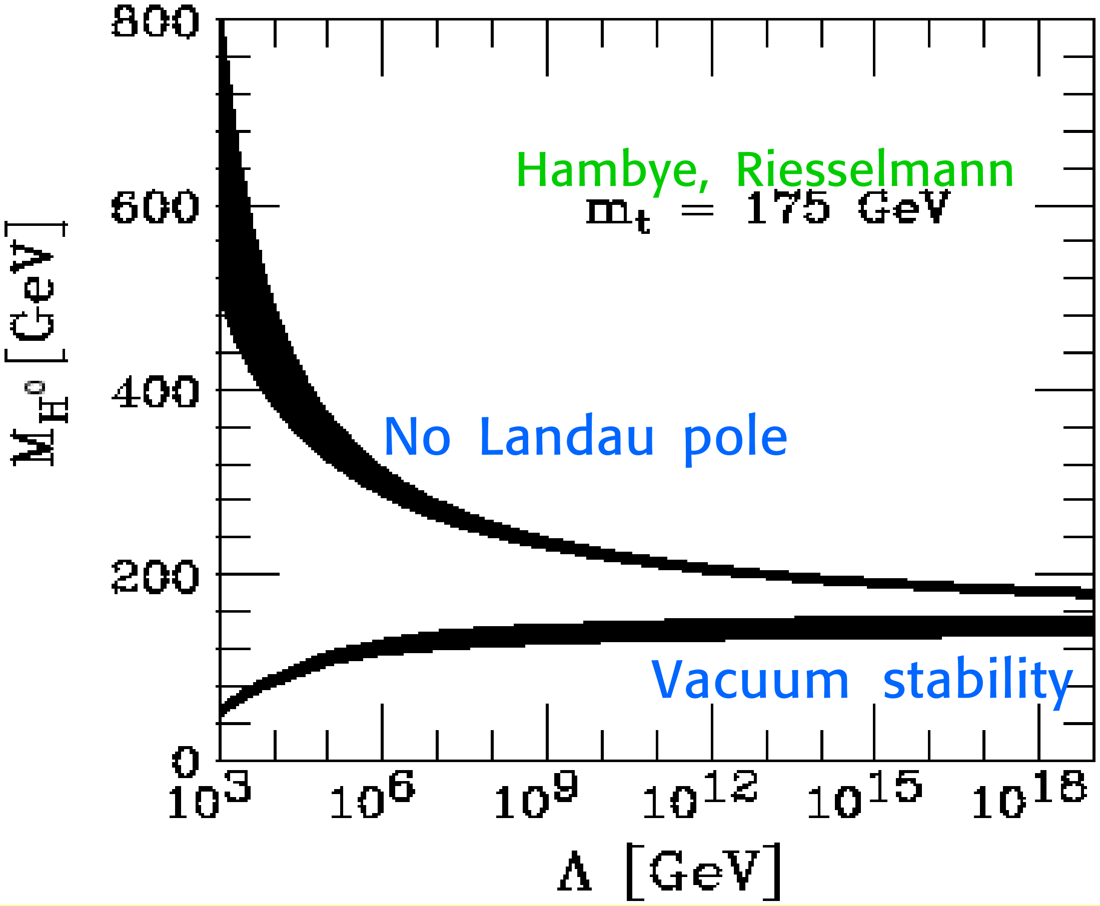
  W′, Z′
  KK recurrences
  resonances from a strong sector
  ……

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



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

depends on m_t and α_s ⟶ 130 GeV $< m_H <$ 180 GeV

Higgs potential

"Wrong" sign

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

$\phi \Rightarrow v + \frac{H}{\sqrt{2}}$ dV/dφ=0 $\Rightarrow$ $v^2 = \frac{\mu^2}{2\lambda} = \frac{m_H^2}{4\lambda}$

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

(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

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

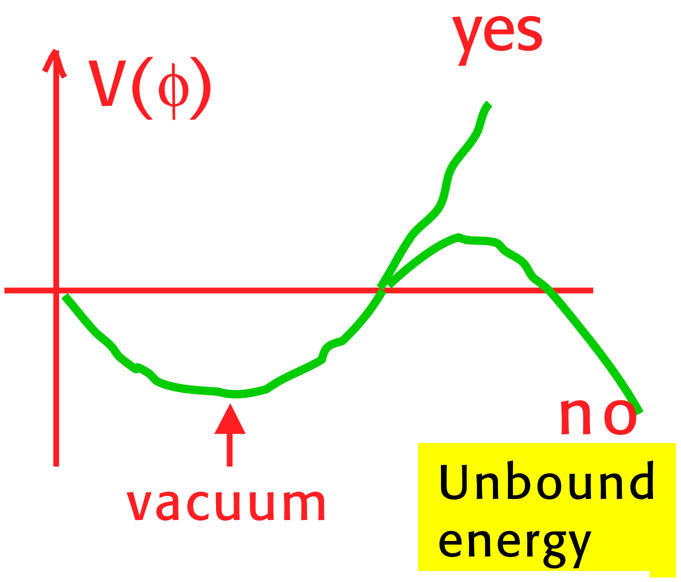
Initial conditions (at $\Lambda = v$) $\lambda_0 = \frac{m_H^2}{4v^2}$ and $h_{0t} = \frac{m_t}{v}$

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

⇨ $m_H \geq \sim 130$ GeV if $\Lambda \sim M_{GUT}$

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

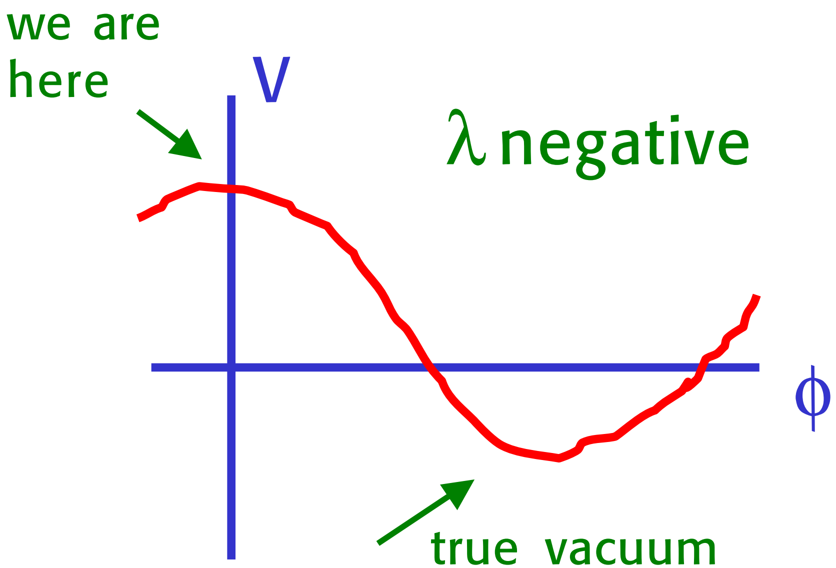
Cabibbo et al, Sher, Altarelli, Isidori



stability $$m_h > 130\,\mathrm{GeV} + 1.8\,\mathrm{GeV}\left(\frac{m_t - 173.2\,\mathrm{GeV}}{0.9\,\mathrm{GeV}}\right) - 0.5\,\mathrm{GeV}\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3\ \mathrm{GeV}$$

But metastability (with sufficiently long lifetime) is enough!

$$V[\phi] = -\mu^2\phi^2 + \lambda\phi^4$$

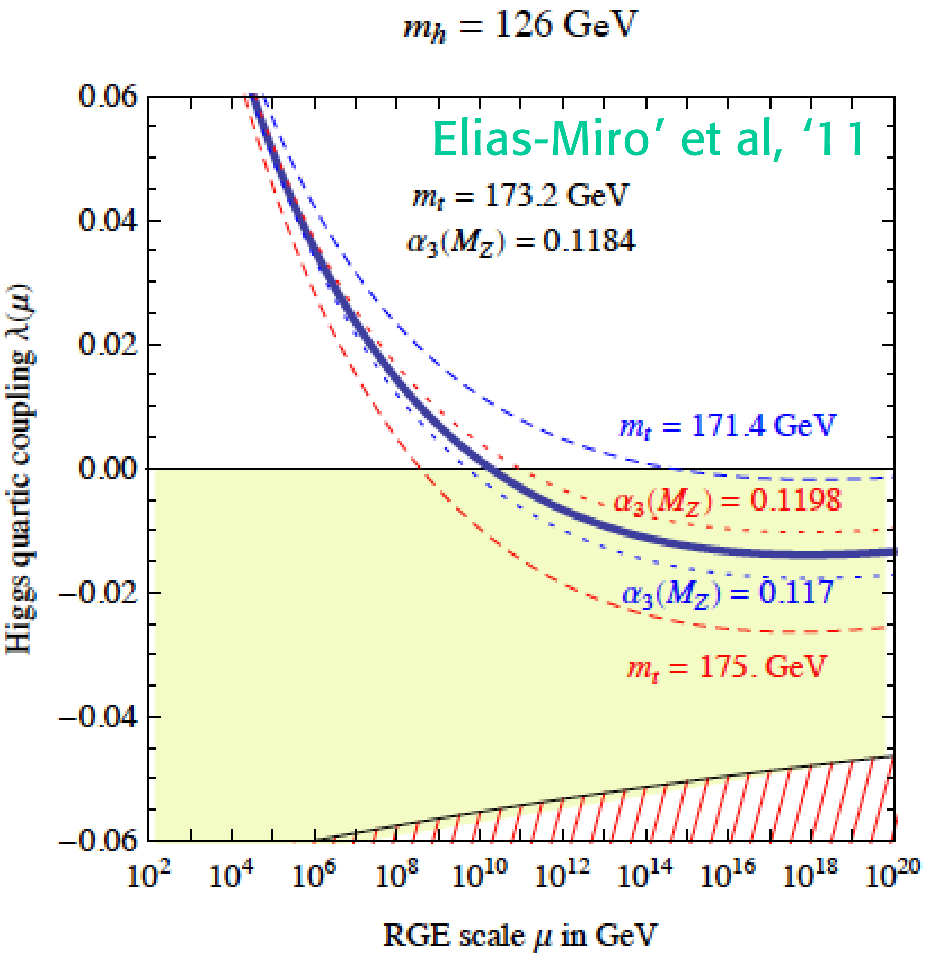


we are here

λ negative

true vacuum

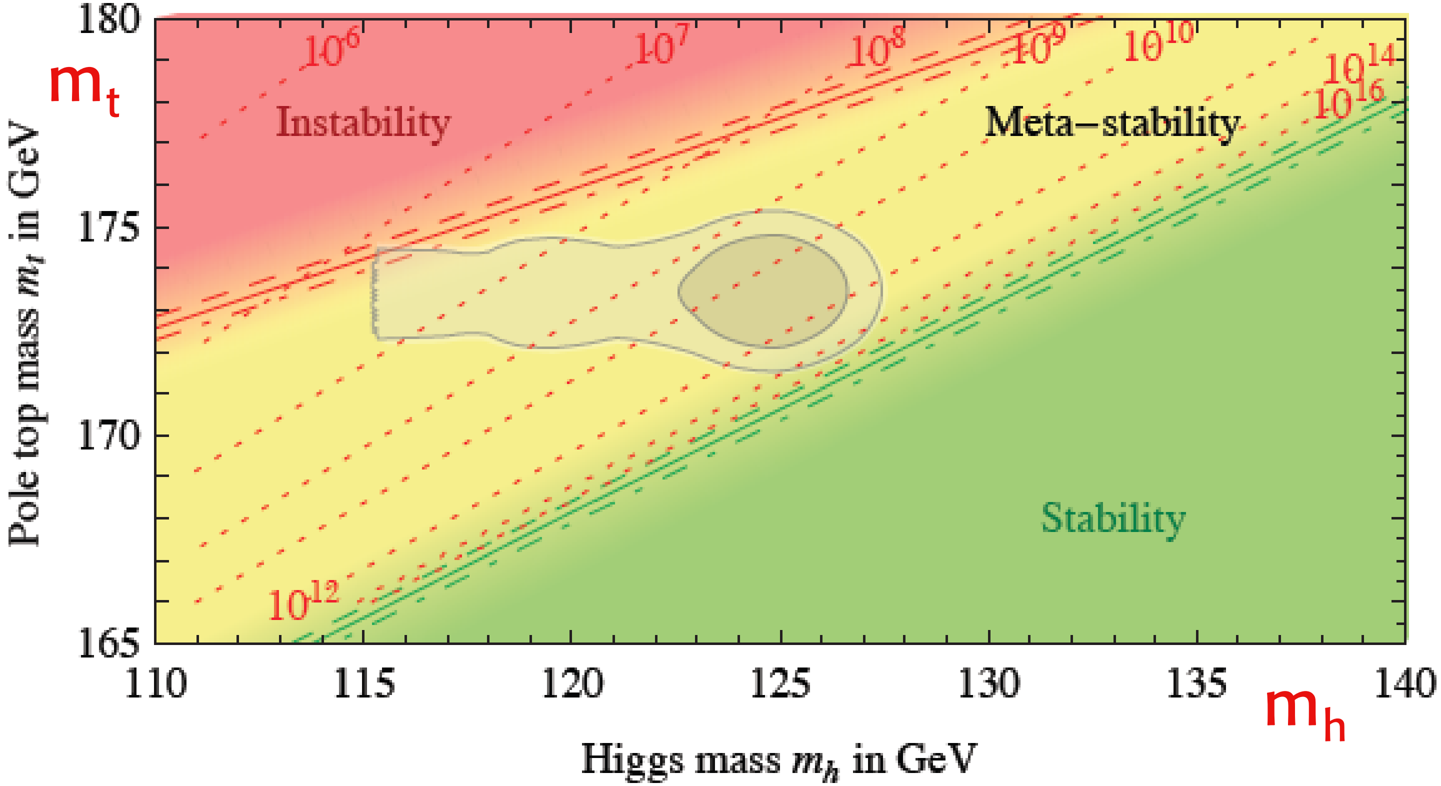
(something is assumed to stabilize V at ~ M_{Pl})



In the absence of new physics, for m_H ~ 125 GeV,
the Universe becomes metastable at a scale Λ ~ 10^{10} GeV

⊕ But the SM remains viable up to M_{Pl} (Early universe implications)

Elias-Miro' et al, '11



for metastability

$$m_h > 111\,\text{GeV} + 2.8\,\text{GeV}\left(\frac{m_t - 173.2\,\text{GeV}}{0.9\,\text{GeV}}\right) - 0.9\,\text{GeV}\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3\,\text{GeV}\,.$$

Isidori, Ridolfi, Strumia '01
Elias-Miro et al '11

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 $\Lambda = v$)

$$\lambda_0 = \frac{m_H^2}{4v^2} \text{ and } h_{0t} = \frac{m_t}{v}$$

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

$m_H \leq \sim 180$ GeV if $\Lambda \sim M_{GUT}$
$\sim$ 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

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

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

Looks pretty unlikely!!

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

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

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

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 first great result is that the LHC has worked very well in 2011!

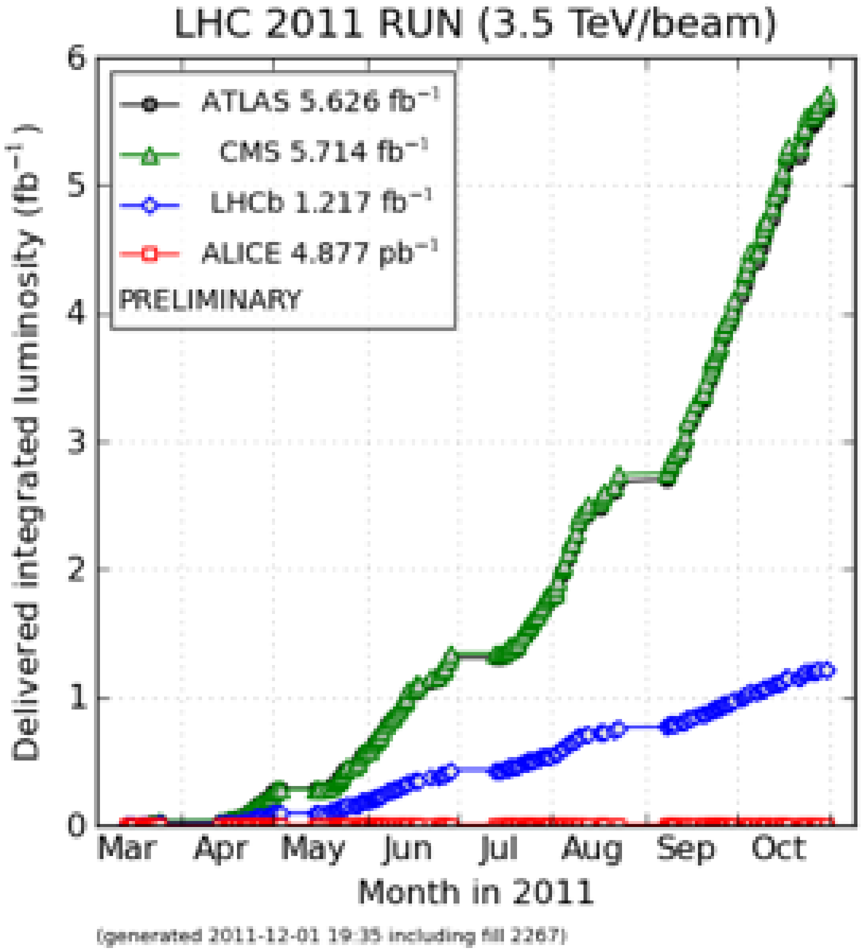
ATLAS&CMS

~5.6 fb^{-1} each

The target of 5 fb^{-1} for 2011 has been largely achieved!!

LHCb

~1.2 fb^{-1}



This is great news for particle physics !!

The SM Higgs is close to be observed or excluded!

A robust exclusion interval for the SM Higgs:

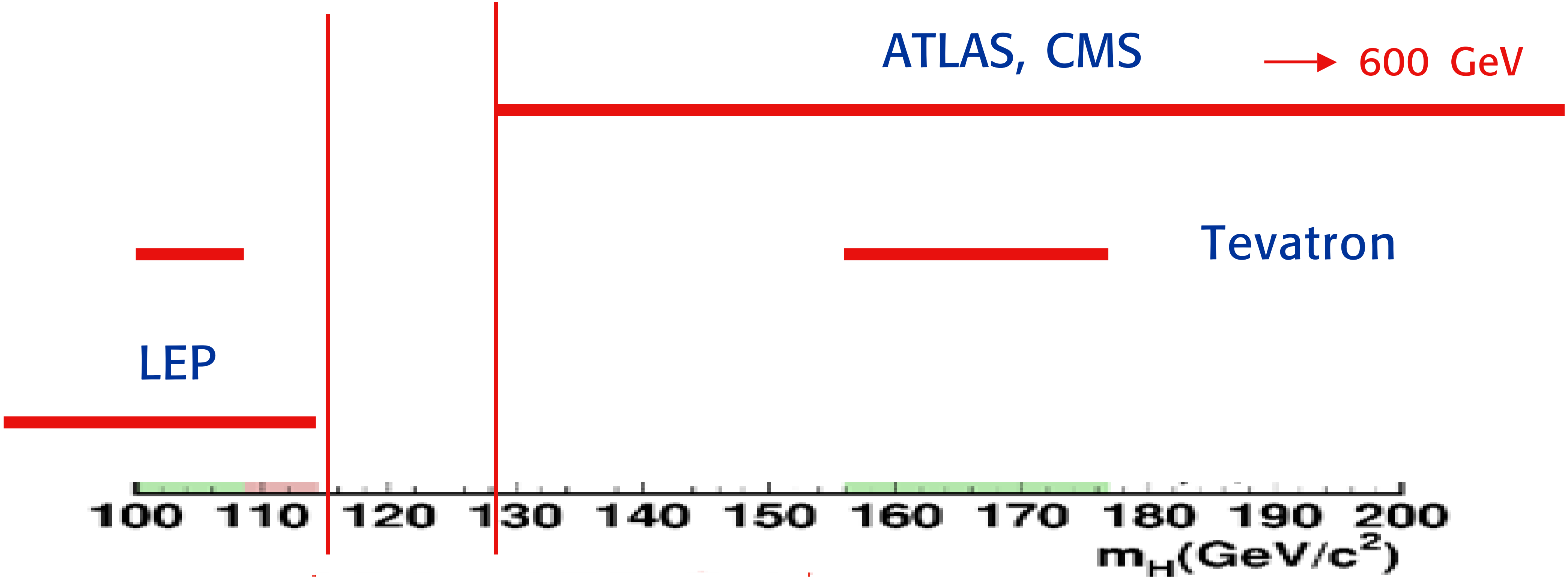
Either the SM Higgs is very light (115.5 - 127 GeV)
or rather heavy (i.e. > 600 GeV)

The range $m_H = 115.5 - 127$ GeV is in agreement with precision tests, compatible with the SM and also with the SUSY extensions of the SM

$m_H \sim 125$ GeV is what you expect from a direct interpretation of EW precision tests: no fancy conspiracy with new physics to fake a light Higgs while the real one is heavy

$m_H > 600$ GeV would point to the conspiracy alternative

The 95% exclusion intervals for the light Higgs



ATLAS, CMS → 600 GeV

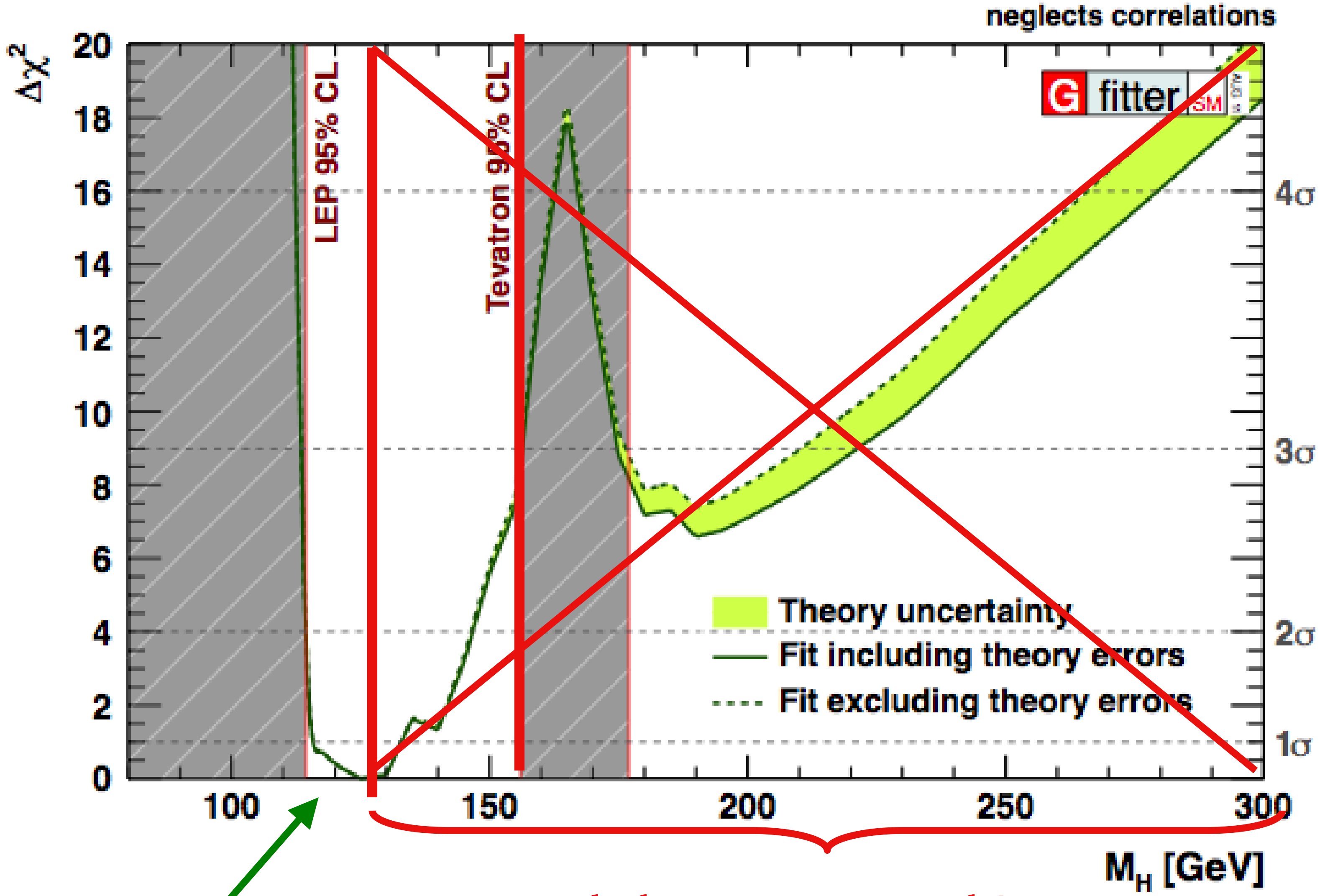
Tevatron

LEP

115.5-127 GeV

The window of opportunity

$m_H > 600$ GeV
also allowed

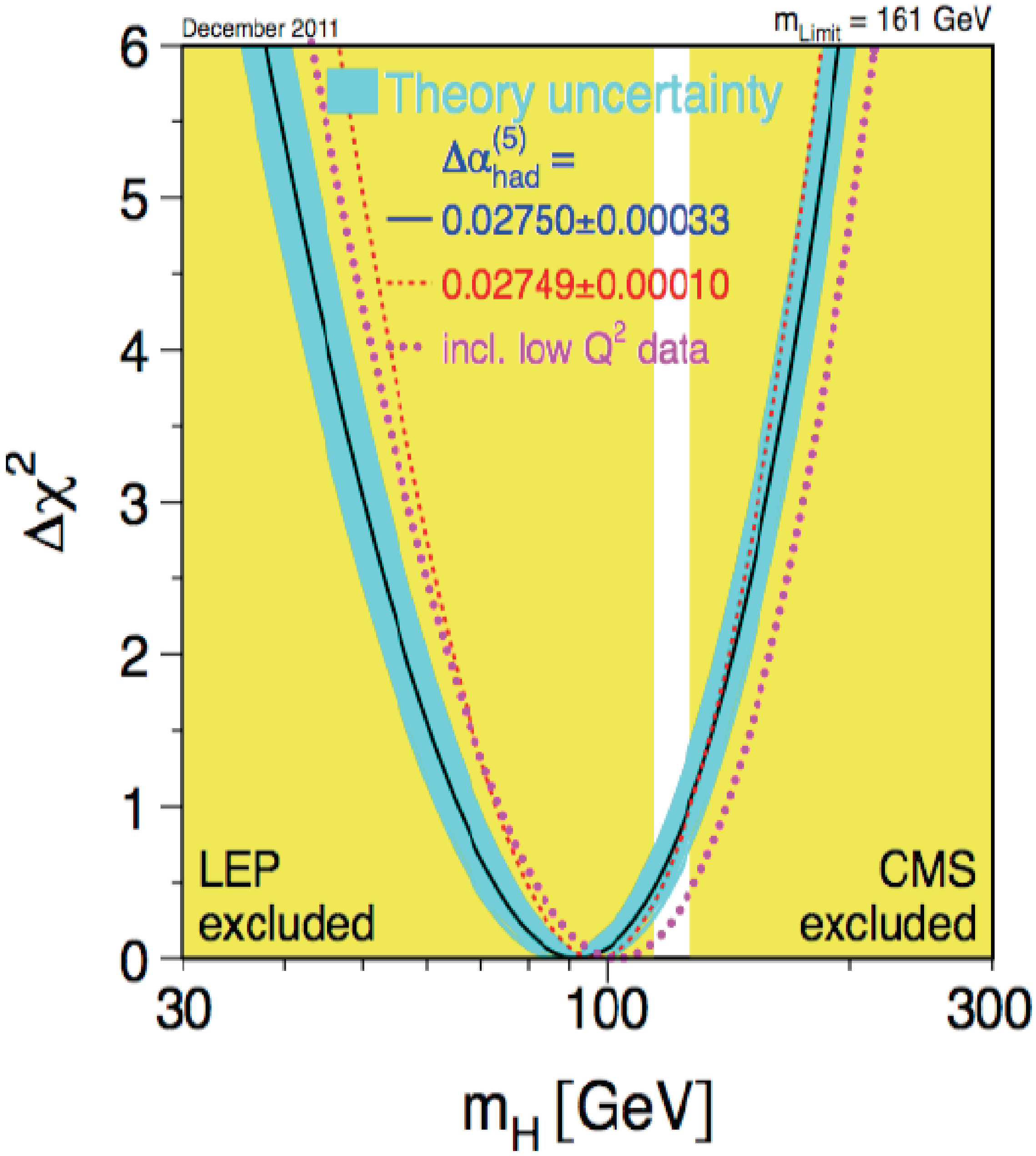


Excl. by ATLAS and/or CMS

A light SM Higgs can only be in 115.5-127 GeV range, in agreement with EW tests

also $300 < m_H < 600$ GeV is excluded

The new blue band diagram

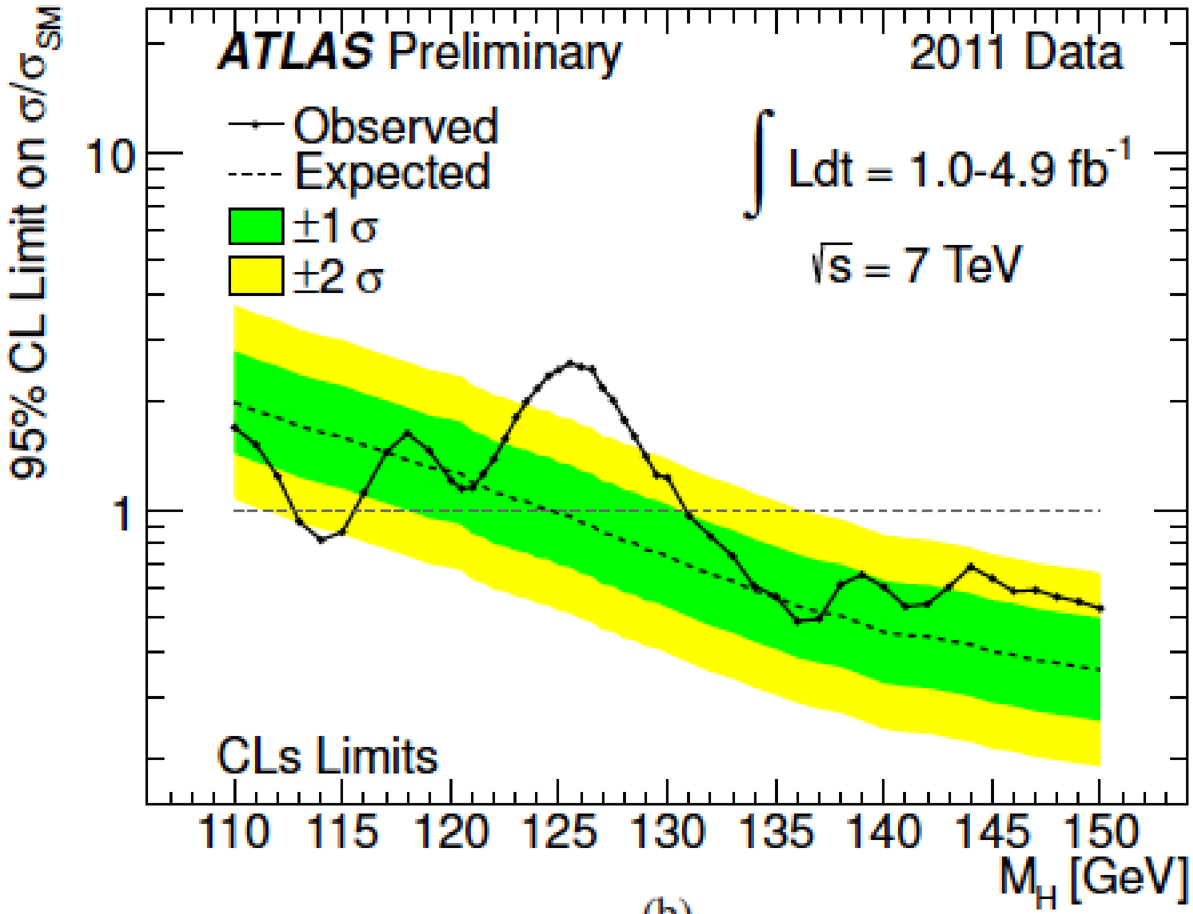


Some “excess” was reported in the allowed m_H window

Is this the Higgs signal?

We hope yes, but the present evidence could still evaporate with more statistics

We need to wait for the 2012 run



(b)

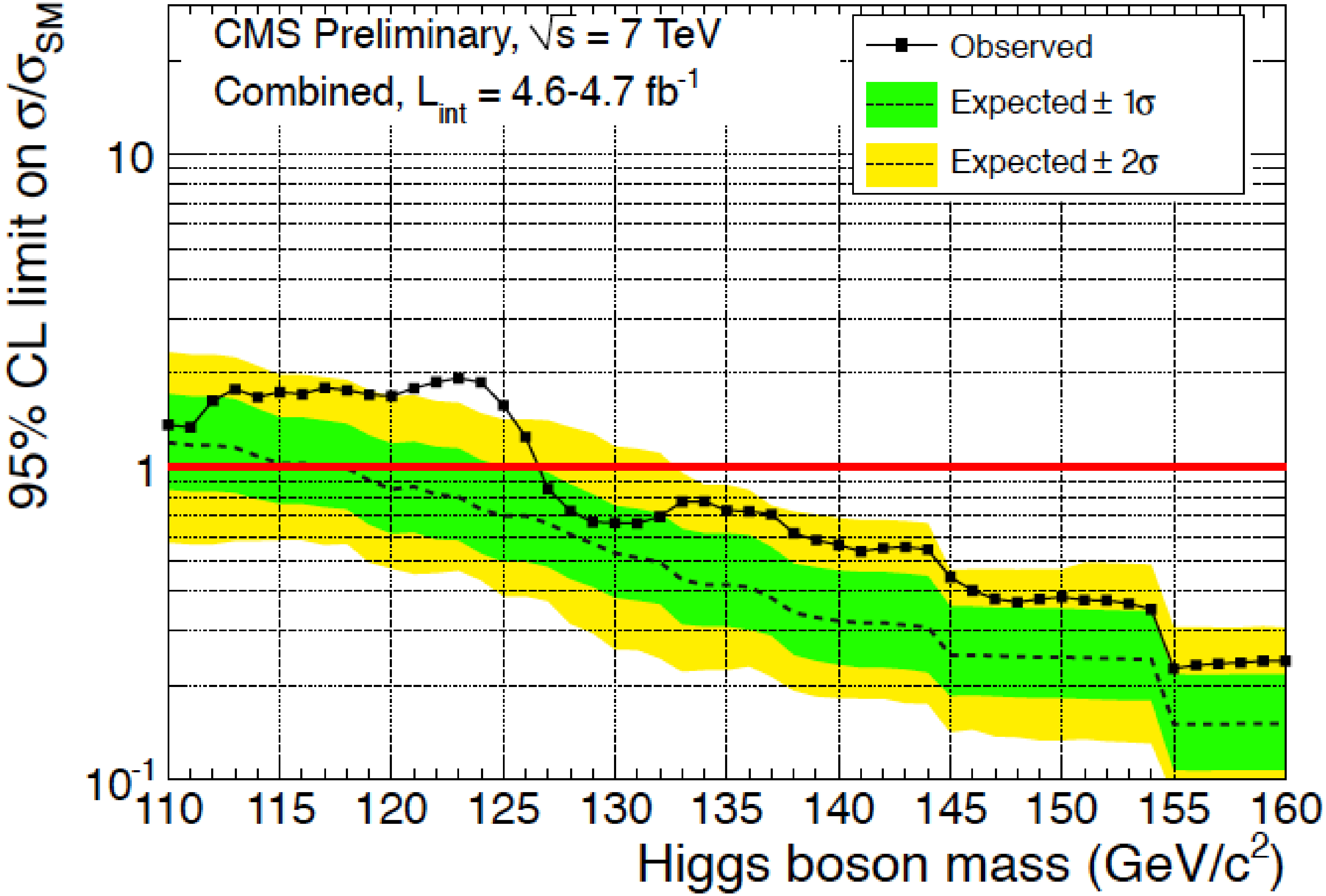
Observed excess over SM for m_H ~ 126 GeV in:

H->γγ (2.8σ), H->ZZ*->4l± (2.1σ), H->WW*-> lνlν (1.4σ).

Combined: 3.6σ (but with look-elsewhere-effect 2.3σ)

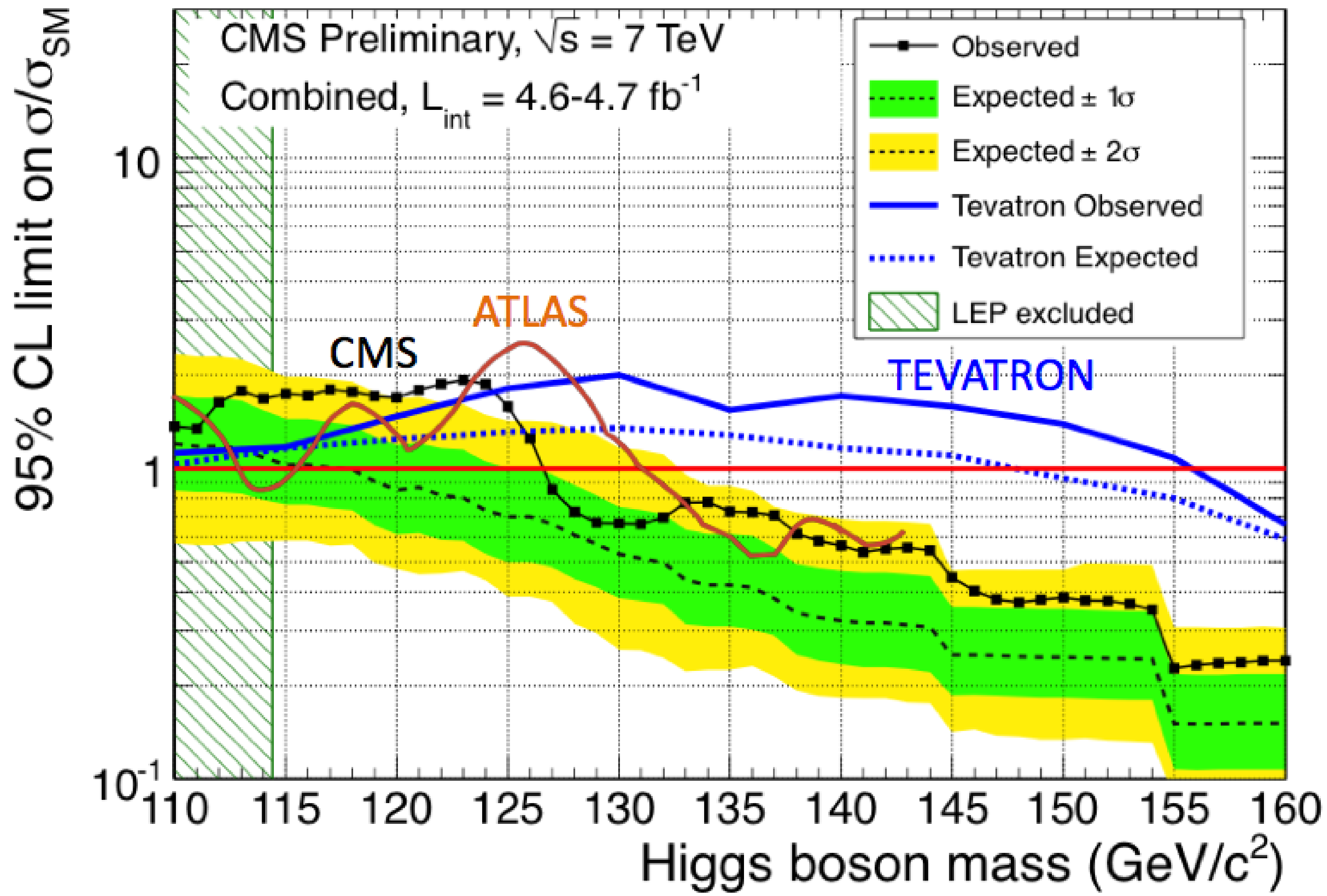
The most obvious "elsewhere" is CMS →

Also in CMS there is an excess, but smaller (2.6 σ)



Here is an attempt to put all the evidence together

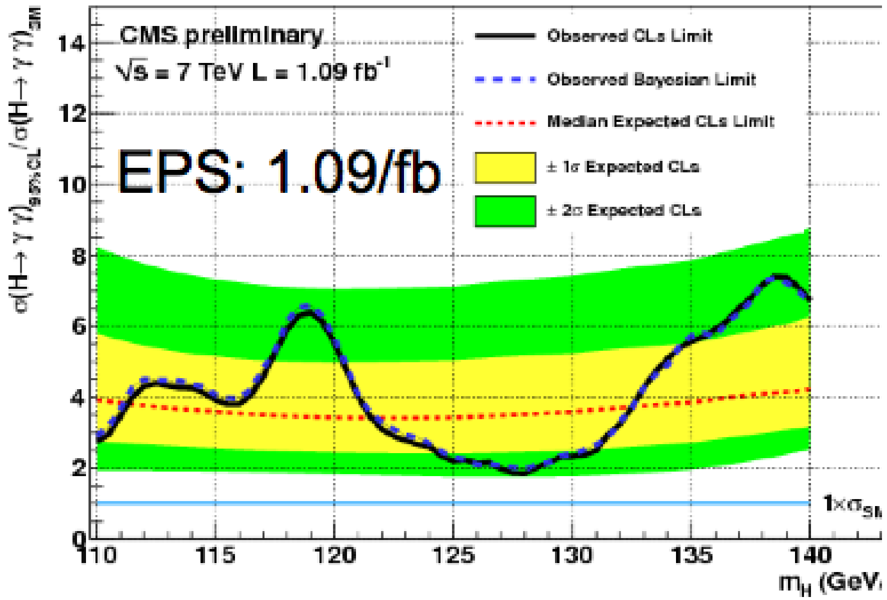
Kilminster
Zurich Jan. '12

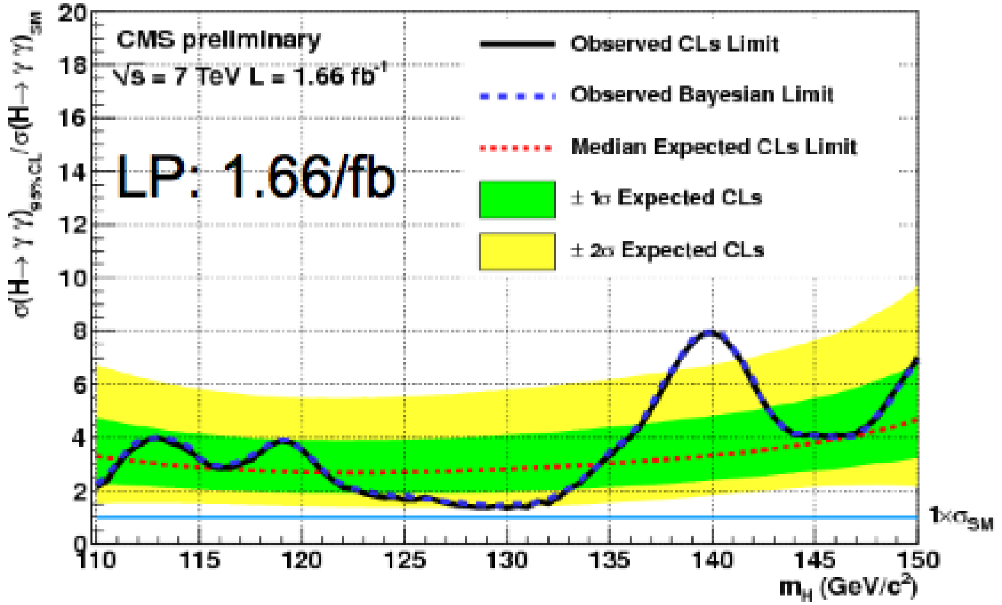


Peaks come and go!

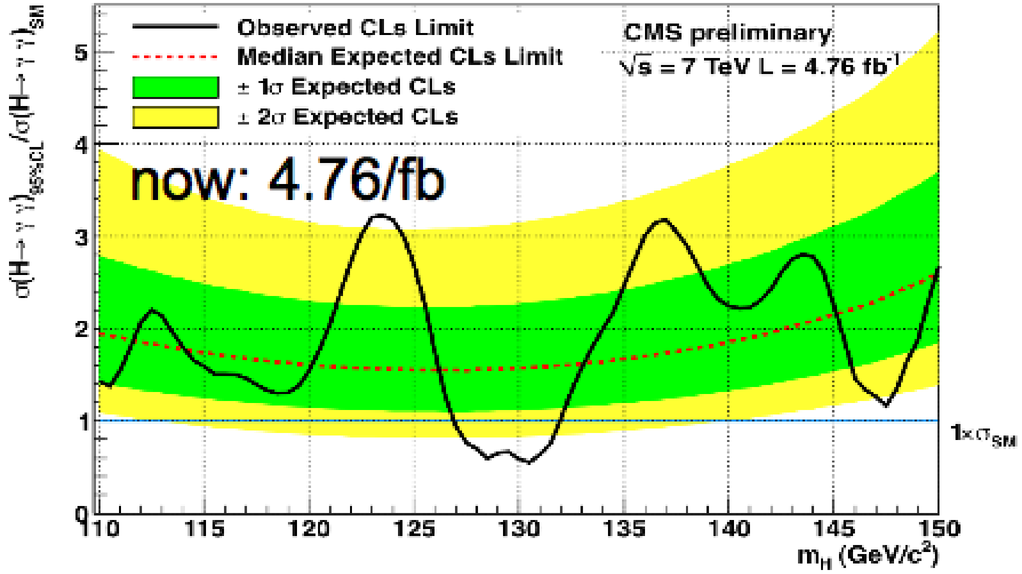
CMS History: $H \to \gamma\gamma$

Paus
Zurich Jan. '12





- EPS (1.09/fb) LP (1.66/fb) Dec 19 (4.76/fb)
- 'peaks' come and go
- of course now we are getting into interesting territory



The Standard Model works very well

So, why not find the Higgs and declare
particle physics solved? Why one expects New Physics?

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- The flavour puzzle

•••••

and experimental clues:

- Neutrino masses
- Coupling unification
- Dark matter
- Baryogenesis
- Vacuum energy
- some experimental anomalies: $(g\text{-}2)_\mu$, ...

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

insert here
your
preferred
hints

Some NP hints from accelerator experiments

A^b_{FB}	LEP	~3σ
$(g-2)_\mu$	Brookhaven	~3σ
tt^{bar} FB asymmetry	Tevatron (mostly CDF)	~3σ at large M_{tt}
Dimuon charge asymmetry	D0	~3.9σ
Wjj excess at M_{jj}~ 144 GeV	CDF	~3.2σ
only candidate to open prod. of NP	not confirmed by D0, LHC	
B_s -> $J/\psi\phi$	Tevatron, LHCb	~went away
B -> $\tau\nu$	BaBar, Belle	~2.5σ
CPV in D->$\pi\pi$, KK	LHCb	
....		

All of them could still go away!

Electron g-2: A new measurement

Odom, Hanneke,
D'Urso, Gabrielse '06

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

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots$$
$$+ a_{\mu\tau} + a_{\text{hadronic}} + \cancel{a_{\text{weak}}},$$

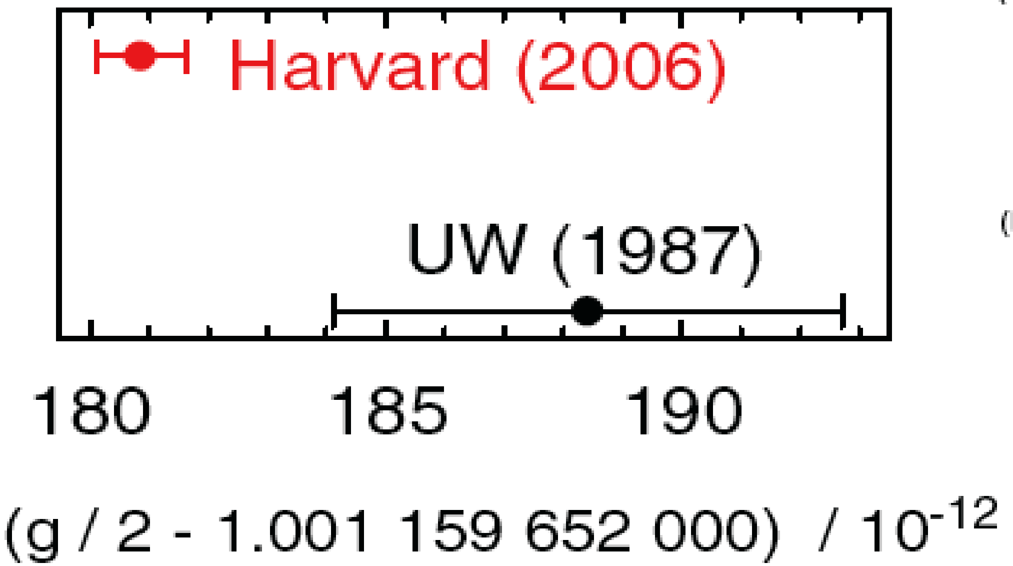
δa_h small

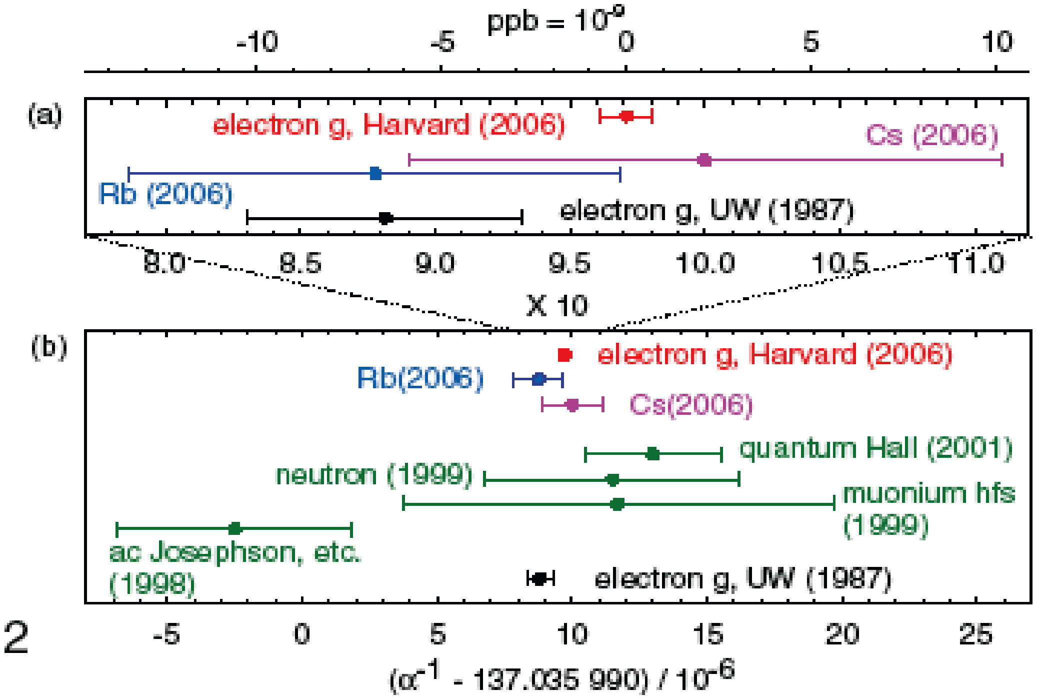
Best determination of α_{QED}

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

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

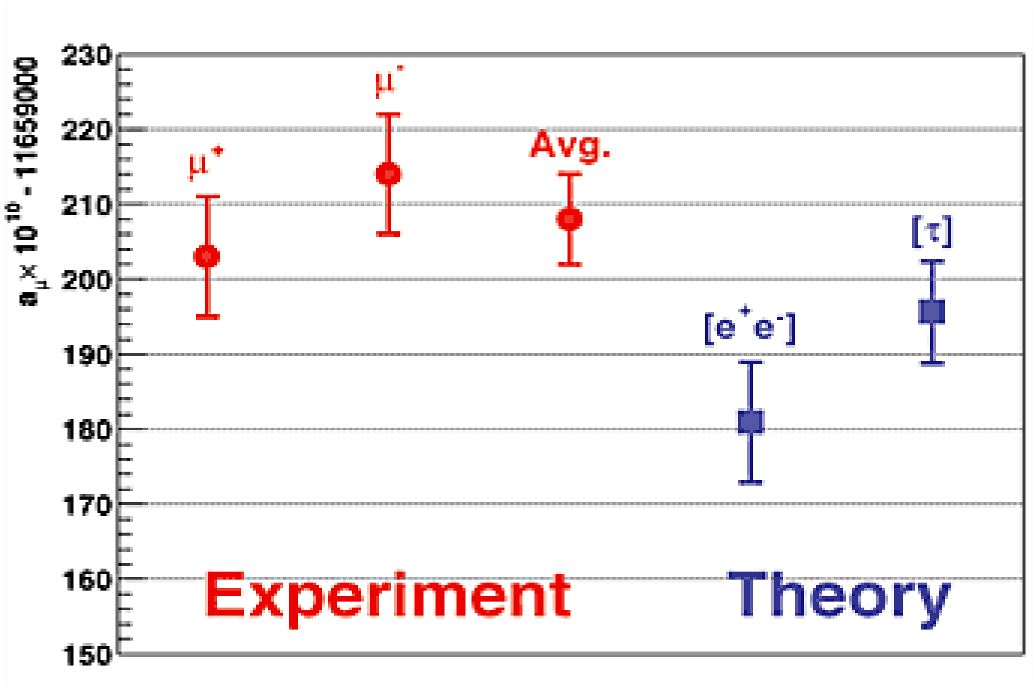
$$a(\text{weak}) = 0.030\ (01) \times 10^{-12}$$



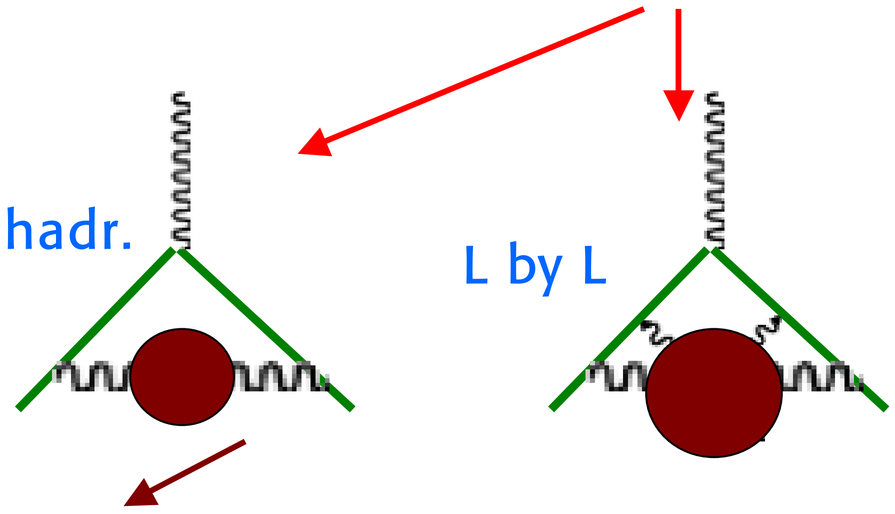


Muon g-2: more sensitive to new physics by $(m_\mu/m_e)^2 \sim 2\ 10^4$

BNL '04-'06: $a_\mu = (116592080 \pm 63)\ 10^{-11}$



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



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

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

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

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

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

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	$27.5 \pm 8.4 \ (3.3\sigma)$

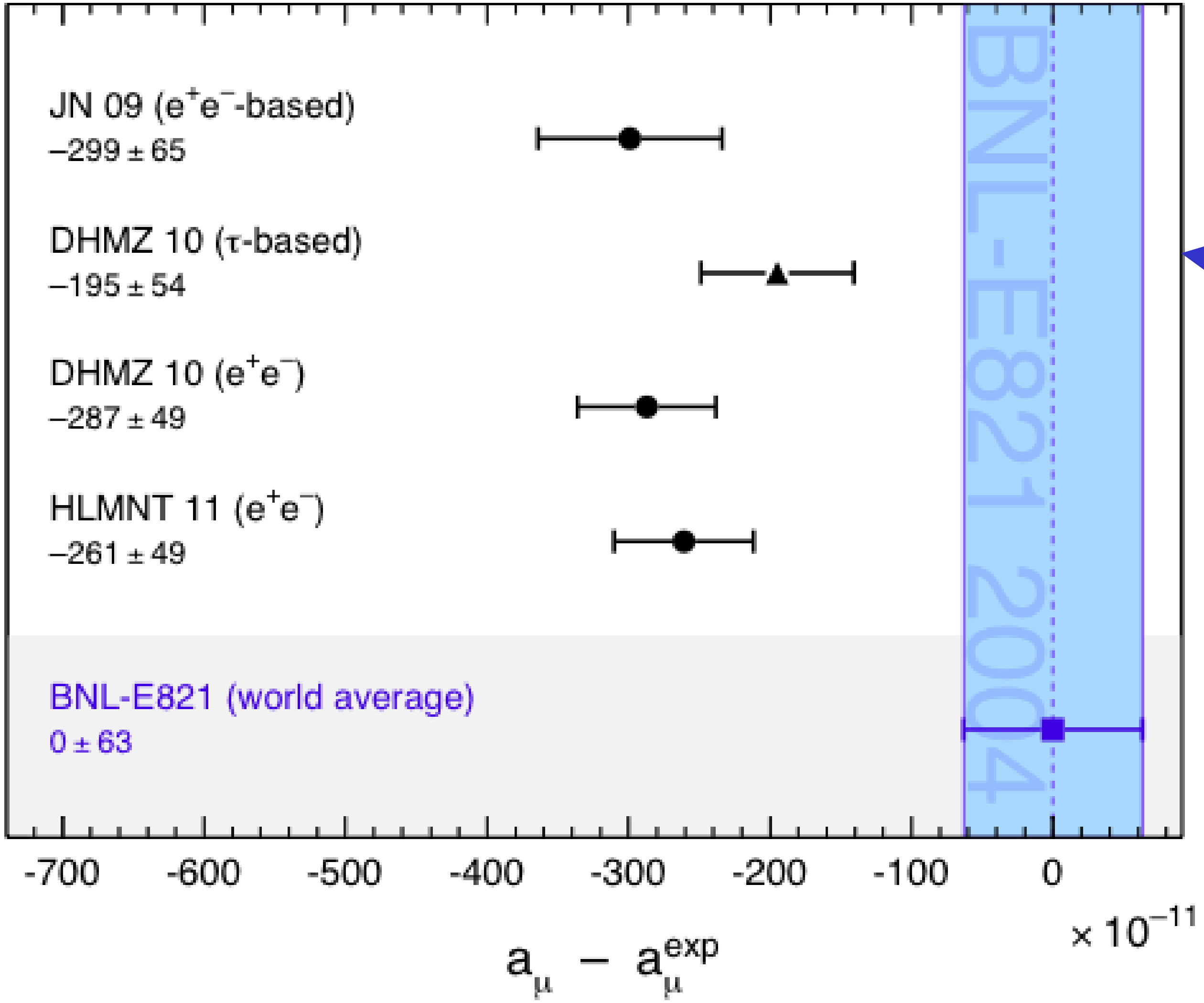
Mostly VP-LO
VP-NLO = -9.8±0.1
LbyL = 12.0±3.5

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

$$\boxed{\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (287 \pm 63 \pm 49) \cdot 10^{-11}}$$

3.6σ

Davier/Hoecker ‘11



Hadronic contr.
from data.
τ (2.4σ) vs e+e- (3.6σ)
discrepancy
now reduced.
But still:
theoretical errors
underestimated?

Present status of $(g\text{-}2)_\mu$ discrepancy

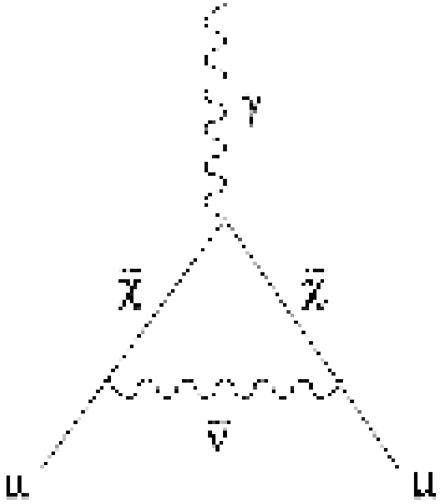
Hoecker '11

$$\boxed{\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (287 \pm 63 \pm 49) \cdot 10^{-11}}$$

3.6σ

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!!

Dark Matter

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

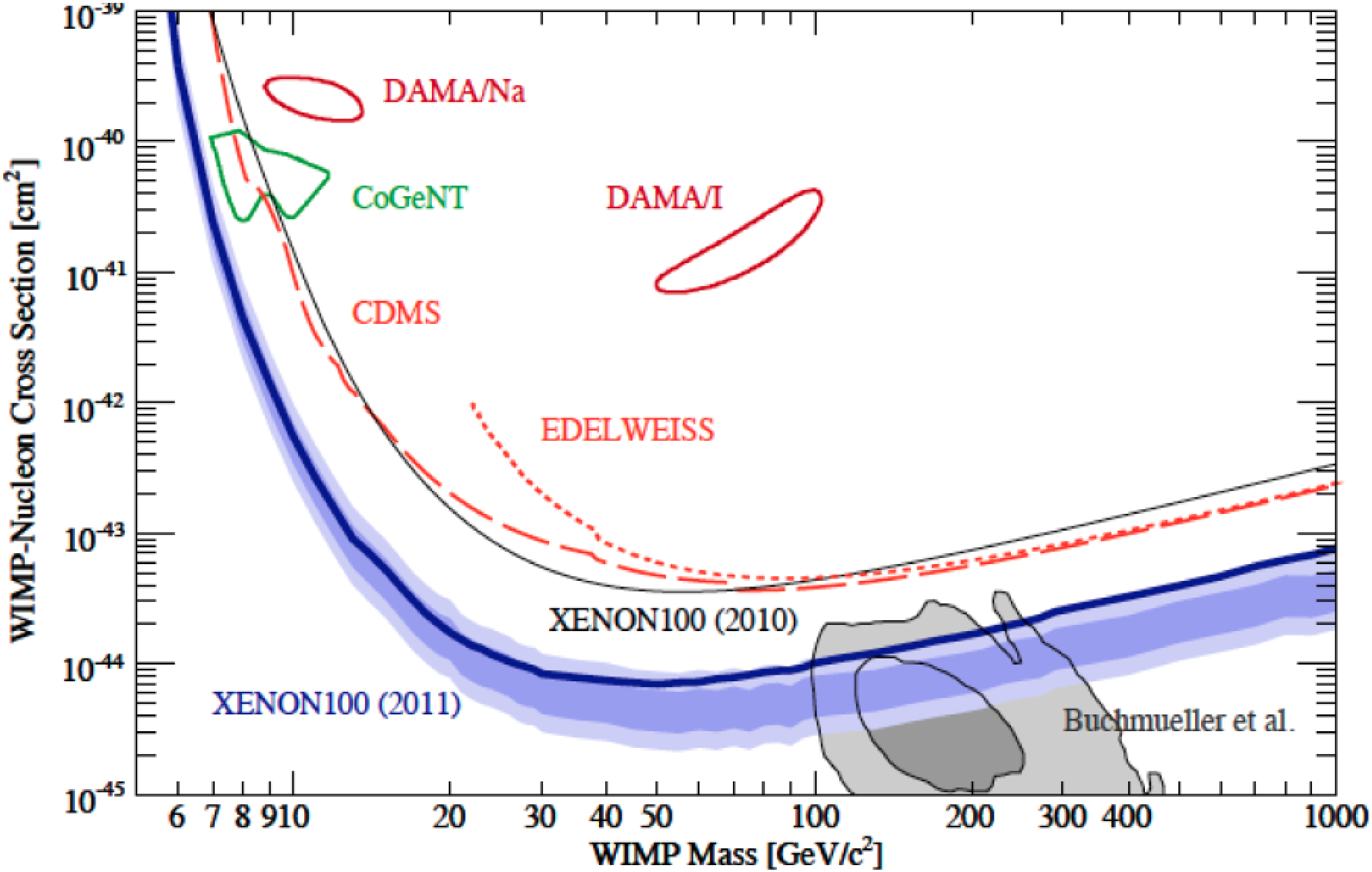
For WIMP's in thermal equilibrium after inflation the density is:

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

can work for typical weak cross-sections!!!

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

Strong competition from underground labs



A crucial question for the LHC

Is Dark Matter a WIMP?

LHC will probably tell yes or no to WIMPS

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)

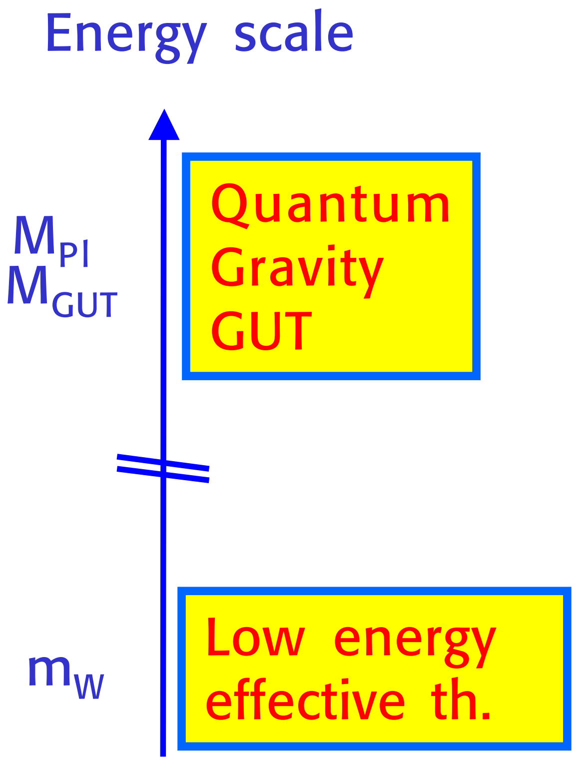
M_{GUT} close to M_{Pl}

- 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!

The hierarchy problem


Energy scale

M_{Pl}
M_{GUT}

Quantum
Gravity
GUT

m_W

Low energy
effective th.

Assume:
- A TOE at Λ~M_{GUT}~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

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

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): $\Lambda \to m\log\Lambda$

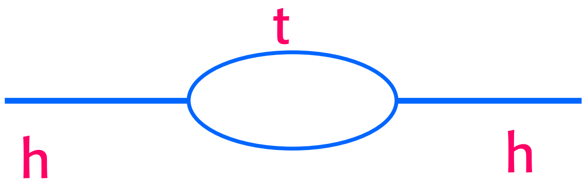
$\mathcal{L}_4$: Renorm.ble interactions, e.g. $\bar{\psi}\gamma^\mu\psi A_\mu$

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

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 close but its effects were not visible at LEP2

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

A crucial question for the LHC

What damps the top loop Λ^2 dependence?

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

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

Precision Flavour Physics

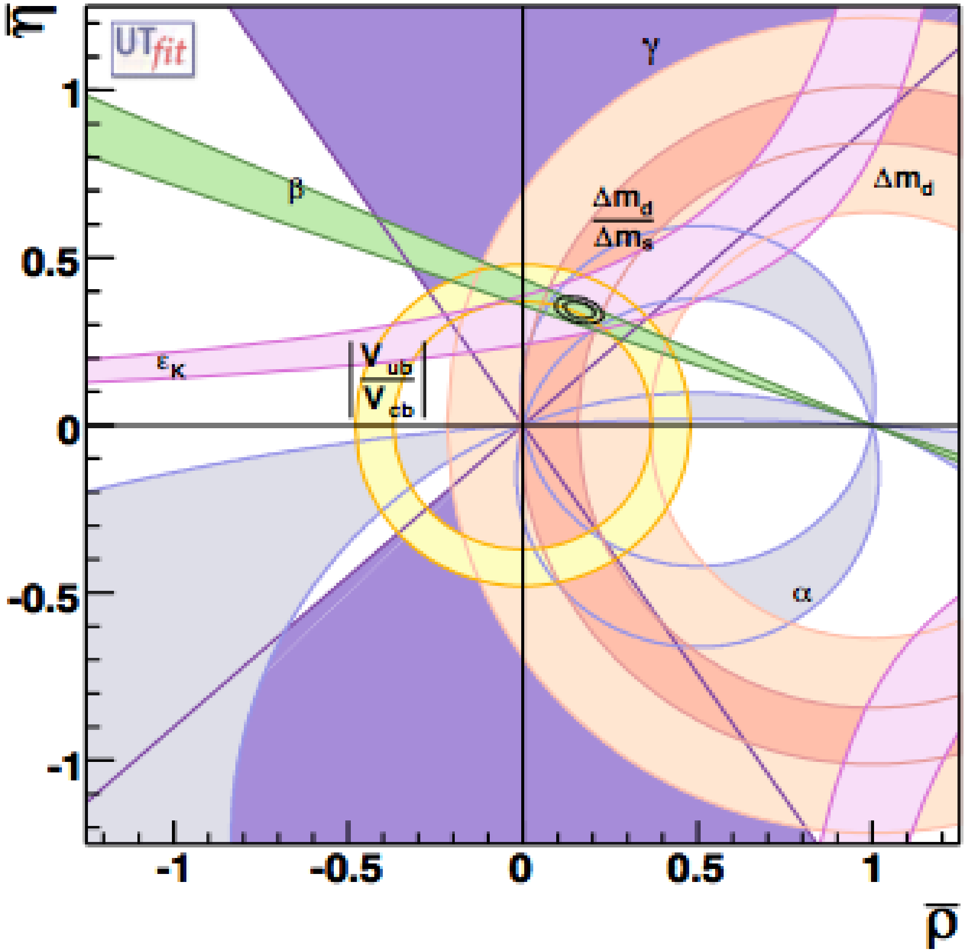
Another area where the SM is good, too good.....

With new physics at ~ 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

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



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

The CKM picture is confirmed as the main source of CPV in the quark sector

This poses strong constraints for models BSM

Adding effective operators to SM generally leads to very large Λ

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

Isidori

$$c_{NP} \to \begin{cases} \sim 1 \xrightarrow{\text{tree/strong + generic flavour}} \Lambda \gtrsim 2{\times}10^4 \text{ TeV [K]} \\ \sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavour}} \Lambda \gtrsim 2{\times}10^3 \text{ TeV [K]} \\ \sim (y_t V_{ti}{}^* V_{tj})^2 \xrightarrow{\text{tree/strong + MFV}} \Lambda \gtrsim 5 \text{ TeV [K \& B]} \\ \sim (y_t V_{ti}{}^* V_{tj})^2/(16\,\pi^2) \xrightarrow{\text{loop + MFV}} \Lambda \gtrsim 0.5 \text{ TeV [K \& B]} \end{cases}$$

But the hierarchy problem demands Λ in the few TeV range

only assuming $c_{NP} \sim (y_t V_{tb}{}^* V_{td})^2$ (or anyway small)

we get a bound on Λ in the TeV range

eg in Minimal Flavour Violation (MFV) models

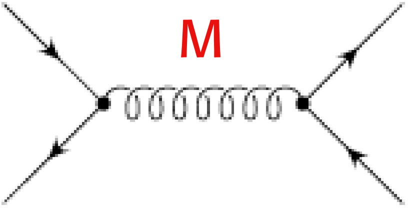
D'Ambrosio, Giudice, Isidori, Strumia'02

A lot of fine-tuning is imposed on us when our present theory is confronted with the data

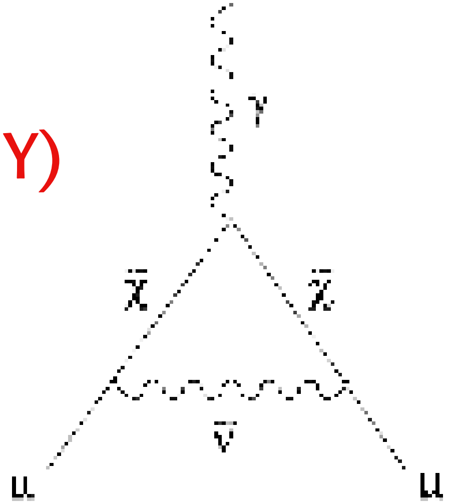
For naturalness we need new physics at ~ 1 TeV but we see no clear deviations in EW Precision Tests and in Flavour Physics

Strong constraints on model building

Typical tree level NP effects too large



Avoided by R-parity (SUSY)
T-parity (Little Higgs) etc



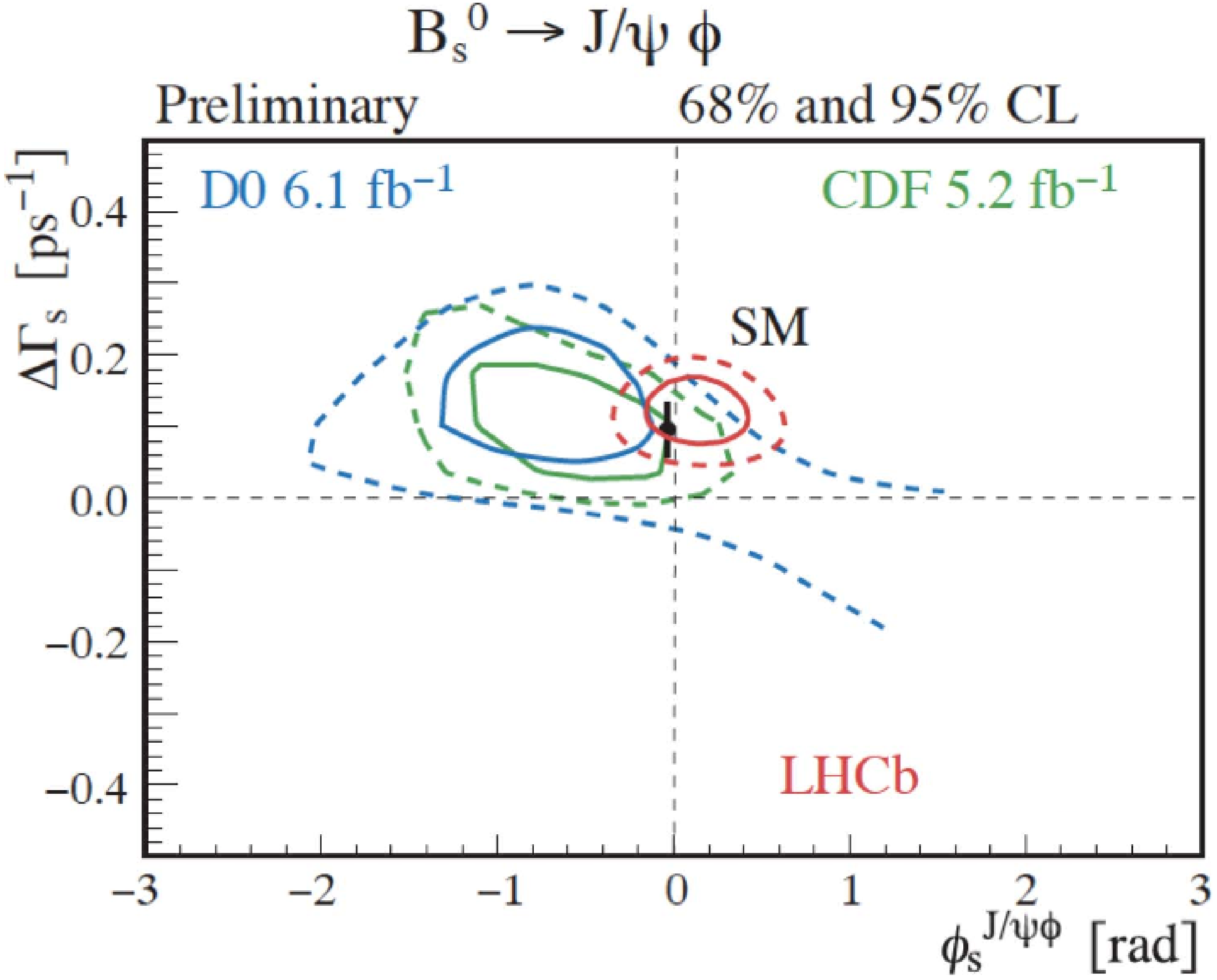
Loop effects preferred

BACKUP

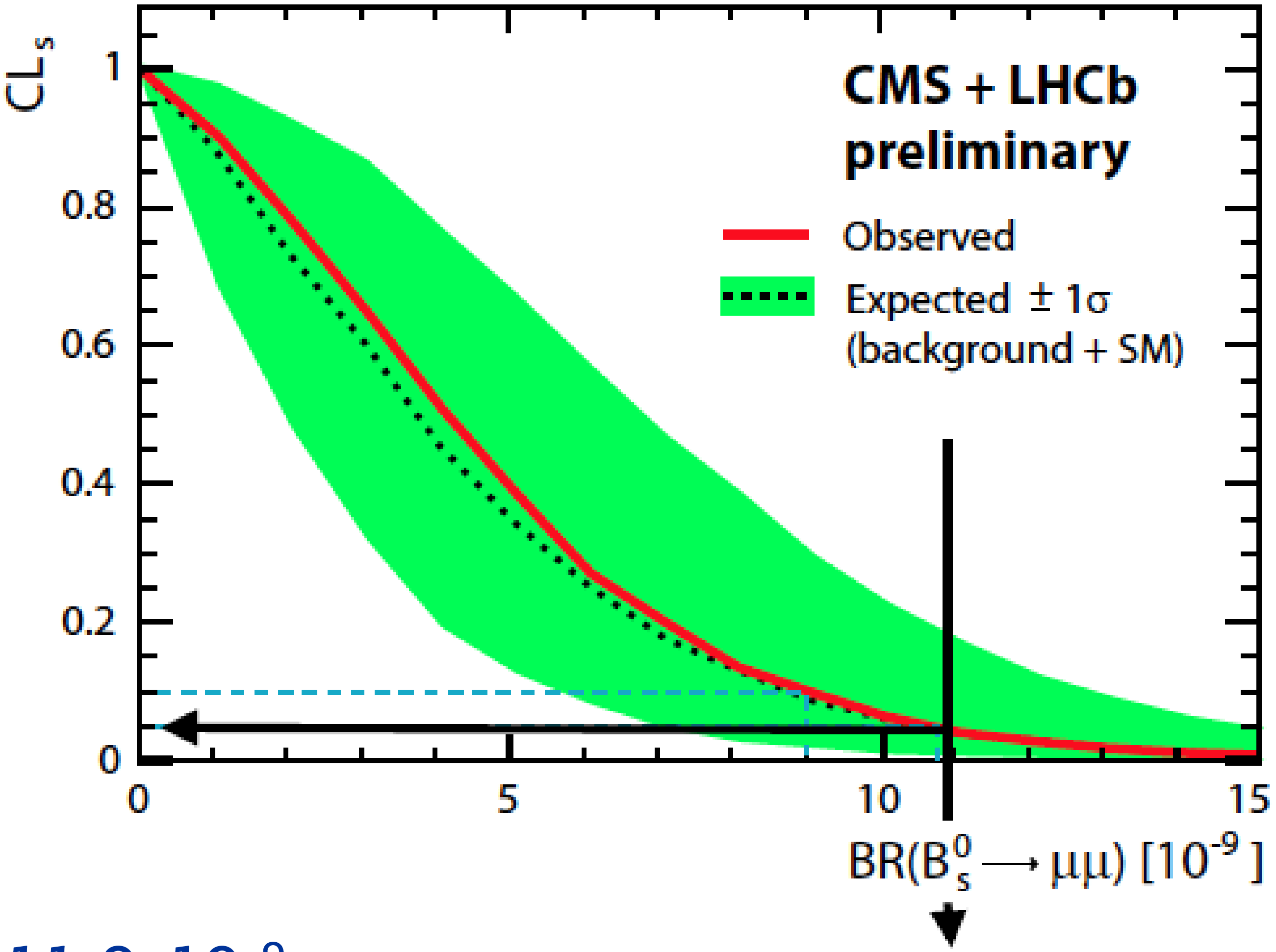
LHC and flavour physics

Important results from LHCb

Back into agreement with SM



CMS & LHCb combined (presented at EPS'11 Grenoble)



$< 11 \times 10^{-9}$ @ 95% CL

cfr
CDF 18+11-9 10^{-9}
SM 3.2±0.2 10^{-9}

A^b_{FB} vs $[\sin^2\theta]_{lept}$: New physics in Zbb vertex?

After all the 3rd generation is somewhat special

The difficulty is that:

- No deviations are seen in A_b (SLD) and R_b
- A quite large shift in g_R, the Zbb right-handed coupling is needed (by ~30%: indicates a tree level effect)

$$A^b_{FB} = \frac{3}{4} A_e A_b \qquad A_f = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}$$

SM: $g_L^2 \approx 0.72 >> g_R^2 \approx 0.02$

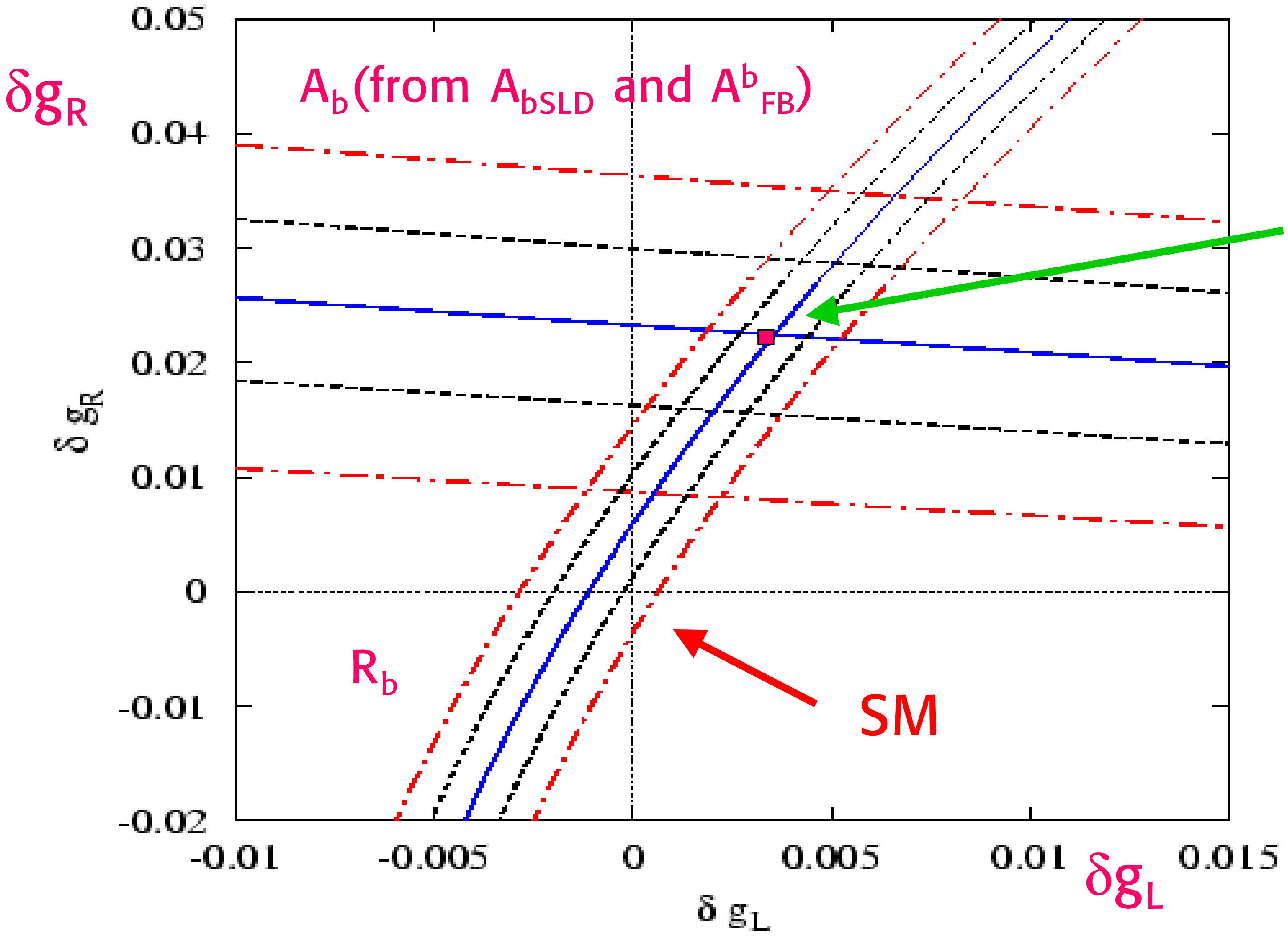
$$(A_b)_{SM} \approx 0.936$$

from A^b_{FB} → $(A_b)_{SM} - A_b = 0.055 \pm 0.018$ -> ~3 σ

But note: $(A_b)_{SLD} = 0.923 \pm 0.020$,

also $R_b = 0.21629 \pm 0.00066$ ($R_{bSM} \sim 0.2157$)

$R_b \sim g_L^2 + g_R^2$



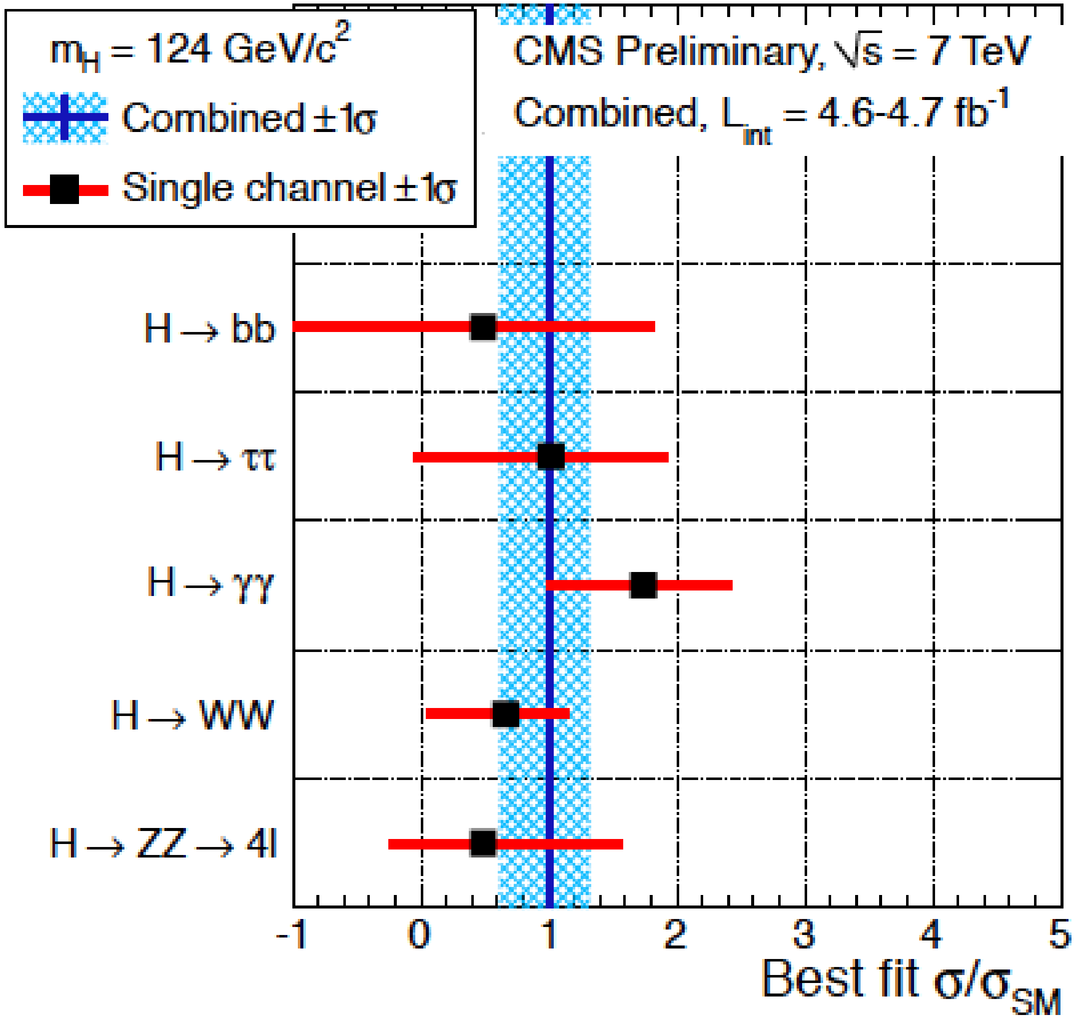
Choudhury,
Tait, Wagner '01

0.992 g_L(SM),
1.26 g_R(SM)

Too large for
a loop effect.
Needs a ad hoc
tree level effect

Mixing of the b quark with a vectorlike doublet (ω,χ) with charges (2/3, -1/3) or (-1/3, -4/3)? CTW'01
Or mixing of Z with Z' and KK recurrences in extra dim models? Agashe, Contino, Pomarol '06; Djouadi, Moreau, Richard '06

A moderate enhancement of the $\gamma\gamma$ rate may be indicated



Do the masses really coincide?

Erler '11