Lecture 2

In the first lecture, we reviewed the realization of the Higgs mechanism in the SM with an elementary scalar doublet

Such a realization is phenomenologically very successful, but suffers from a naturalness problem when we extrapolate the SM to physical scales much larger than the Fermi scale

We will now comment on extensions/modifications of the SM at the Fermi scale that try to address the naturalness problem without destroying the phenomenological success of the SM (otherwise, no strong motivation to look for complications)

As already anticipated on general grounds at the end of last lecture, this is not an easy task: no “full solution” yet, but some (well-)motivated candidates to be tested at the LHC

Supersymmetry at the LHC scale?

SUSY may solve the gauge hierarchy problem

[Maiani,1979; Veltman,1981; Witten,1981; …]

thanks to its special renormalization properties

[Wess-Zumino,1974; Iliopoulos-Zumino,1974; …;Ferrara-Girardello-Palumbo,1979; …]

In supersymmetric extensions of the SM:

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda^2}{m_{\tilde{t}}^2}$$

Power-dependence on SUSY-breaking masses
only mild logarithmic dependence on cutoff

Naturalness preserved up to very high scales
if superparticle masses are at the weak scale

Two important bonuses: unification, dark matter

Supersymmetric Higgs sectors

At least 2 Higgs doublets [Fayet,1975-77], as in the MSSM:

$$H_1 \equiv \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \sim (1,2,-1/2) \qquad H_2 \equiv \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \sim (1,2,+1/2)$$

(chargino masses; quark and lepton masses; anomalies)

Possibly an extra singlet N ~ (1,1,0) , as in the NMSSM

special two-Higgs models with natural FCNC suppression
(only one neutral Higgs couples to each charge sector)

The MSSM tree-level potential:

$$V_0 = m_1^2|H_1|^2 + m_2^2|H_2|^2 + m_3^2(H_1H_2 + h.c.) + \frac{g^2}{8}(H_2^\dagger\sigma^a H_2 + H_1^\dagger\sigma^a H_1)^2 + \frac{g'^2}{8}(|H_2|^2 - |H_1|^2)^2$$

SUSY ➔ quartic Higgs couplings related to gauge couplings

Gauge symmetry breaking and MSSM Higgs spectrum

$$\langle H_1^0 \rangle = v_1 \neq 0 \quad \langle H_2^0 \rangle = v_2 \neq 0 \qquad v^2 = v_1^2 + v_2^2 \qquad \tan\beta = \frac{v_2}{v_1}$$

Fermi scale

$$G^\pm \quad G^0 \qquad H^\pm \qquad (h, H) \qquad A$$

Goldstone charged CP-even CP-odd

Tree-level masses and couplings

Measured SM parameters + two more, e.g.: $(m_A, \tan\beta)$

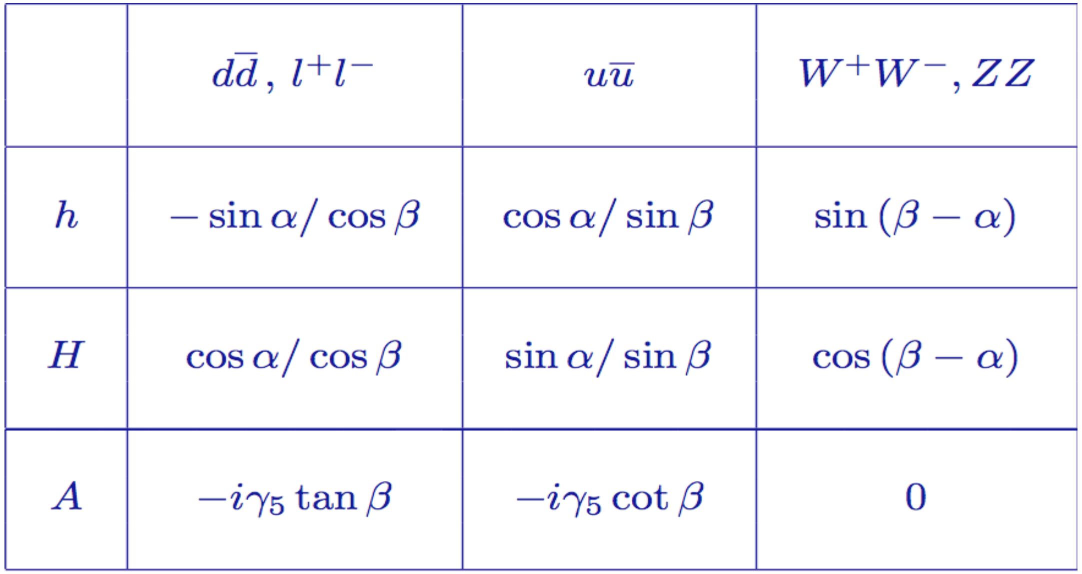
$$m_{H^\pm}^2 = m_W^2 + m_A^2 \qquad m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right]$$

$$m_W, m_A < m_{H^\pm} \qquad m_h < m_Z |\cos 2\beta| < m_Z < m_H \qquad m_h < m_A < m_H$$

$$\cos 2\alpha = -\cos 2\beta \, \frac{m_A^2 - m_Z^2}{m_H^2 - m_h^2} \qquad -\frac{\pi}{2} < \alpha \leq 0$$

Mixing angle in
CP-even sector

Modified couplings of neutral MSSM Higgs bosons



	$d\bar{d}\,,\, l^+l^-$	$u\bar{u}$	W^+W^-, ZZ
h	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin(\beta-\alpha)$
H	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos(\beta-\alpha)$
A	$-i\gamma_5\tan\beta$	$-i\gamma_5\cot\beta$	0

- Coupling to vector bosons are never stronger than in SM
- Coupling to SM fermions can be much stronger, e.g. bottom and tau couplings for large values of tan(beta)

Decoupling limit (towards the “unnatural” SM):

$$m_A^2 \gg m_Z^2 \quad \Rightarrow \quad h \sim h_{SM} \quad \& \quad \alpha \sim (\beta - \pi/2)$$

(H,A,H^+,H^-) = nearly degenerate decoupling heavy doublet

Radiative corrections to MSSM Higgs sector

Inclusion of radiative corrections to the MSSM Higgs sector
[dominated for moderate tan(beta) by top and stop loops]
can drastically change the tree-level spectrum and couplings
[Ellis-Ridolfi-FZ+Okada-Yamaguchi-Yanagida+Haber,Hempfling,1991; …]

Some approximate one-loop formulae

[moderate tan(beta) & decoupling limit]

$$\Delta m_h^2 \sim \frac{3\, g^2\, m_t^4}{16\pi^2\, m_W^2} \log \frac{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}{m_t^4}$$

←Negligible stop mixing

Stop mixing theta↓

$$(\Delta m_h^2)_{mix} \simeq \frac{3\, g^2\, m_t^2\, s_{2\theta}^2\, (m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2)}{32\pi^2\, m_W^2} \left[\log \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} + \frac{s_{2\theta}^2\, (m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2)}{4\, m_t^2} \left(1 - \frac{1}{2} \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \log \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \right) \right]$$

Main 1-loop corrections to couplings absorbed by running
couplings and by loop-corrected values of alpha & beta

Upper bound on m_h in the MSSM

Two-loop corrections to neutral MSSM
Higgs boson masses almost all computed
[Hempfling-Hoang 94; Heinemeyer et al 98-04;
Espinosa-Zhang 98-00; Slavich et al 01-03; Martin 02-04]

even some (small) three loop effects [Martin 07]

Typically, $m_h^{max} \sim 130$ GeV

Slight increase when stretching model parameters
& including errors in the determination of m_{top}

Slight decrease when considering specific
models of supersymmetry breaking/mediation

MSSM post-LEP tension

concrete MSSM realization poses some tuning problems, especially when extrapolating the MSSM to high scales

$$m_Z^2 \sim -2m_H^2 = -2\mu^2 + \frac{3\lambda_t^2}{2\pi^2} m_{\tilde{t}}^2 \log\frac{M_P}{m_{\tilde{t}}} + \ldots \sim -2\mu^2 + O(1) m_{\tilde{t}}^2 + \ldots$$

naturalness suggests light SUSY: $m_{\tilde{t}} \sim \mu \sim m_Z$

However, no susy particle found at LEP2 & Tevatron!

Things are made worse by the upper bound on the Higgs mass

$$m_h^2 < m_Z^2 + m_t^2 \frac{3\lambda_t^2}{2\pi^2} \log\frac{m_{\tilde{t}}}{m_t} \quad \& \quad m_h > 114.4\, GeV \quad \Rightarrow \quad m_{\tilde{t}} > 500\text{-}1000\, GeV$$

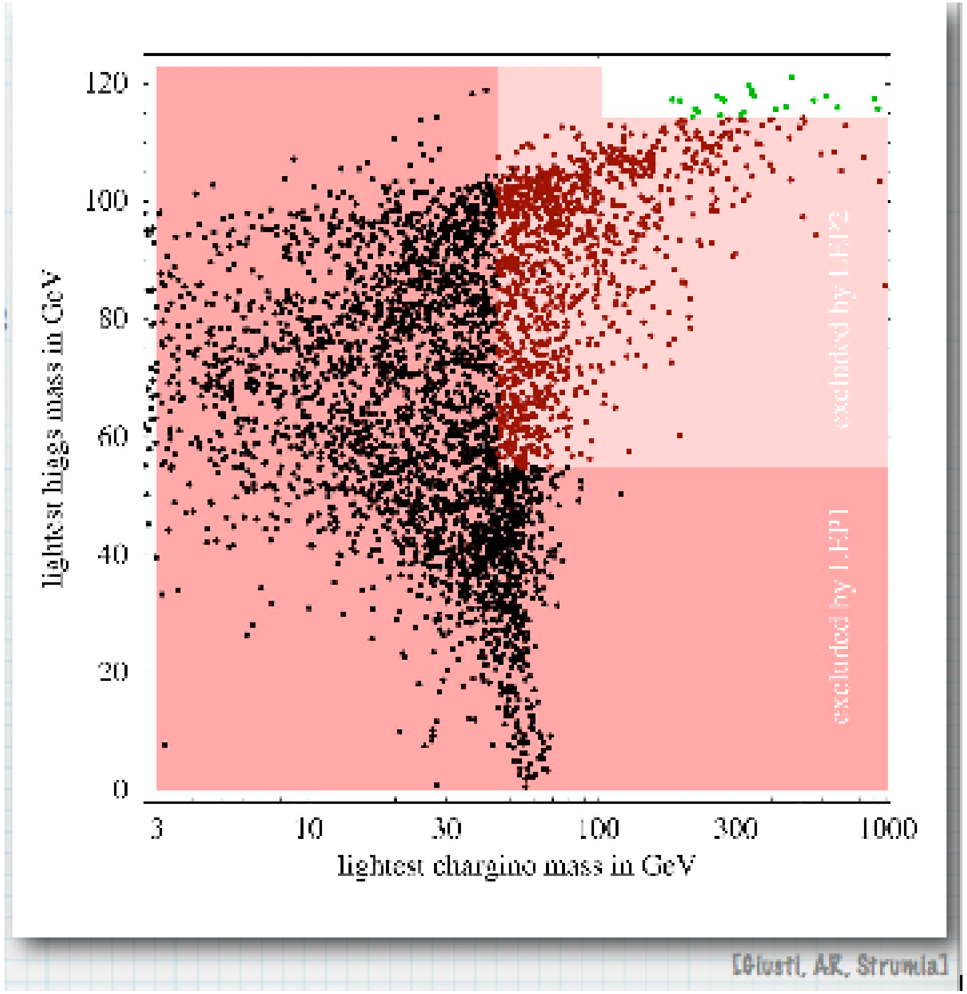
O(few%) fine-tuning required without further theoretical input

(might be explained in dynamical models)

There are ways to do better, e.g. adding a singlet (NMSSM) or lowering the cutoff scale of the MSSM (but unification?)

An empirical measure of fine-tuning

After LEP-2 ↘



lightest
Higgs
mass
(GeV)

← After LEP-1

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

lightest chargino mass (GeV)

Plausibility of MSSM & variations

Taking SUSY at face value, its appealing properties

- Solution of “big” gauge hierarchy problem
- Effective unification of gauge couplings
- Natural candidate for dark matter

come with a number of unanswered questions

- Special flavour structure of soft terms
- Relative scale of different soft terms
- Absolute scale of soft terms
- Little hierarchy problem
- Vacuum energy problem (as any other realistic model)

some may have plausible explanations in the underlying theory, but we may still miss some important ingredient

The verdict is left to the (Tevatron and) LHC experiments

Other new physics at the LHC scale?

What if naturalness fails for the weak scale?
(as it may fail for the vacuum energy scale)
A logical possibility, although not my favourite

Light SM Higgs boson and nothing else at the LHC
(called by some supersplit supersymmetry)

- A triumph for the SM
- A triumph for the LHC and its experiments
- A failure for many theorists
- Hard to understand what comes next

Before such possibility, rather consider solutions to the SM naturalness problem, alternative/complementary to SUSY, they also predict testable new physics at the LHC scale

Only briefly summarized here because of time constraints

A strongly interacting EW-breaking sector?

The would-be Goldstone bosons in (W_L,Z_L) come from an elementary scalar doublet in the SM: could be instead bound states of a new strong interaction (see superconductors)

Traditional realization with no light Higgs (technicolor) strongly disfavoured by EW+flavor precision tests (and by our limited understanding of non-perturbative dynamics)

The idea is now being revived with a modern twist:
also a light Higgs as pseudo-Goldstone boson,
holographic intepretation with extra dimensions
A lot of recent related activity in model building,
cannot be covered here because of time constraints
[some references for further reading in the next page]

Foreseeable difficulties with naturalness and precision tests, but also some promising progress: technicolor strikes back?

Some references for further reading

Technicolor:
Weinberg+Susskind, 79; … Recent review: Hill-Simmons, hep-ph/0203079.

Higgs as pseudo-Goldstone boson (Little Higgs) :
Georgi-Kaplan, 1984; …; Arkani-Hamed et al., 01-02; … Recent reviews:
Schmaltz-TuckerSmith, hep-ph/0502182; Perelstein, hep-ph/0512128.

Higgsless models with extra dimensions:
Csaki-Grojean-Murayama-Pilo-Terning-…, 03-04
Gauge-Higgs unification with extra dimensions:
Manton+Fairlie, 79; …; Hosotani, 89; …
A recent review on both: Csaki, hep-ph/0510275

EW breaking with deconstructed extra dimensions
ArkaniHamed et al, hep-ph/0105239; Cheng et al, hep-th/0104179.

Light Higgs as holographic pseudo-Goldstone boson:
Contino et al, 03-06, e.g. hep-ph/0412089

No-lose: a Higgs or new physics at the TeV scale

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; …]

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

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

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

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

Chiral Lagrangian for electroweak interactions

[Appelquist-Bernard, 1980; Longhitano, 1981; …]

Without the Higgs particle, can still write a gauge-invariant theory in the so-called non-linear realization. It is the chiral Lagrangian for the Goldstone bosons, analogous to the one for pions in QCD: a non-renormalizable effective theory with a cutoff scale O(2 TeV), where V_L interactions become strong, and new states must appear to restore unitarity.

Signals of the new strong dynamics should show up in the scattering of longitudinal weak bosons at high enough energy

- A challenging task for the LHC, which can probe the easiest cases but may not have enough sensitivity to all possibilities
- As we shall see later, still permitted but highly unlikely, in view of the precision tests of EW symmetry breaking

What is sure vs. likely vs. possible

Sure:

the Higgs mechanism breaks the EW gauge symmetry, with
either a Higgs particle with mass < 1 TeV, or a strongly
interacting sector with new physics below a couple of TeV
New states must appear at the TeV scale
(beyond the SM states we have already observed)

Very likely:

there is at least one Higgs particle with mass << 1 TeV

Likely:

Higgs particle is accompanied by new physics,
at the TeV scale to preserve naturalness,
Supersymmetry (perhaps MSSM) still best candidate,
no sufficient confidence to ignore other possible candidates
Non-trivial to be as successful phenomenologically as the SM!

F. Zwirner
University & INFN, Padova

The Hunt for the Higgs particle

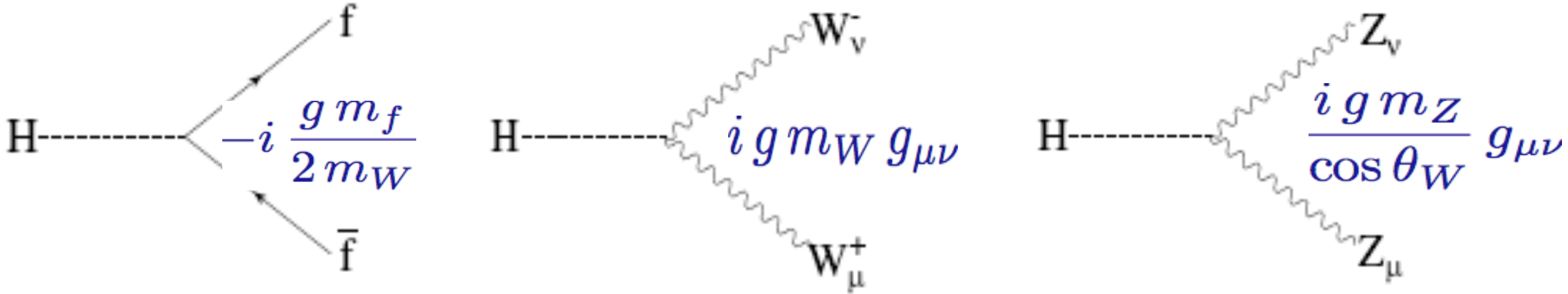
Part 2

Cern Academic Training, 27/2-1/3/2007

SM Higgs decays

In the SM, the only unknown parameter is m_H

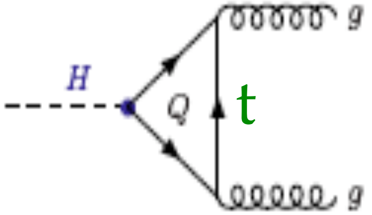
Tree-level decays



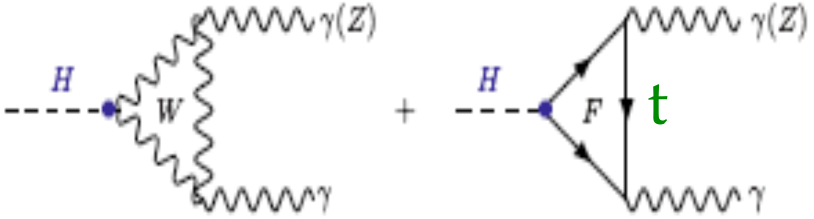
$$-i\,\frac{g\,m_f}{2\,m_W} \qquad i\,g\,m_W\,g_{\mu\nu} \qquad \frac{i\,g\,m_Z}{\cos\theta_W}\,g_{\mu\nu}$$

Asymptotically : $\Gamma_{f\bar{f}} \sim G_F\,m_f^2\,m_h$ $\quad\Gamma_{VV} \sim G_F\,m_h^3$

Loop decays



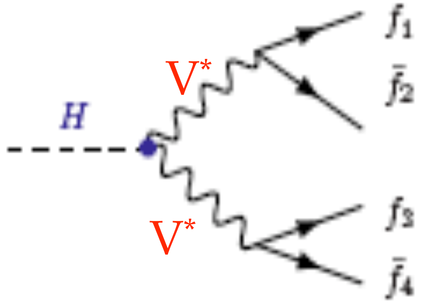
[Wilczek, 1977; …]



[Ellis-Gaillard-Nanopoulos, 1976; …]

Comments on SM Higgs decays

Decays into VV pairs = four-fermion final states via virtual V^*V^* exchange



QCD corrections very important for

$q\bar{q}$ gg $\gamma\gamma$ channels

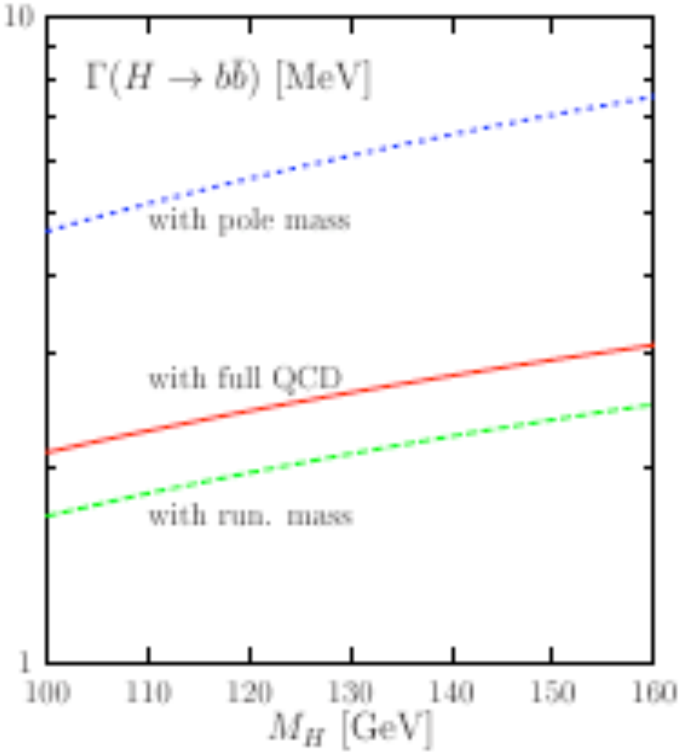
NLO and some NNLO available

main EW corrections also available

$q\bar{q}$ leading corrections absorbed in $m_q(m_h)$

gg increase the partial width by 60-70%

but origin understood, still under control

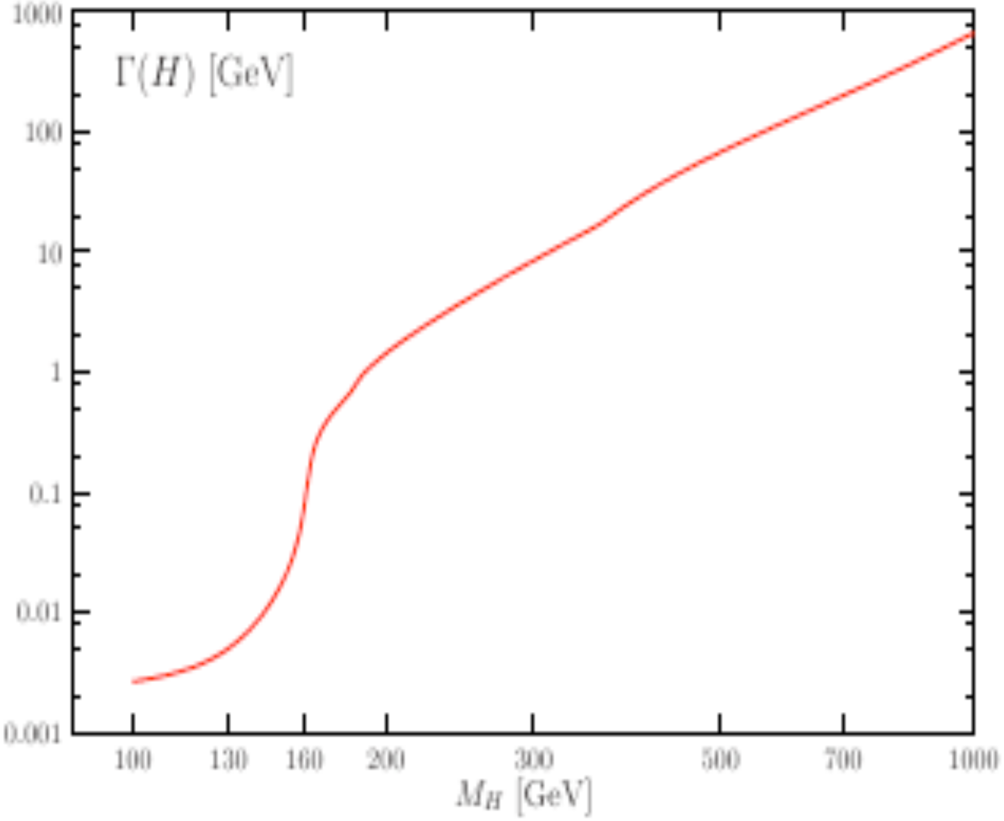


[Djouadi, hep-ph/0503172]

Total SM Higgs width

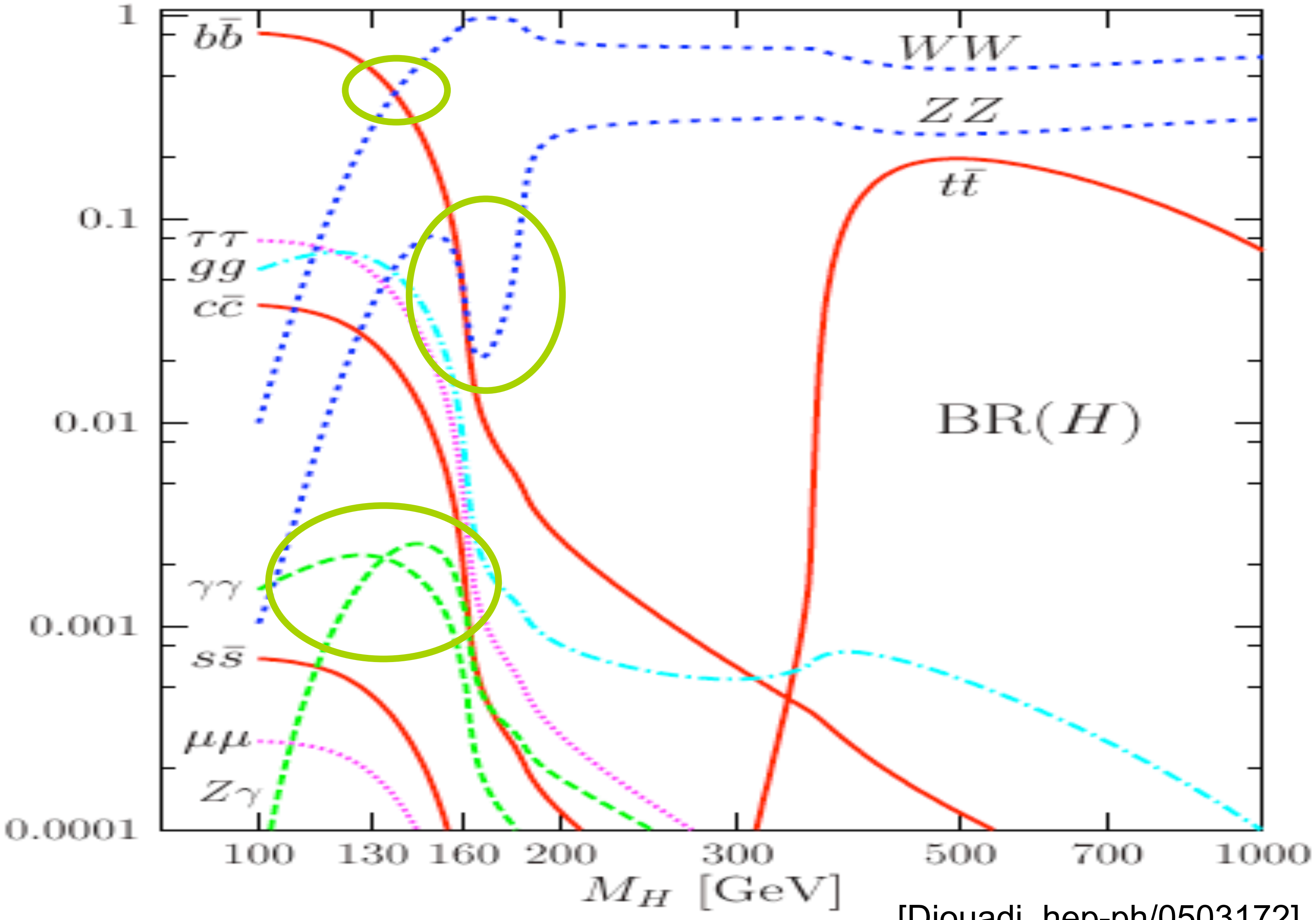
Three typical mass regions:

Low mass:
$m_h < 130$ GeV
(VV negligible)
Intermediate mass:
130 GeV $< m_h <$ 180 GeV
(VV competitive)
High mass:
$m_h > 180$ GeV
(VV dominant)



[Djouadi, hep-ph/0503172]

SM Higgs branching ratios



[Djouadi, hep-ph/0503172]

Some BSM variations

How could the SM Higgs decay properties be altered?

Main mechanisms:

- New Higgs couplings to light enough exotic particles (if not excluded by direct searches or indirect constraints): not only new final states, also new virtual states in loops

- Modified tree-level couplings to SM particles, e.g. due to the mixing of the SM-like Higgs with other scalar states

Innumerable examples in extensions of the SM,
both supersymmetric and non-supersymmetric,
large number of possibilities to be kept in mind
detection can be easier or more difficult

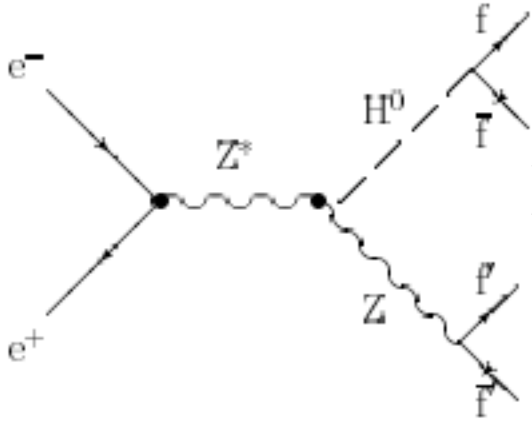
LEP direct searches [Aleph, Delphi, L3, Opal]

LEP signals for a SM Higgs

$$e^+ \, e^- \to Z^* \to Z^* \; H^* \to f \, \overline{f} \; f' \, \overline{f'}$$

LEP-1: 1.7 × 10^7 Z^0 decays

LEP-2: 2.46 fb^{-1} at 189-209 GeV



[Ioffe-Khoze, 1976]

Useful final states (LEP-2):

$(H \to b\bar{b})(Z \to q\bar{q})$ Four-jet (~60%)

$(H \to b\bar{b})(Z \to \nu\bar{\nu})$ Missing energy (~17%)

$(H \to b\bar{b})(Z \to l^+l^-)$ Leptonic (l=e,mu) (~6%)

$(H \to b\bar{b})(Z \to \tau^+\tau^-)$ $(H \to \tau^+\tau^-)(Z \to q\bar{q})$

Tau-lepton (~10%)

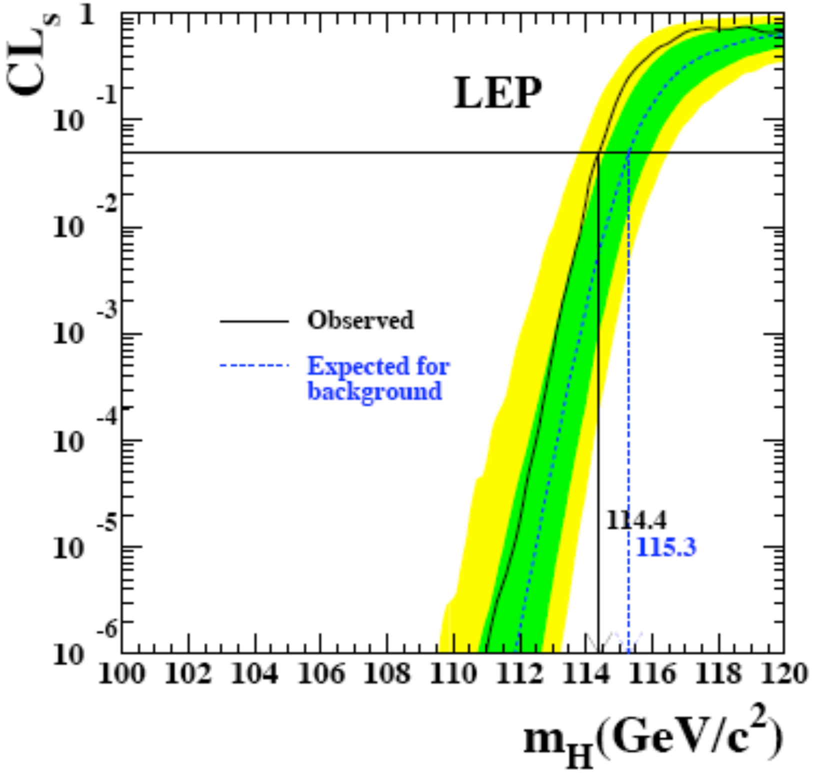
The standard LEP search [LHWG, hep-ex/0306033]

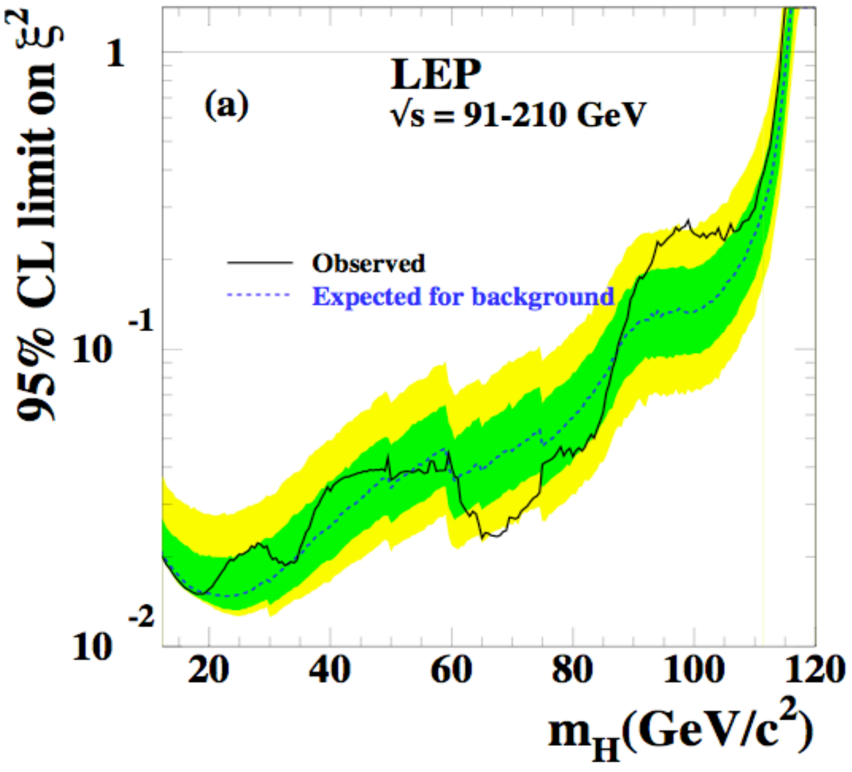
SM: $m_h > 114.4$ GeV at 95% c.l. [4 expts combined]

ALEPH excess, mostly in the four-jet channel, near 115-6 GeV

After the combination: $(1-CL_b) \sim 0.09$ against $CL_{s+b} \sim 0.15$

Also bounds on HZZ coupling varying m_h and decay modes





Some non-standard LEP searches

Exotic decays with SM hZZ:

100% hadronic ➔ 112.9 GeV

100% invisible ➔ 114.4 GeV

Fermiophobic ➔ 108.2 GeV

MSSM: complementarity

$$\sigma(e^+ e^- \to h\ Z) \propto \sin^2(\beta - \alpha)$$

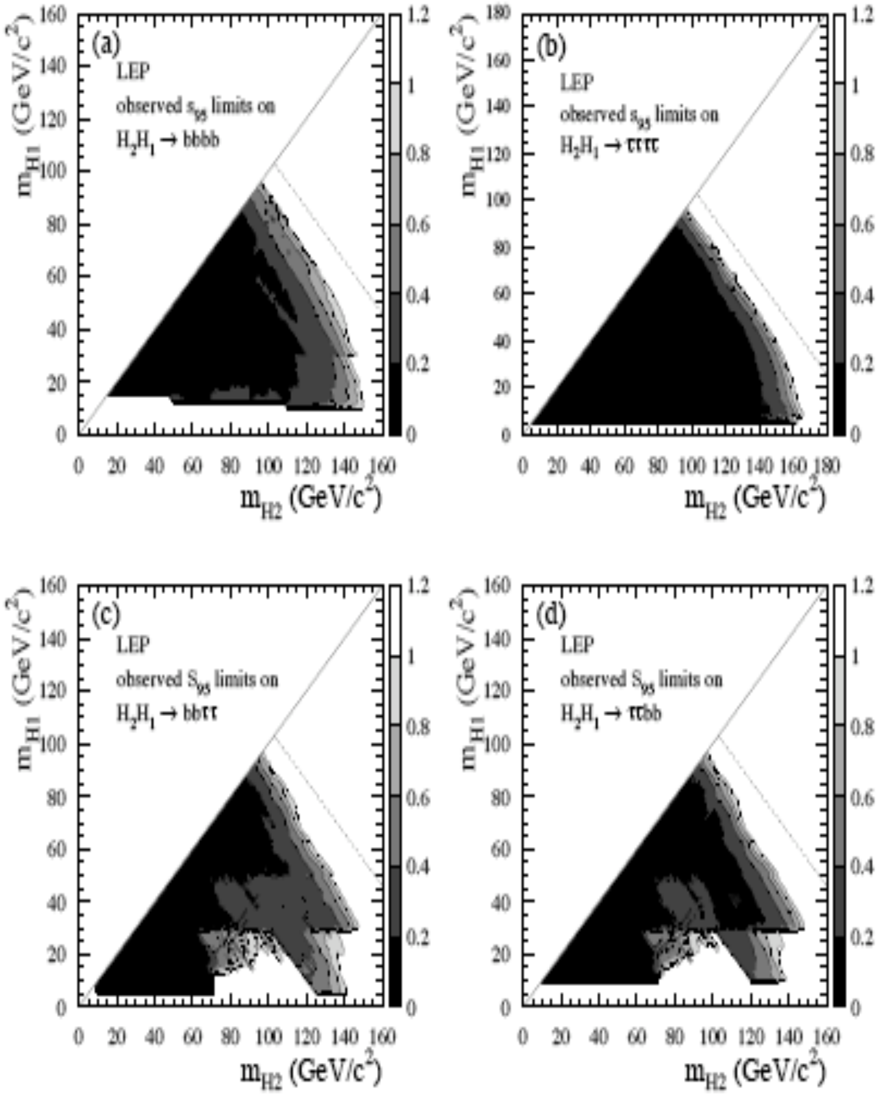
$$\sigma(e^+ e^- \to h\ A) \propto \cos^2(\beta - \alpha)$$

m_h ,m_A > 93 GeV at 95% c.l

in most parameter space

possible h ➔ A A decays

easily lost in parameter space



[LHWG, hep-ex/0602042]

Higgs mass vs. precision tests

Electroweak theory tested at the level of quantum corrections by precision measurements at SLC, LEP, Tevatron and more: large number of observables, many with per-mille accuracy

SM analysis:

E.g., for fixed values of the remaining SM input parameters:

$$\Delta m_W \simeq -(57\,MeV)\ \log X_h - (9\,MeV)\ (\log X_h)^2 + (0.54\,GeV)\ (X_t^2 - 1)$$

$$\Delta \sin^2_{eff} \simeq 4.9 \times 10^{-4}\ \log X_h + 3.4 \times 10^{-5}\ (\log X_h)^2 - 2.8 \times 10^{-3}\ (X_t^2 - 1)$$

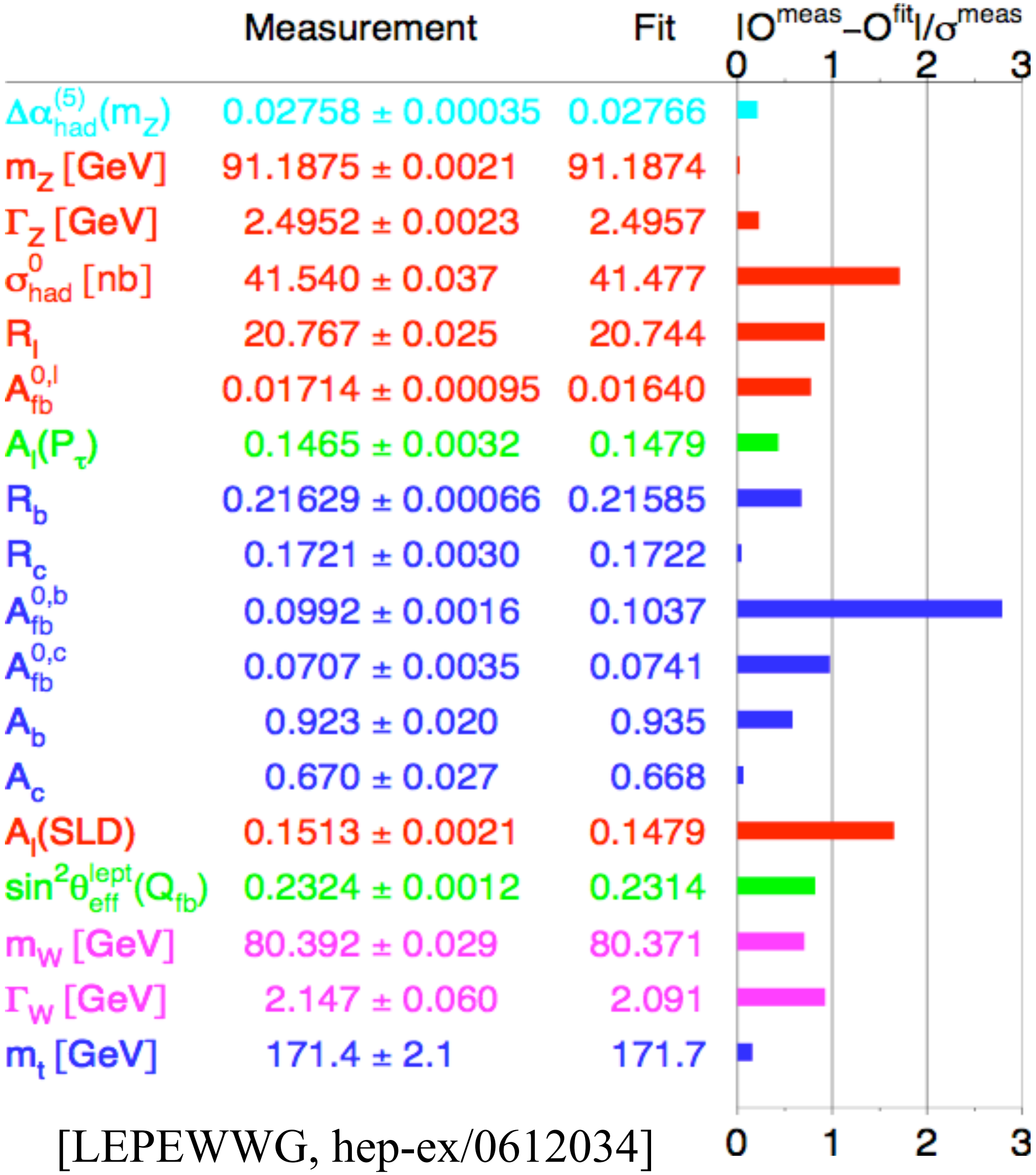
$$X_h = \frac{m_h}{100\,GeV} \qquad X_t = \frac{m_t}{174.3\,GeV}$$

[Ferroglia-Ossola-Passera-Sirlin hep-ph/0203224]

Now that m_t is precisely known, indirect constraints on m_h

Correlations: $m_{t\downarrow} \Rightarrow m_{h\downarrow}$ $m_{W\downarrow} \Rightarrow m_{h\uparrow}$ $s2w_{l\downarrow} \Rightarrow m_{h\downarrow}$

Precision tests of EW breaking



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
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]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7

[LEPEWWG, hep-ex/0612034]

Recent improvement
(included in the table):
$m_t = 171.4 \pm 2.1$ GeV
(CDF & D0)

Very recent
(not included in the table):
$m_W = 80398 \pm 25$ MeV
(LEP & Tevatron, after
new run-II CDF prel.)

SM still fits well at
such high precision!

The SM Higgs fit

Indicates (too?) light Higgs

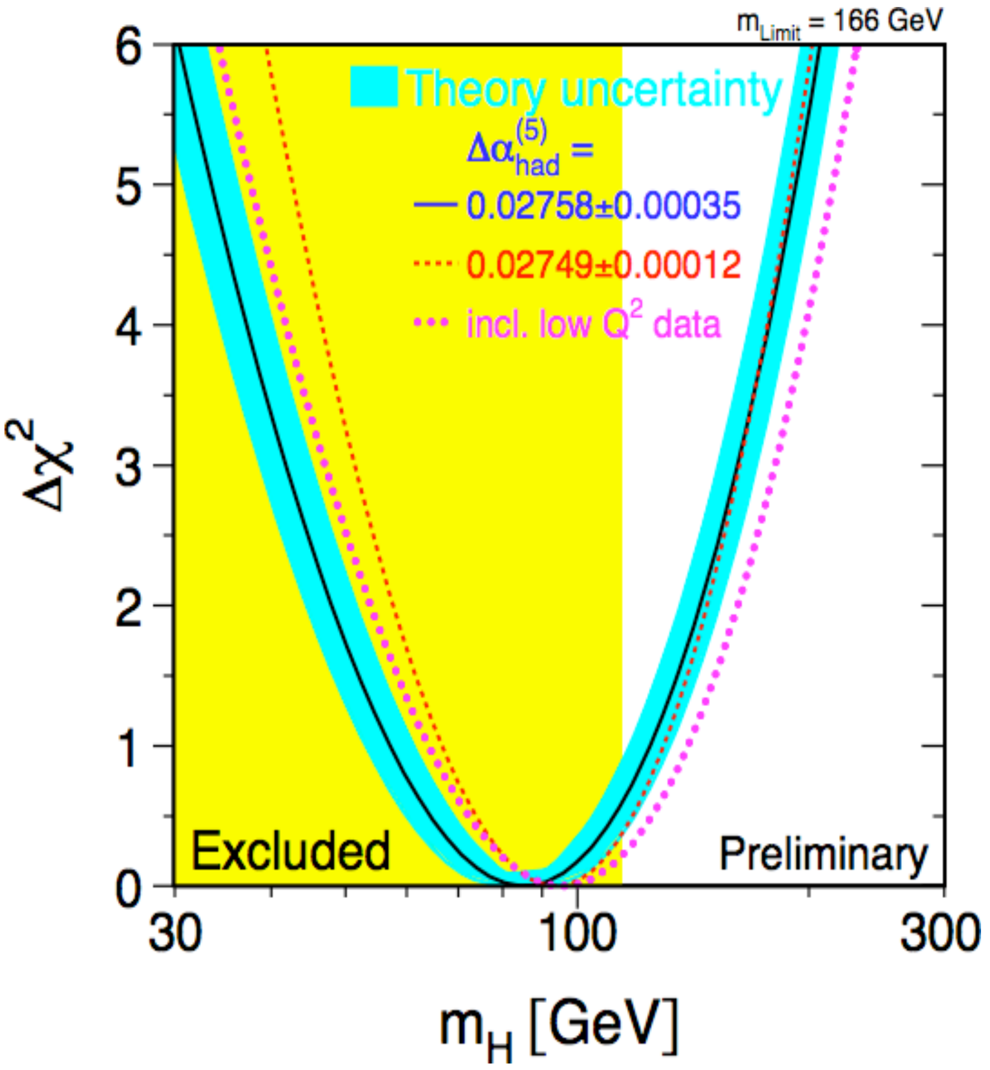
After including the new m_W
[M.Grunewald, unpublished,
as quoted in several talks]:

$m_h = 80^{+36}_{-26}$ GeV

$m_h < 153$ GeV at 95% c.l.

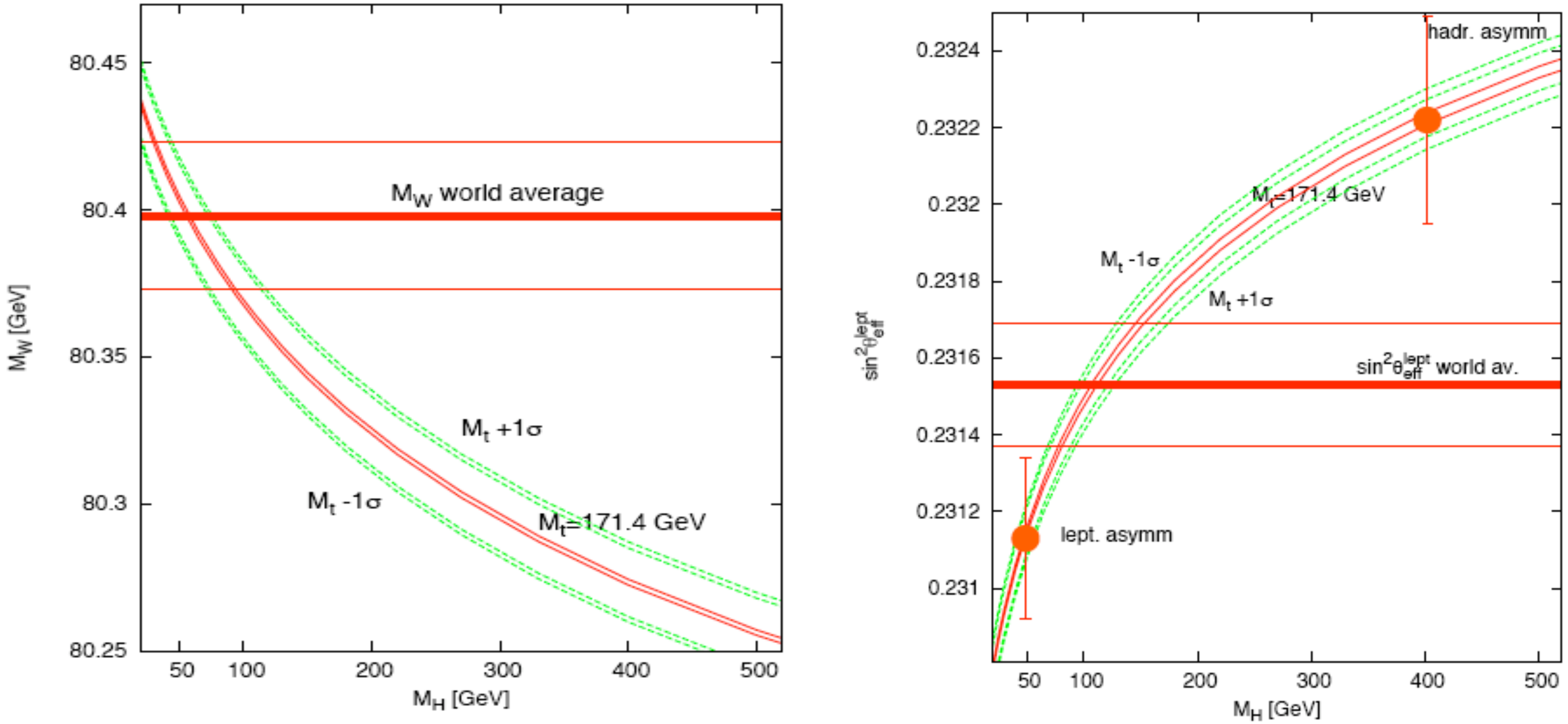
$m_h < 189$ GeV at 95% c.l.
including direct bound

(slightly more stringent
than before new CDF m_W)



[LEPEWWG, hep-ex/0612034]

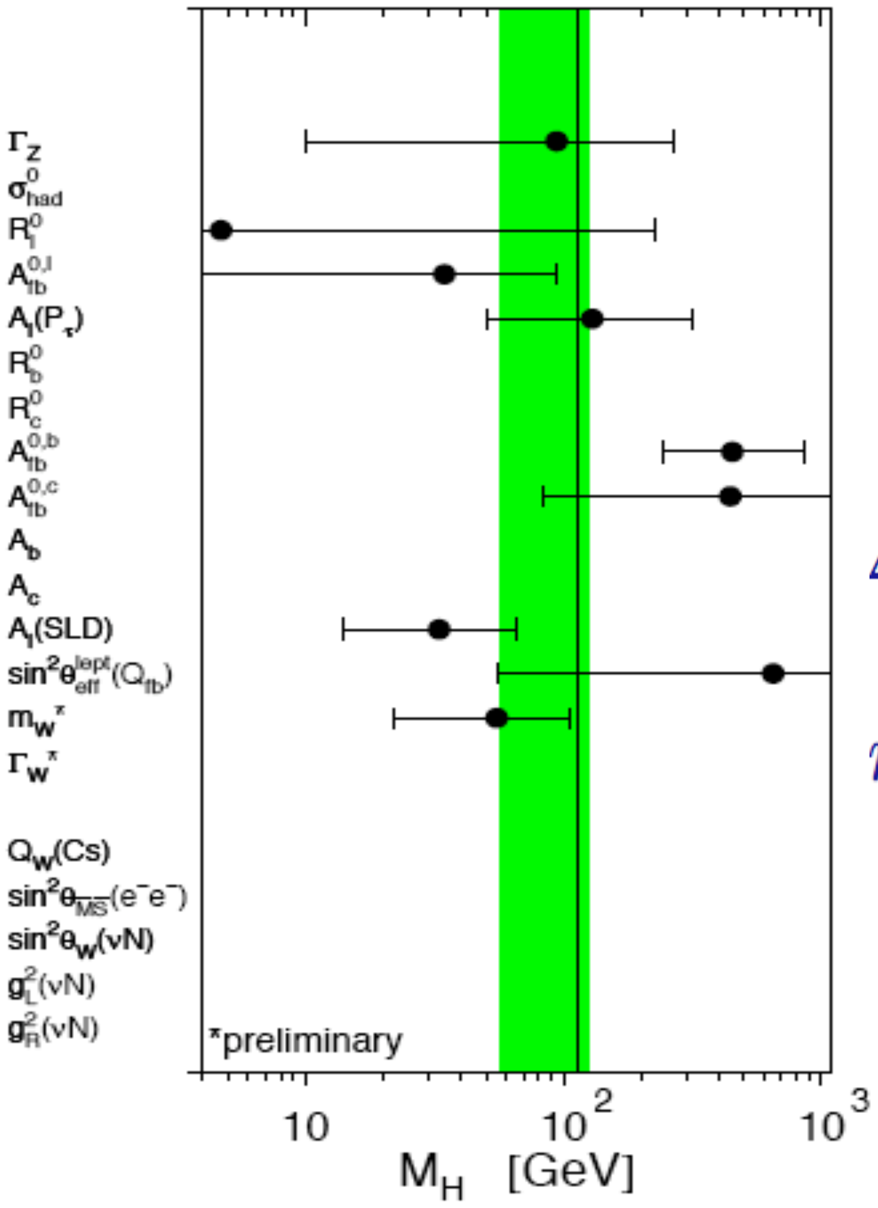
What prefers a light Higgs?



[P.Gambino, updated to Jan.07]

- m_W points to a light Higgs, with good accuracy
- Some tension in leptonic vs. hadronic asymmetries

Fit pseudo-observables vs. Higgs boson mass



$$\alpha_S(m_Z^2) = 0.118 \pm 0.003$$

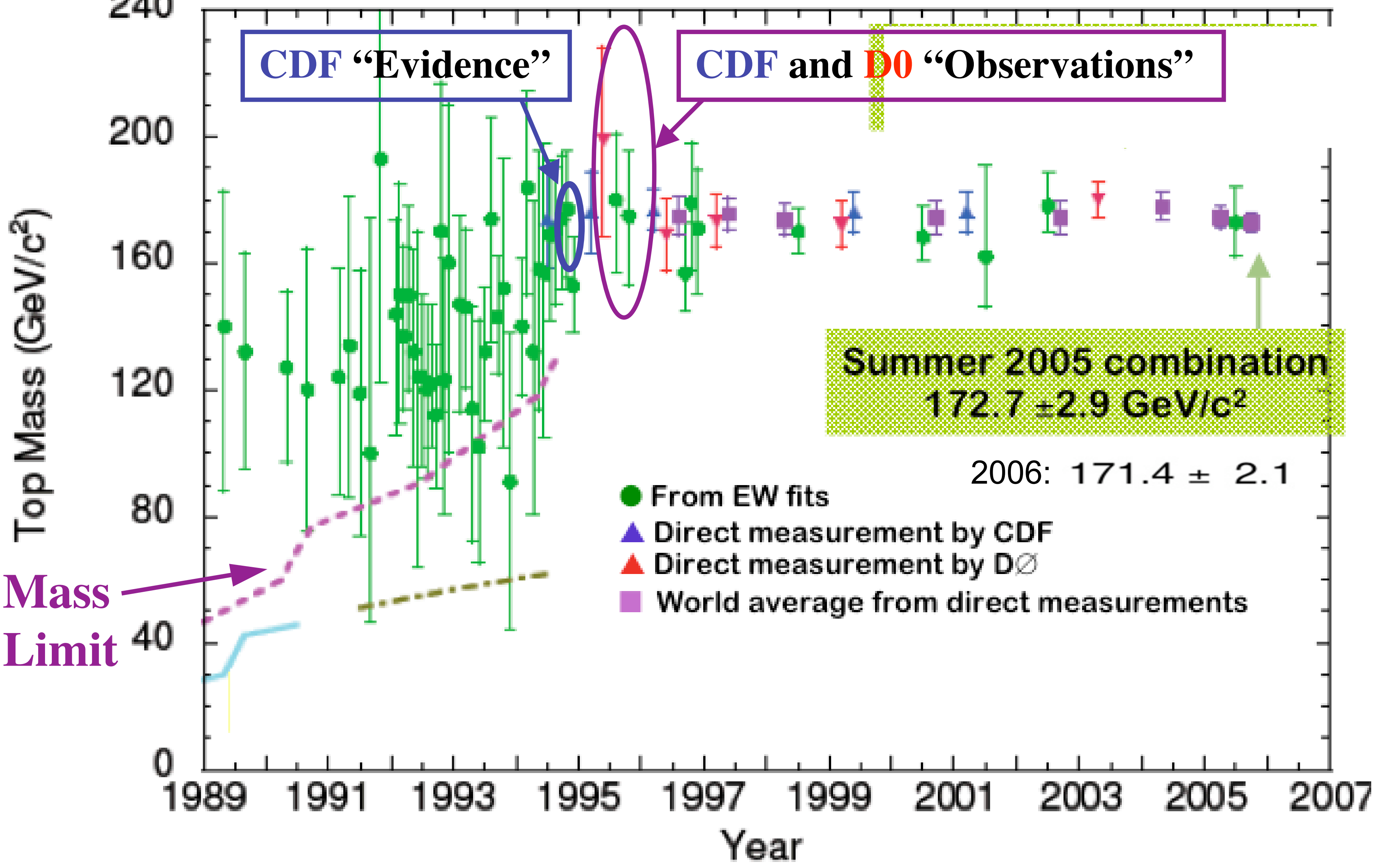
$$m_t = 171.4 \pm 2.1 \text{ GeV}$$

$$\Delta\alpha^{(5)}_{had}(m_Z^2) = 0.02761 \pm 0.00036$$

$$m_Z = 91.1875 \pm 0.0021 \text{ GeV}$$

[LEPEWWG, hep-ex/0612034]

Top Mass vs. Year (from **K. Tollefson**)



CDF **“Evidence”**

CDF and D0 “Observations”

Summer 2005 combination
172.7 ±2.9 GeV/c²

2006: 171.4 ± 2.1

Mass Limit

Precision tests beyond the SM

How to intepret precision tests without assuming the SM?
Success of the SM fit ➔ only minimal deviations tolerable

Within a concrete and calculable model (e.g. MSSM), one can just compute observables as functions of parameters: MSSM fits as well as SM in wide regions of its (large!) parameter space, even slightly better in some corners

Use an effective field theory approach to be agnostic

Extreme choice: effective theory without the Higgs field

$$\mathcal{L}_{eff} = \frac{v^2}{4} Tr \left(D_\mu \Sigma D^\mu \Sigma^\dagger \right) + \sum_i \tilde{c}_i \widetilde{\mathcal{O}}_i(\Sigma, \tilde{\Lambda}, \ldots)$$

[Appelquist-Bernard, 1980;
Longhitano, 1981; …]

More conservative: effective theory with the Higgs field

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}(\phi) + \sum_i c_i \, \mathcal{O}_i(\Phi, \Lambda, \ldots)$$

[Buchmuller-Wyler, 1986;
Grinstein-Wise, 1991; …]

End of lecture 2

Beginning of lecture 3