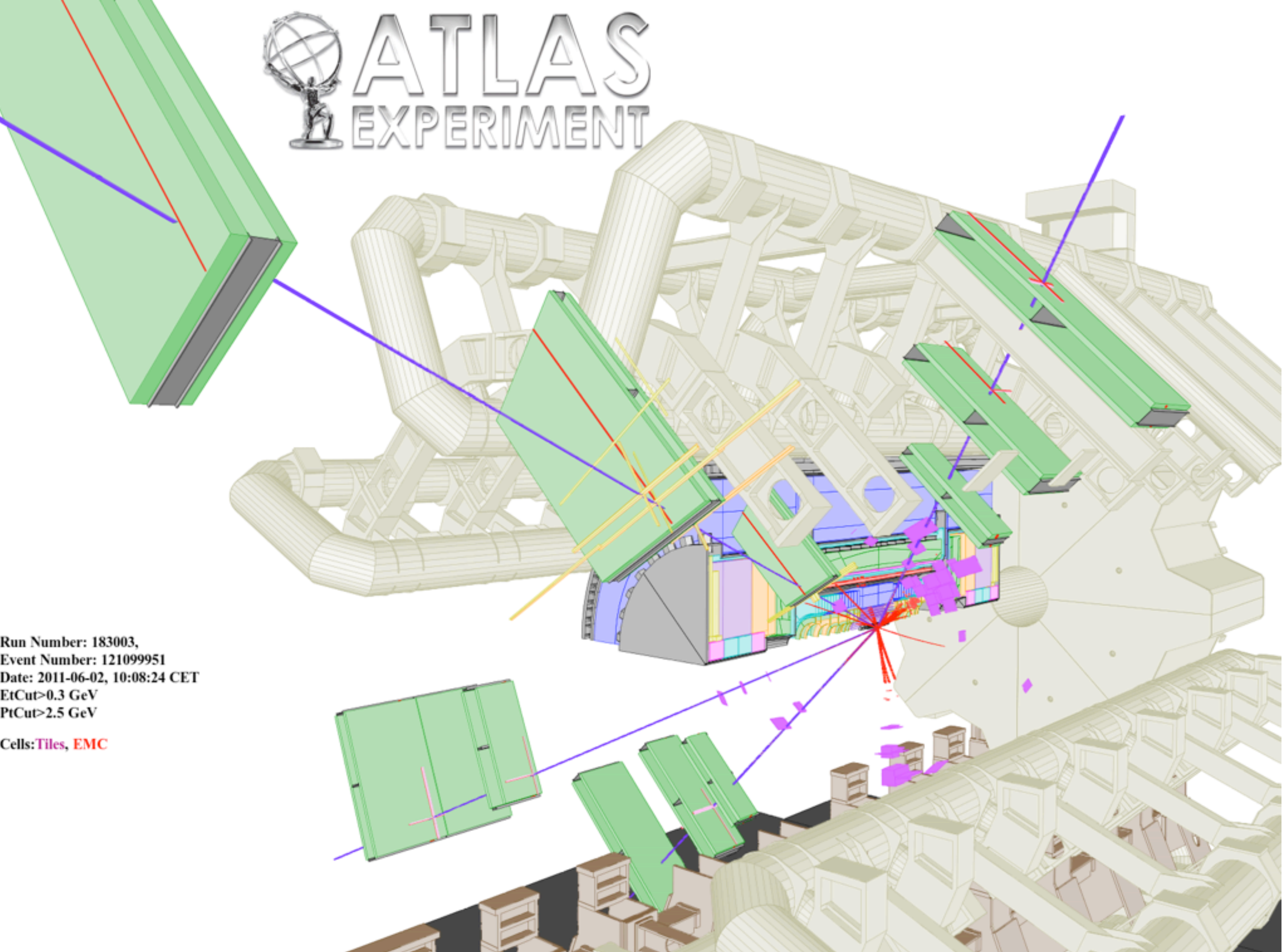

PP7 - Higgs Boson Physics

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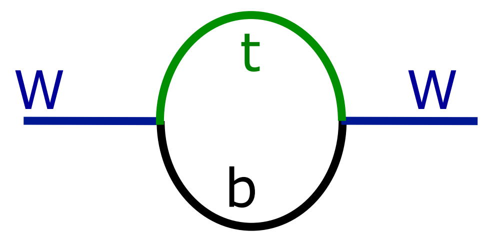
MPAGS
January, 2014

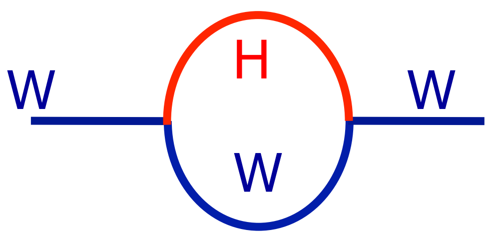
The Standard Model and the radiative corrections

As discussed in earlier lectures, the observables appearing in the SM Lagrangian (couplings, masses, etc) are renormalized. The actual parameters appearing in the Lagrangian (the bare parameters) are receiving corrections from higher-order loop diagrams.

In these loops, the fermions and and bosons of the SM appear, and in this way, the radiative corrections introduced dependencies between the electroweak observables and Standard Model Parameters

$M_W(\mathrm{Phys}) = \quad M_W(\mathrm{Born}) +$





$\ldots\ m_t^2 \qquad + \qquad \ldots\ \ln(M_H)$

In general, the dependence of the the corrections on the Higgs boson mass is logarithmic at the one loop level (Veltman's screening theorem). The corrections proportional to m_H^2 appear only at two loop thus "screened" or "dumped" by another power of the weak coupling constant squared.

$$\Delta \propto g^2 \left(\ln \frac{M_\mathrm{H}}{M_\mathrm{W}} + g^2 \frac{M_\mathrm{H}^2}{M_\mathrm{W}^2} \right)$$

Electroweak radiative corrections

The electroweak radiative corrections can be cast into three main categories; Fig. 1.4:

a) The fermionic corrections to the gauge boson self–energies. They can be divided themselves into the light fermion $f \neq t$ contributions and the contribution of the heavy top quark $f = t$. For the contributions of quarks, one has to include the important corrections stemming from strong interactions.

b) The contributions of the Higgs particle to the W and Z boson self–energies both at the one–loop level and at the two–level when e.g. the heavy top quark is involved.

c) Vertex corrections to the Z decays into fermions, in particular into $b\bar{b}$ pairs, and vertex plus box contributions to muon decay [in which the bosonic contribution is not gauge invariant by itself and should be combined with the self–energy corrections]. There are also direct box corrections, but their contribution at the Z–peak is negligible.

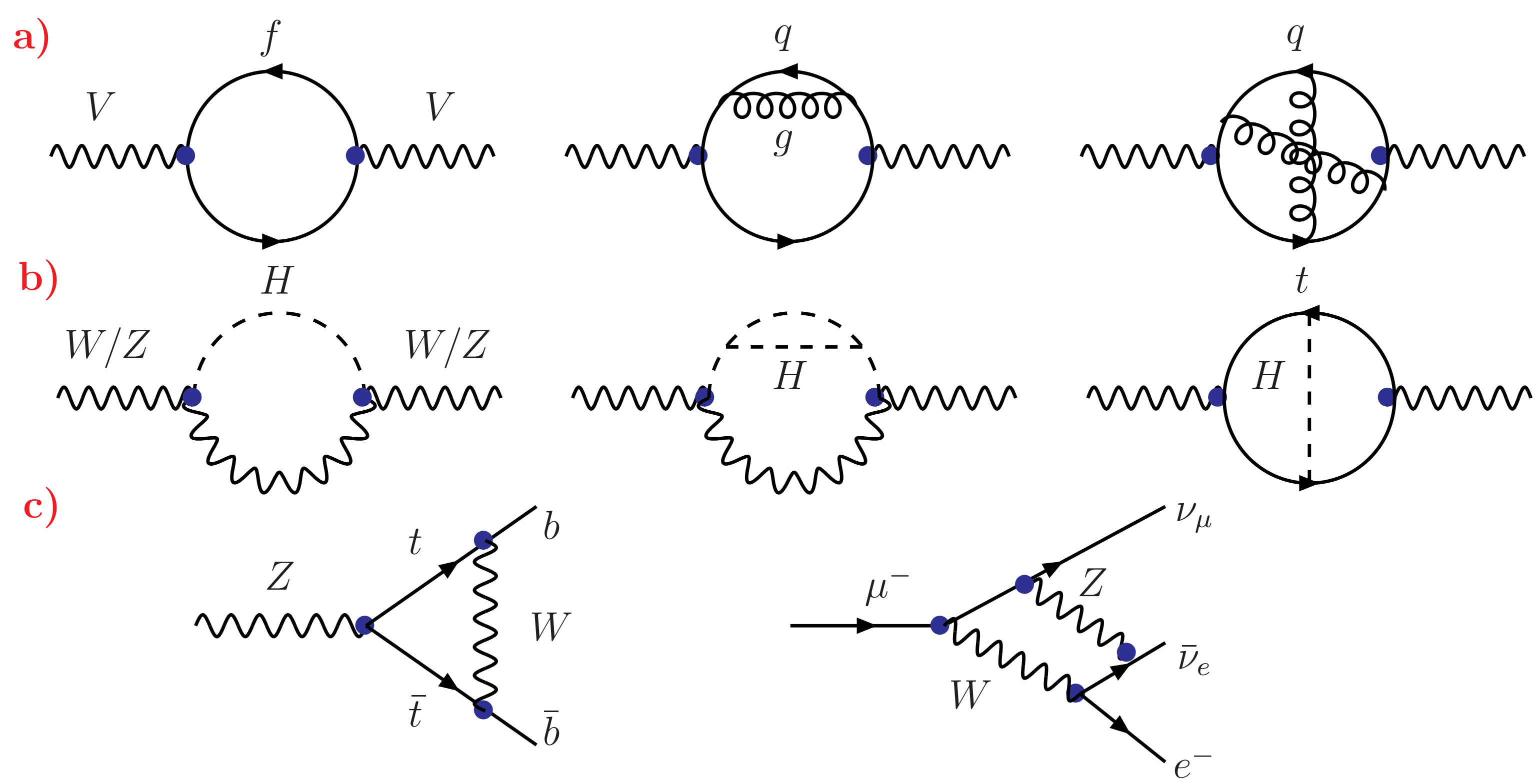


Figure 1.4: Generic Feynman diagrams for the main electroweak radiative corrections: a) fermionic contributions to the two–point functions of the $V = W/Z$ bosons, b) Higgs boson contributions to the two–point functions and c) vertex and box corrections.

The observables

The following classes of observables are used in the fit.

Z resonance parameters:

Z mass and width, and total $e^+e^- \to Z \to$ hadron production cross section (i.e., corrected for photon exchange contributions).

Partial Z cross sections:

Ratios of leptonic to hadronic, and heavy-flavour hadronic to total hadronic cross sections.

Neutral current couplings:

Effective weak mixing angle, and left-right and forward-backward asymmetries for universal leptons and heavy quarks.

W boson parameters:

W mass and width.

Higgs boson parameters:

Higgs mass.

Additional input parameters:

Heavy-flavour (c,b,t) quark masses (masses of lighter quarks and leptons are fixed to their world averages), QED and QCD coupling strengths at the Z-mass scale.

Global Electroweak Fit Inputs

Parameter	Input value	Free in fit	Results from global EW fits: *Standard fit*	*Complete fit*	*Complete fit w/o exp. input in line*
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1878 ± 0.0021	$91.1951\,^{+0.0136}_{-0.0112}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4958 ± 0.0015	2.4955 ± 0.0014	2.4952 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.478 ± 0.014	$41.477\,^{+0.016}_{-0.013}$	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.018	20.741 ± 0.017	$20.717\,^{+0.027}_{-0.008}$
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01637 ± 0.0002	$0.01627\,^{+0.0002}_{-0.0001}$	$0.01620\,^{+0.0002}_{-0.0001}$
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1477^{+0.0009}_{-0.0008}$	$0.1473^{+0.0008}_{-0.0006}$	–
A_c	0.670 ± 0.027	–	$0.6682\,^{+0.00042}_{-0.00035}$	$0.6680\,^{+0.00037}_{-0.00028}$	$0.6680\,^{+0.00034}_{-0.00030}$
A_b	0.923 ± 0.020	–	$0.93468\,^{+0.00008}_{-0.00007}$	$0.93463\,^{+0.00007}_{-0.00005}$	0.93466 ± 0.00005
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0740\,^{+0.0005}_{-0.0004}$	$0.0738\,^{+0.0005}_{-0.0003}$	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1036\,^{+0.0007}_{-0.0006}$	$0.1032\,^{+0.0006}_{-0.0005}$	$0.1037\,^{+0.0003}_{-0.0005}$
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21474 ± 0.00003	0.21474 ± 0.00003	0.21474 ± 0.00003
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23144\,^{+0.00010}_{-0.00013}$	$0.23150\,^{+0.00008}_{-0.00011}$	$0.23145\,^{+0.00012}_{-0.00006}$
M_H [GeV] $^{(\circ)}$	95% CL limits	yes	$94^{+25[+59]}_{-22[-41]}$	–	$94^{+25[+59]}_{-22[-41]}$
M_W [GeV]	80.385 ± 0.015	–	$80.380\,^{+0.011}_{-0.012}$	$80.370\,^{+0.006}_{-0.007}$	$80.360\,^{+0.014}_{-0.012}$
Γ_W [GeV]	2.085 ± 0.042	–	2.092 ± 0.001	2.092 ± 0.001	2.092 ± 0.001
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	yes	$1.27\,^{+0.07}_{-0.11}$	$1.27\,^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	yes	$4.20\,^{+0.17}_{-0.07}$	$4.20\,^{+0.17}_{-0.07}$	–
m_t [GeV]	173.2 ± 0.9	yes	173.2 ± 0.9	173.4 ± 0.8	$175.1\,^{+3.3}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2757 ± 11	2756 ± 11	2728^{+51}_{-50}
$\alpha_s(M^2_Z)$	–	yes	$0.1192\,^{+0.0028}_{-0.0027}$	0.1191 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	4.7	1.5	–

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements. The *complete fit* w/o the LEP (SLD) measurement gives $A_\ell = 0.1474\,^{+0.0006}_{-0.0007}$ ($A_\ell = 0.1469 \pm 0.0006$). $^{(\circ)}$In brackets the 2σ. $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

Input values and fit results for parameters of the global electroweak fit.

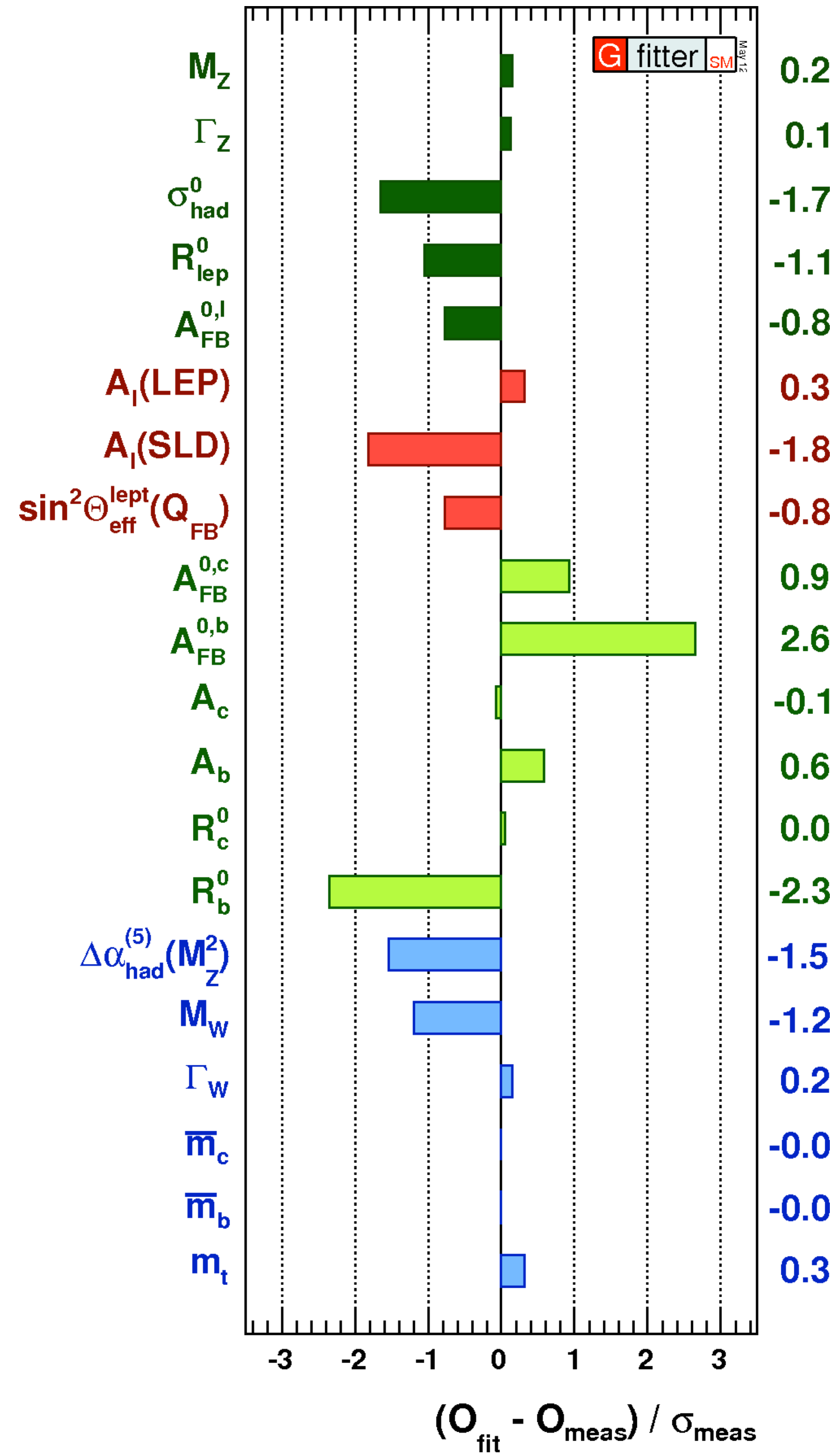
Columns 1&2: list respectively the observables/parameters used in the fit, and their experimental values or theoretical estimates. The subscript ``theo'' labels theoretical error ranges.

Column 3: indicates whether a parameter is floating in the fit.

Columns 4 and 5: quote the results of the standard (complete) fit not including (including) the constraints from the direct Higgs searches at LEP and Tevatron in the fit.

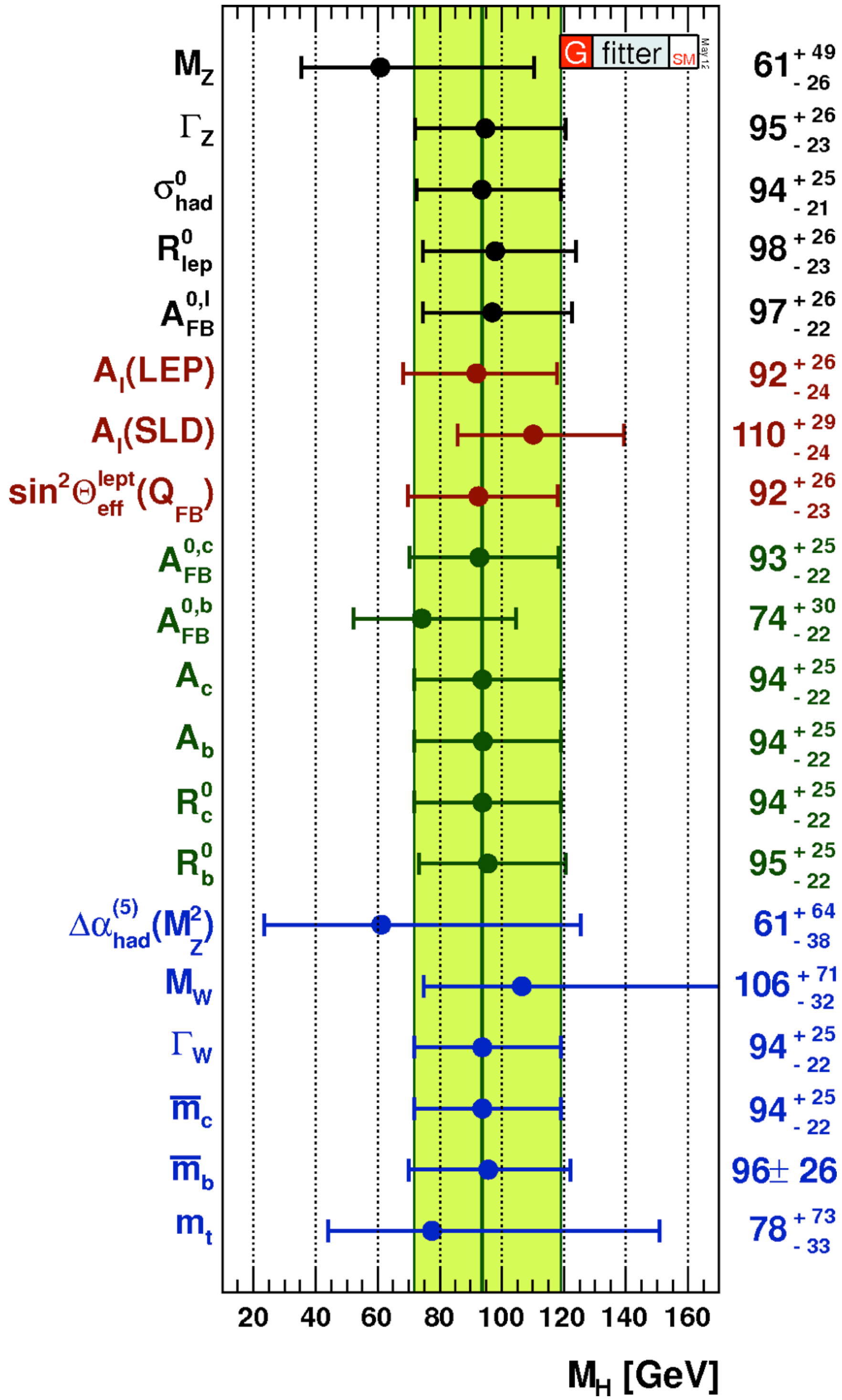
Column 6: gives the fit results for each parameter without using the corresponding experimental constraint in the fit (indirect determination).

Pulls

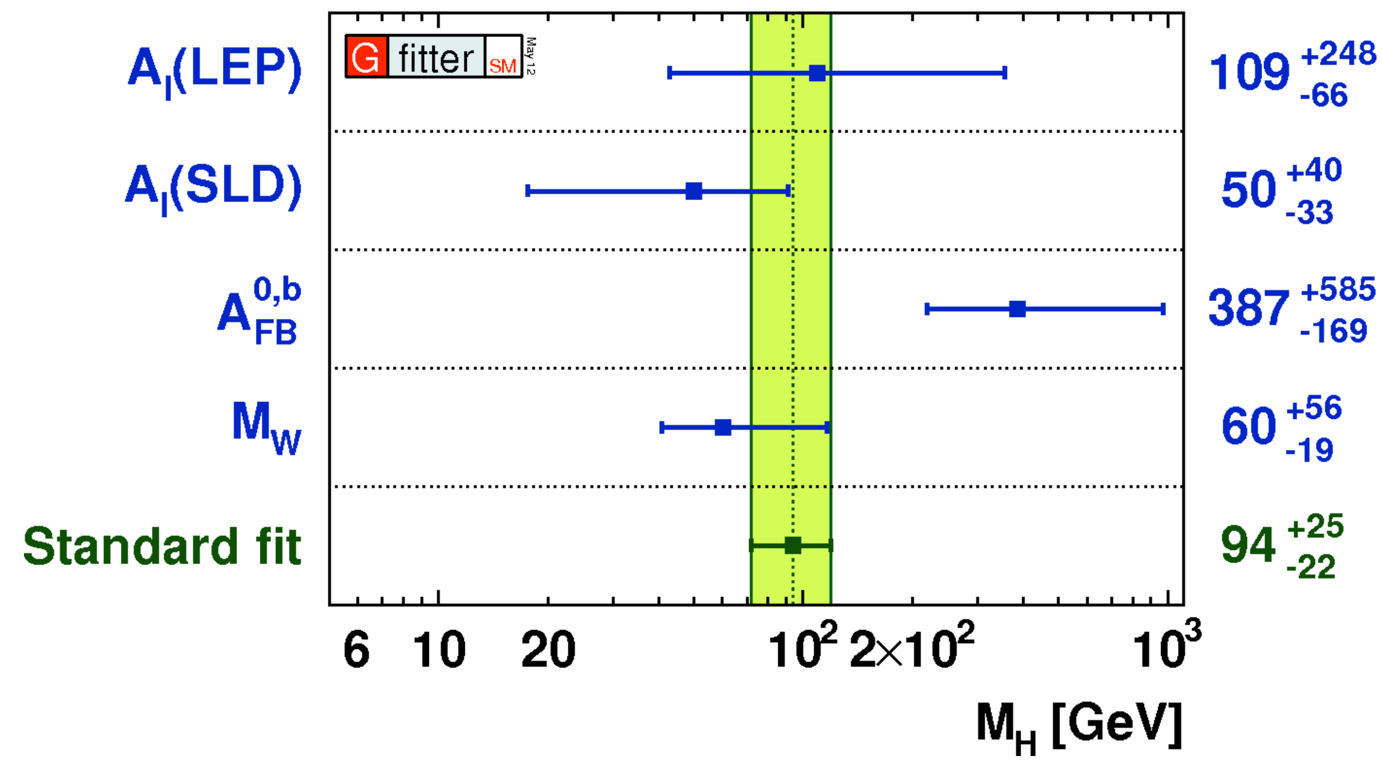


Comparing fit results with direct measurements: pull values for the complete fit

M_H

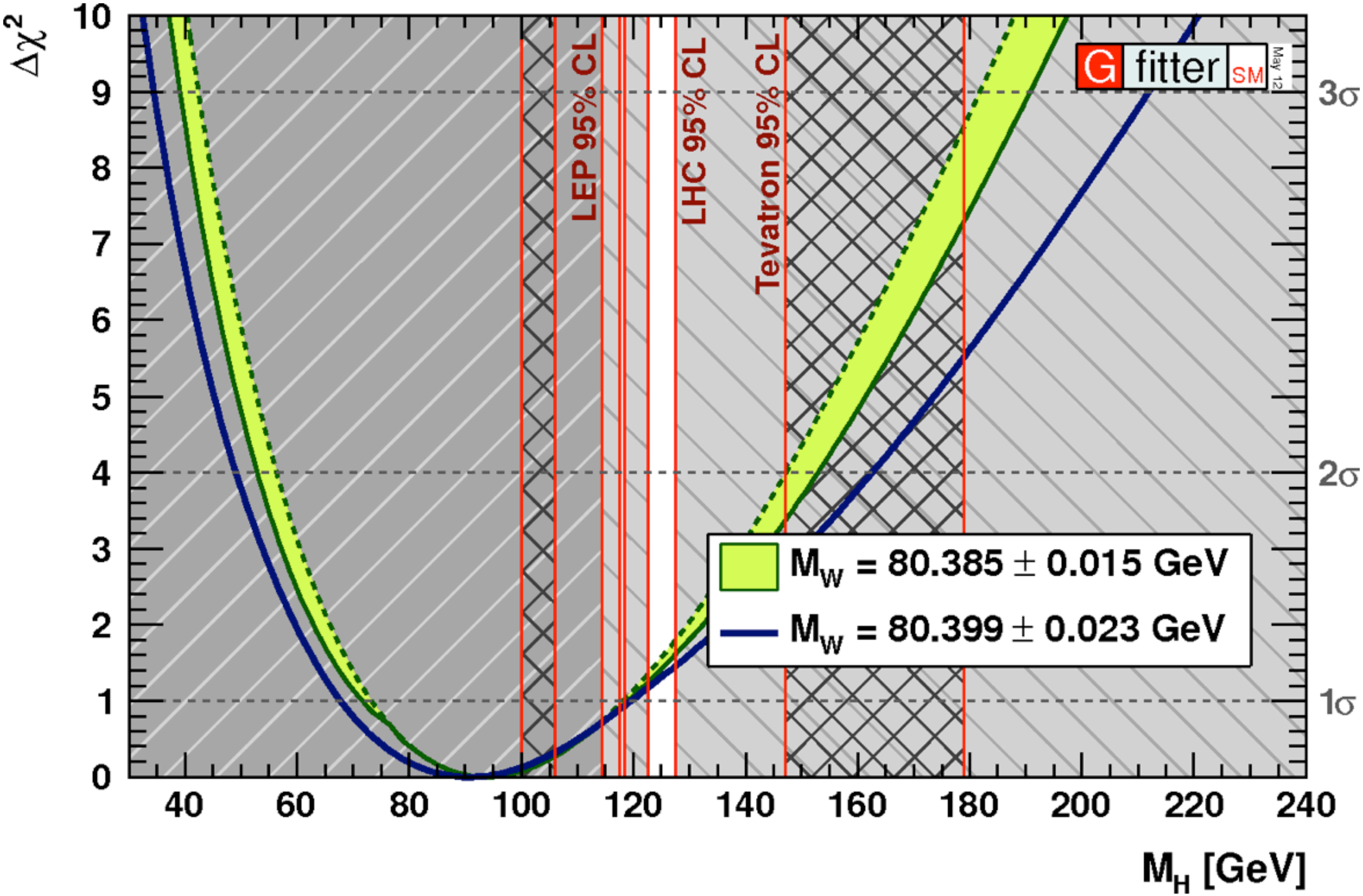


Results for M_H from the standard fit excluding the respective measurements

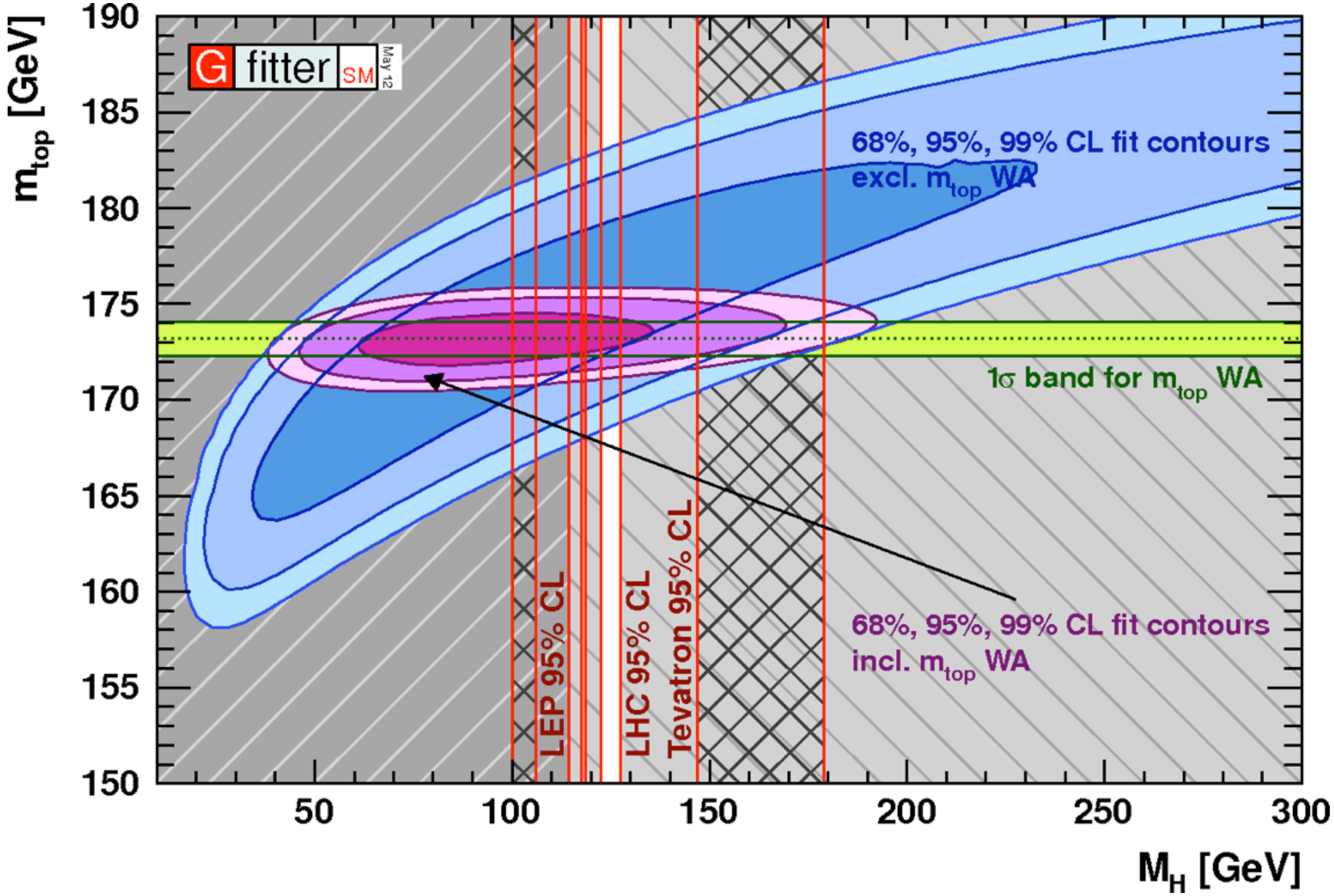


Determination of M_H excluding all the sensitive observables from the standard fit, except for the one given.

$\Delta\chi^2$ vs M_H

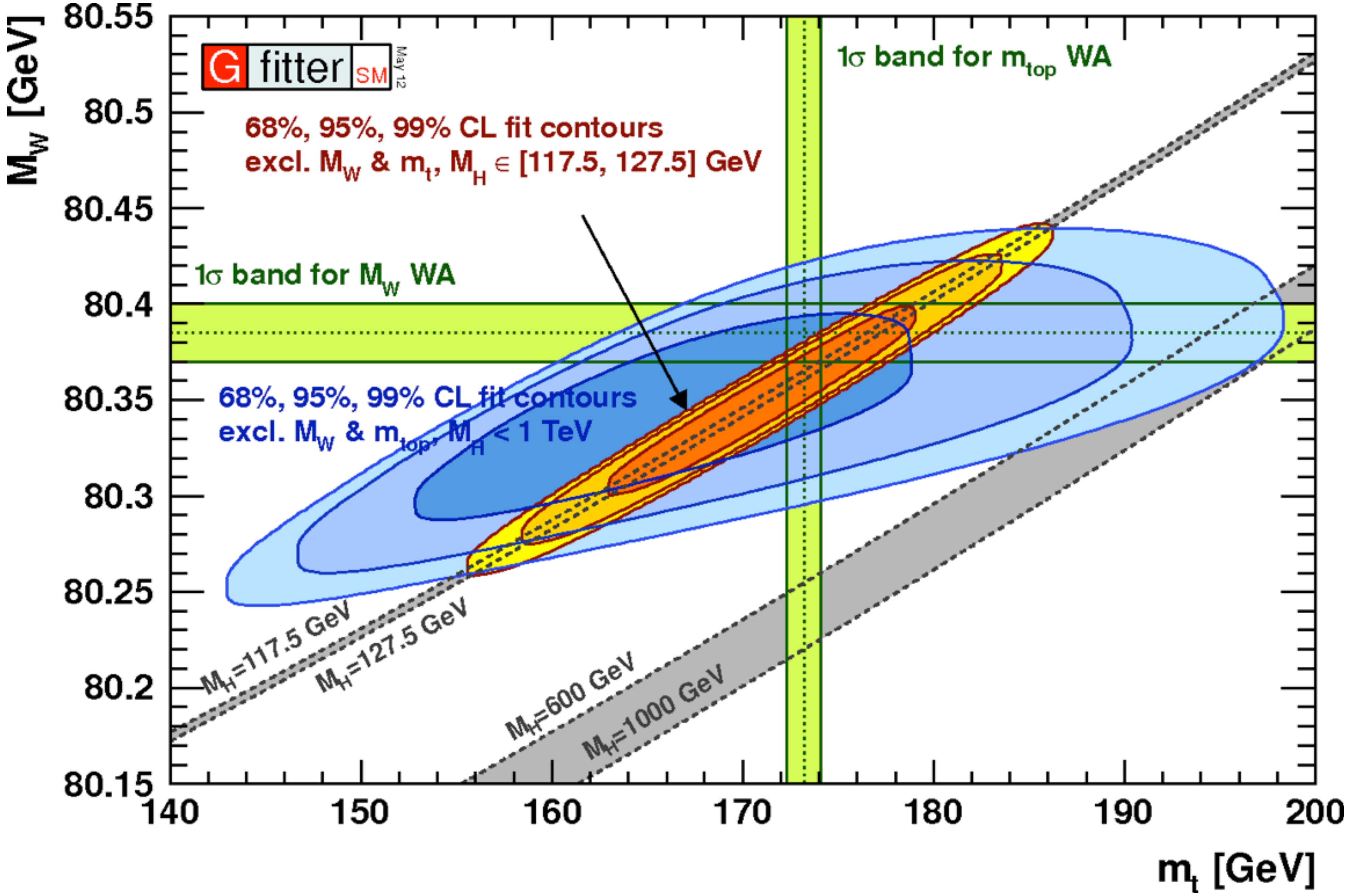


M_H vs m_t



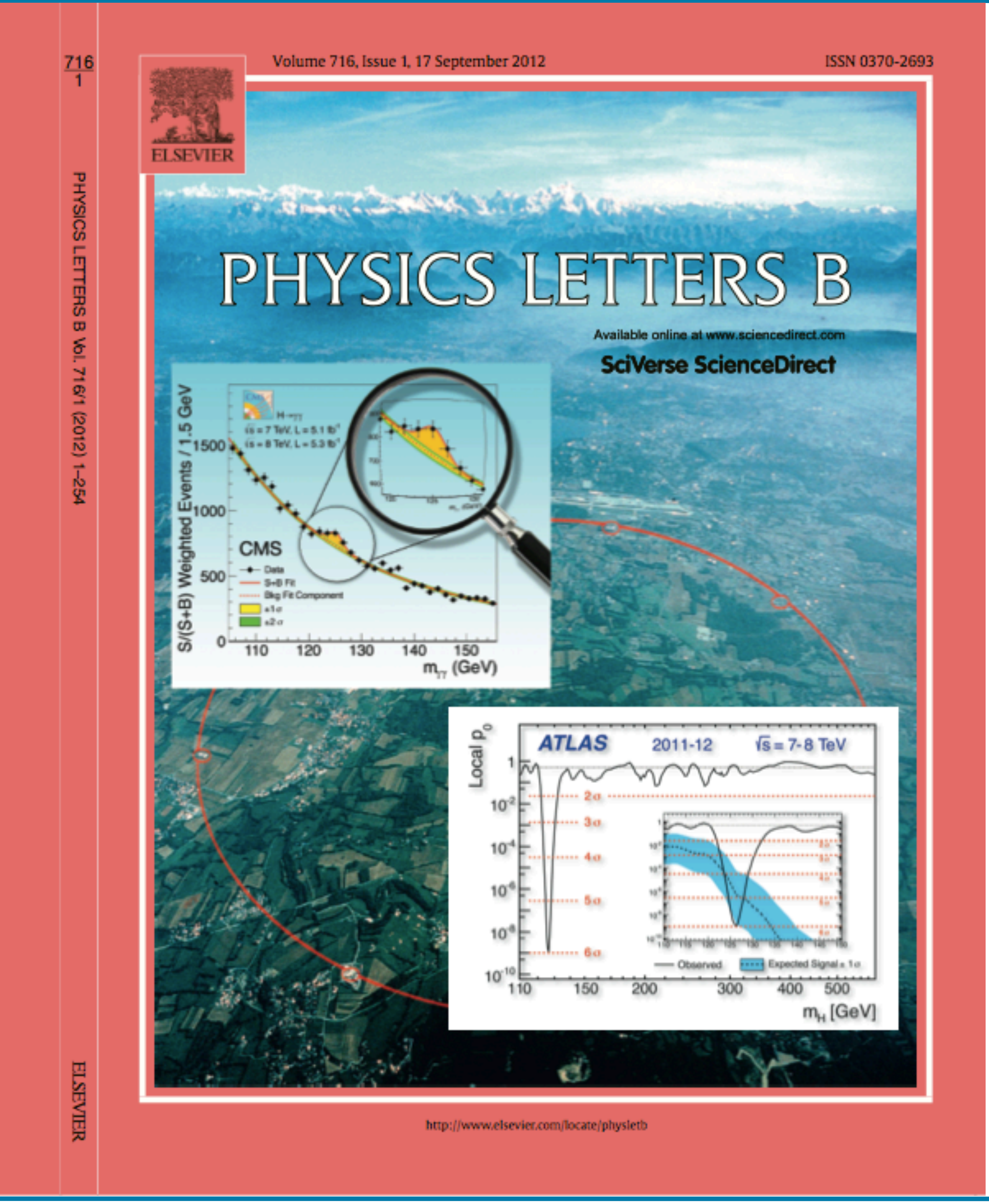
Contours of 68%, 95% and 99% CL obtained from scans of fits with fixed variable pairs m_t vs. M_H . The largest/blue (narrower/purple) allowed regions are the results of the standard fit excluding (including) the measurements of m_t. The horizontal bands indicate the 1σ regions of the current world average of m_t measurements.

m_t vs M_W



Contours of 68%, 95% and 99% CL obtained from scans of fits with fixed variable pairs M_W vs. m_t. The largest/blue (narrower/yellow) allowed regions are the results of the standard fit for free floating Higgs mass (Higgs mass constrained to 117.5-127.5 GeV). The grey shaded array shows the prediction of the masses as a function of the Higgs mass. The horizontal bands indicate the 1σ regions of measurements (world averages).

... the observation of a new particle ...



Physics Letters B 716 (2012) 1–29

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Physics Letters B

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ELSEVIER

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form 8 August 2012
Accepted 11 August 2012
Available online 14 August 2012
Editor: W.-D. Schlatter

ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Physics Letters B 716 (2012) 30–61

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Physics Letters B

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ELSEVIER

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form 9 August 2012
Accepted 11 August 2012
Available online 18 August 2012
Editor: W.-D. Schlatter

Keywords:
CMS
Physics
Higgs

ABSTRACT

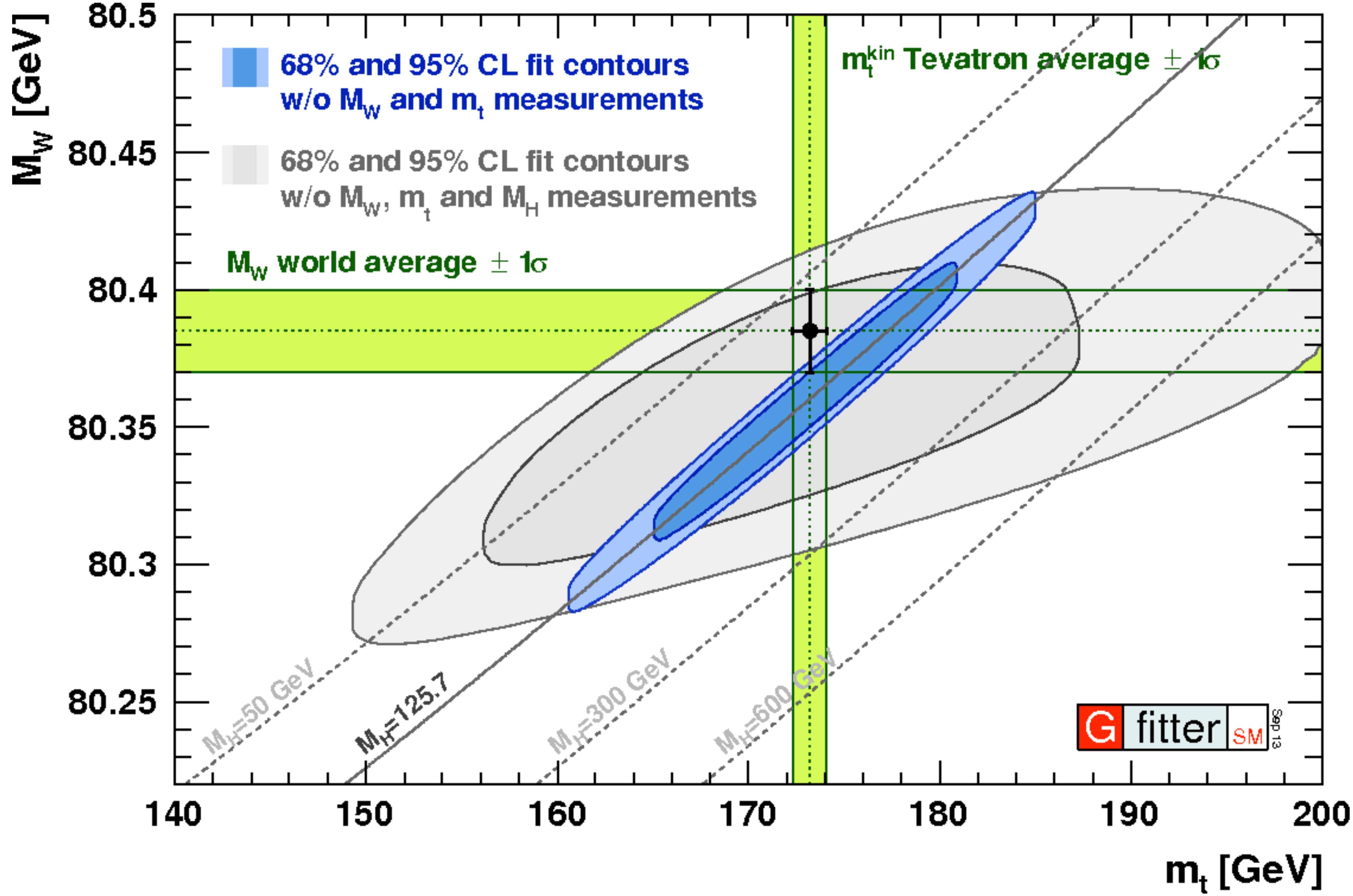
Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4(stat.) ± 0.5(syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

Global Electroweak Fit Inputs

Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]$^{\circ}$	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$	94.7^{+25}_{-22}	94.7^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.367^{+0.006}_{-0.007}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1878 ± 0.0021	91.1978 ± 0.0114
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4954 ± 0.0014	2.4950 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23149^{+0.00010}_{-0.00008}$	$0.23149^{+0.00010}_{-0.00008}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6679^{+0.00034}_{-0.00028}$	$0.6679^{+0.00034}_{-0.00028}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93464^{+0.00005}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21548 ± 0.00005	0.21548 ± 0.00005	0.21547 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.20 ± 0.87	yes	173.53 ± 0.82	173.53 ± 0.82	$176.11^{+2.88}_{-2.35}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11	2755 ± 11	2718^{+49}_{-43}
$\alpha_s(M^2_Z)$	–	yes	$0.1190^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1190 ± 0.0027
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-0.6	-0.5	–

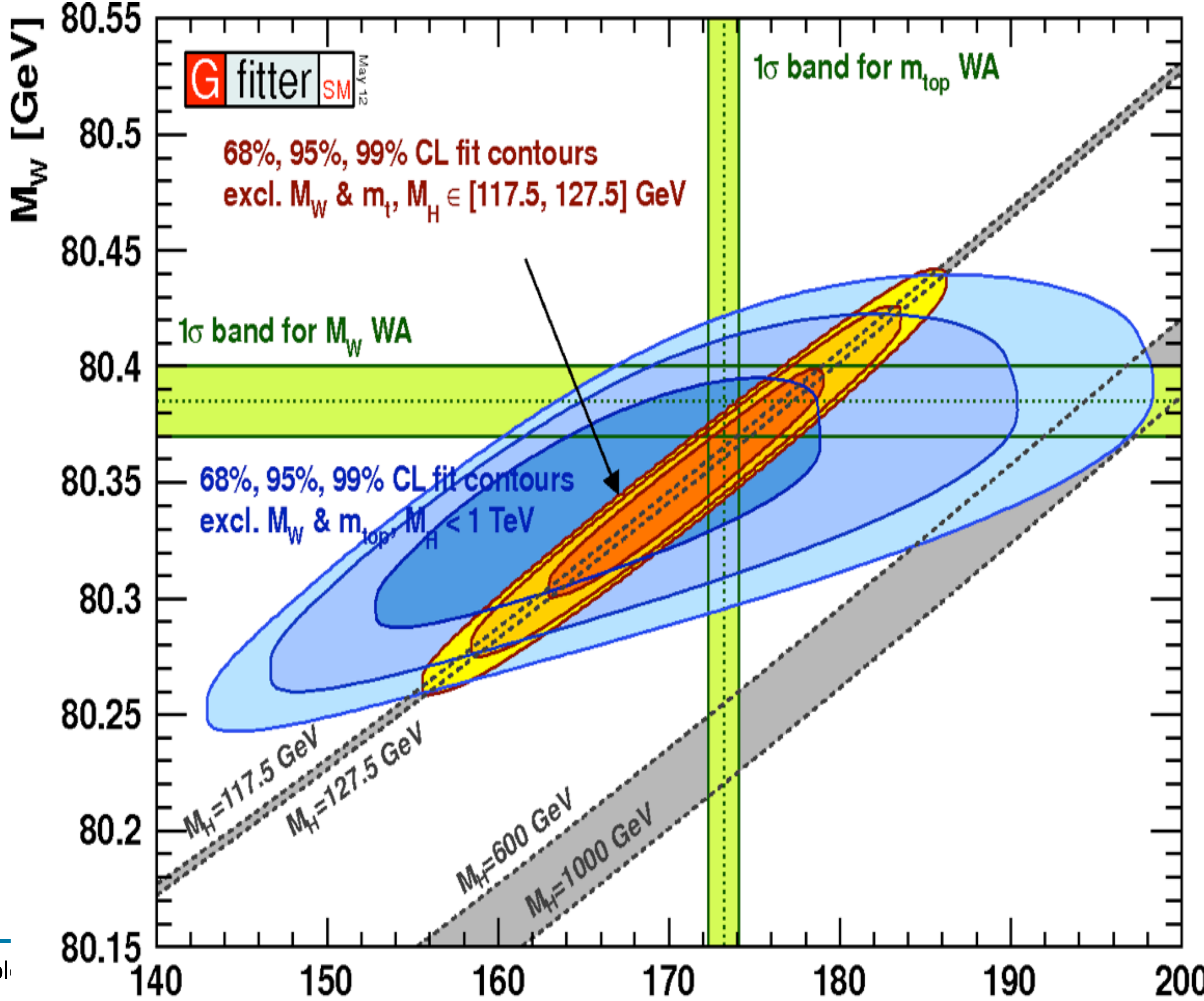
$^{(\circ)}$Average of ATLAS ($M_H = 126.0 \pm 0.4\,(\text{stat}) \pm 0.4\,(\text{sys})$) and CMS ($M_H = 125.3 \pm 0.4\,(\text{stat}) \pm 0.5\,(\text{sys})$) measurements assuming no correlation of the systematic uncertainties. $^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1474^{+0.0008}_{-0.0009}$ ($A_\ell = 0.1467^{+0.0006}_{-0.0004}$). $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

m_t vs M_W

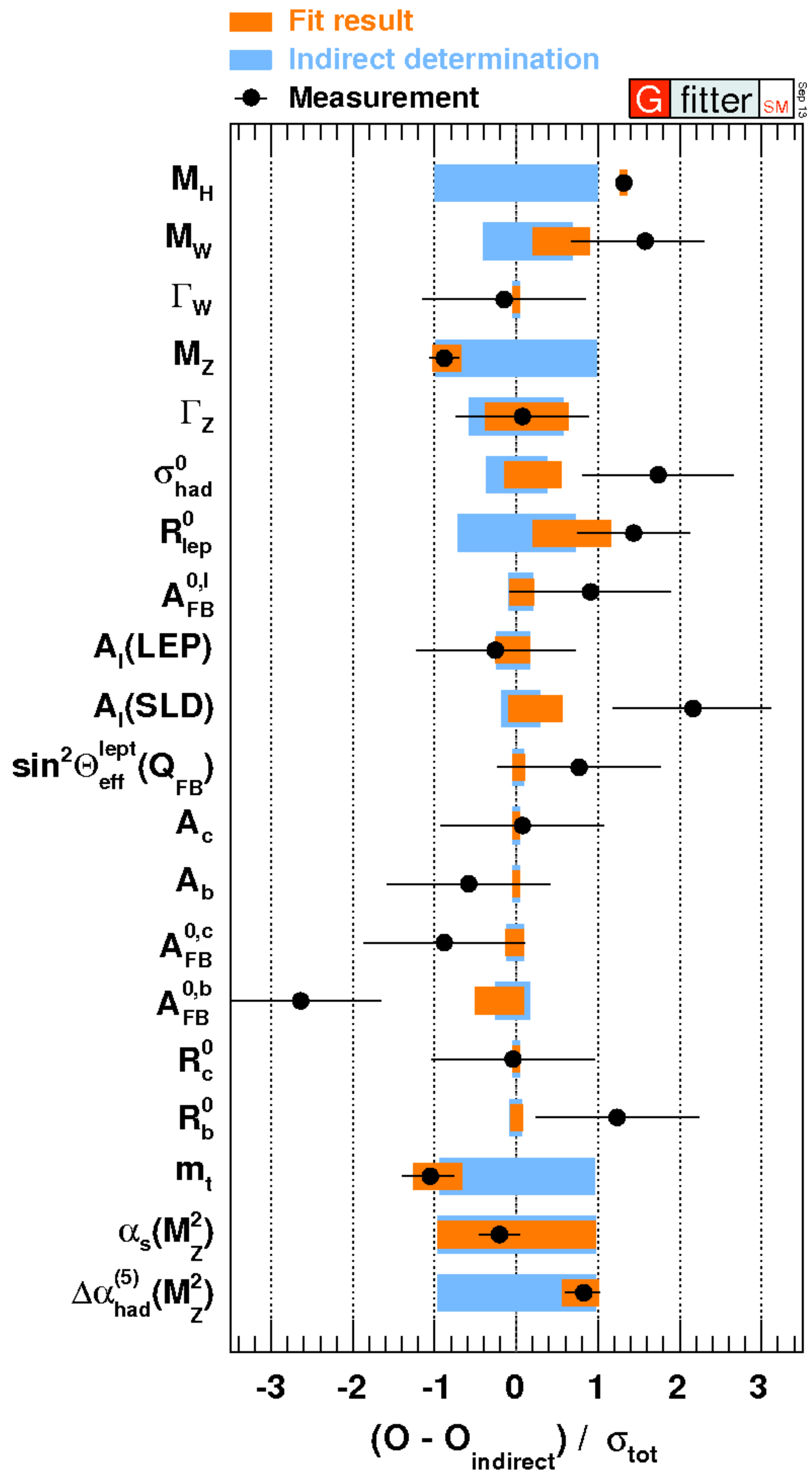


68% and 95% CL fit contours
w/o M_W and m_t measurements
68% and 95% CL fit contours
w/o M_W, m_t and M_H measurements
M_W world average ± 1σ
m_t^kin Tevatron average ± 1σ
M_H=50 GeV
M_H=125.7
M_H=300 GeV
M_H=600 GeV
G fitter SM
Sep 13
M_W [GeV]
m_t [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190
200

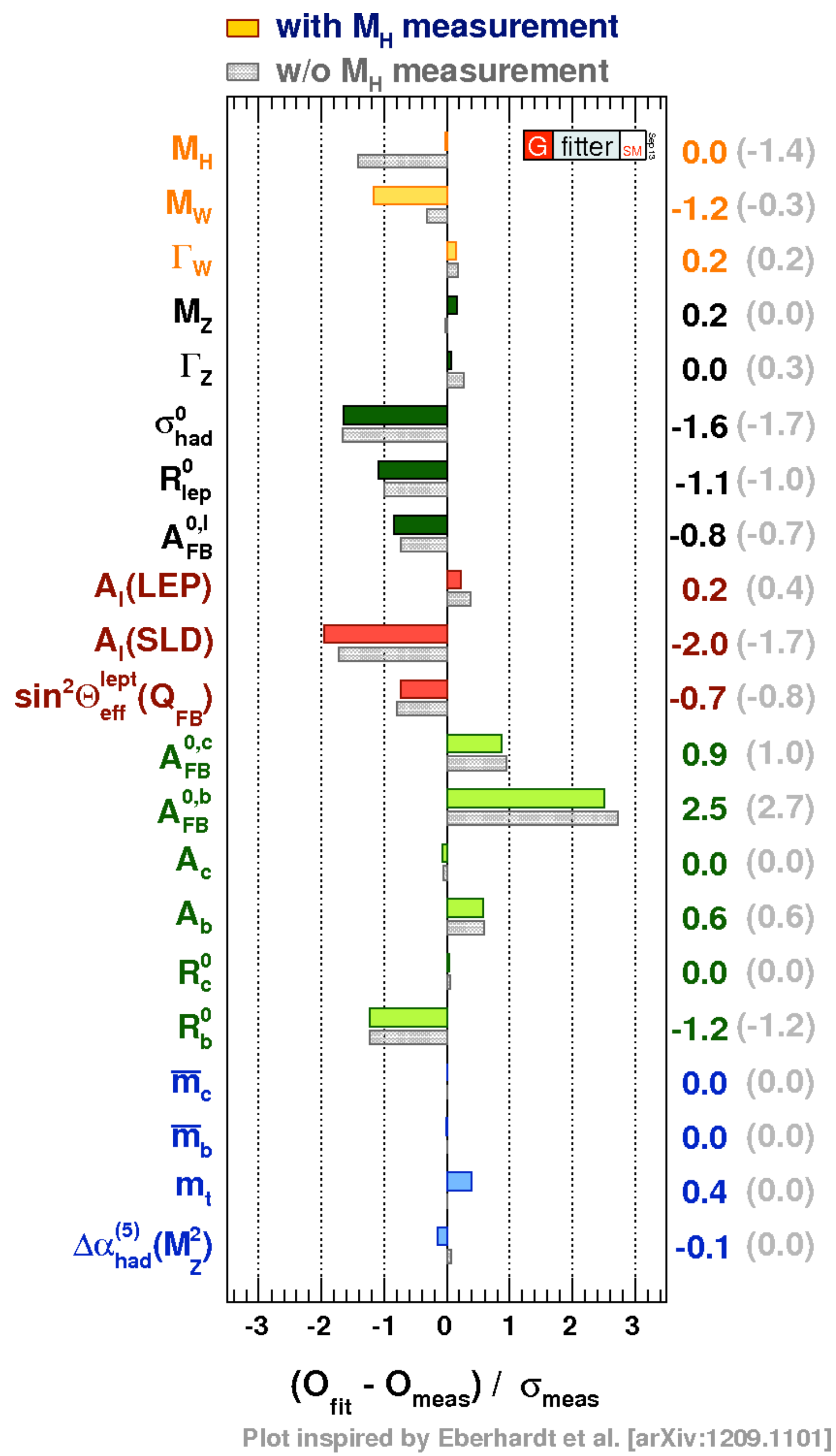
m_t vs M_W (before discovery)



Pulls

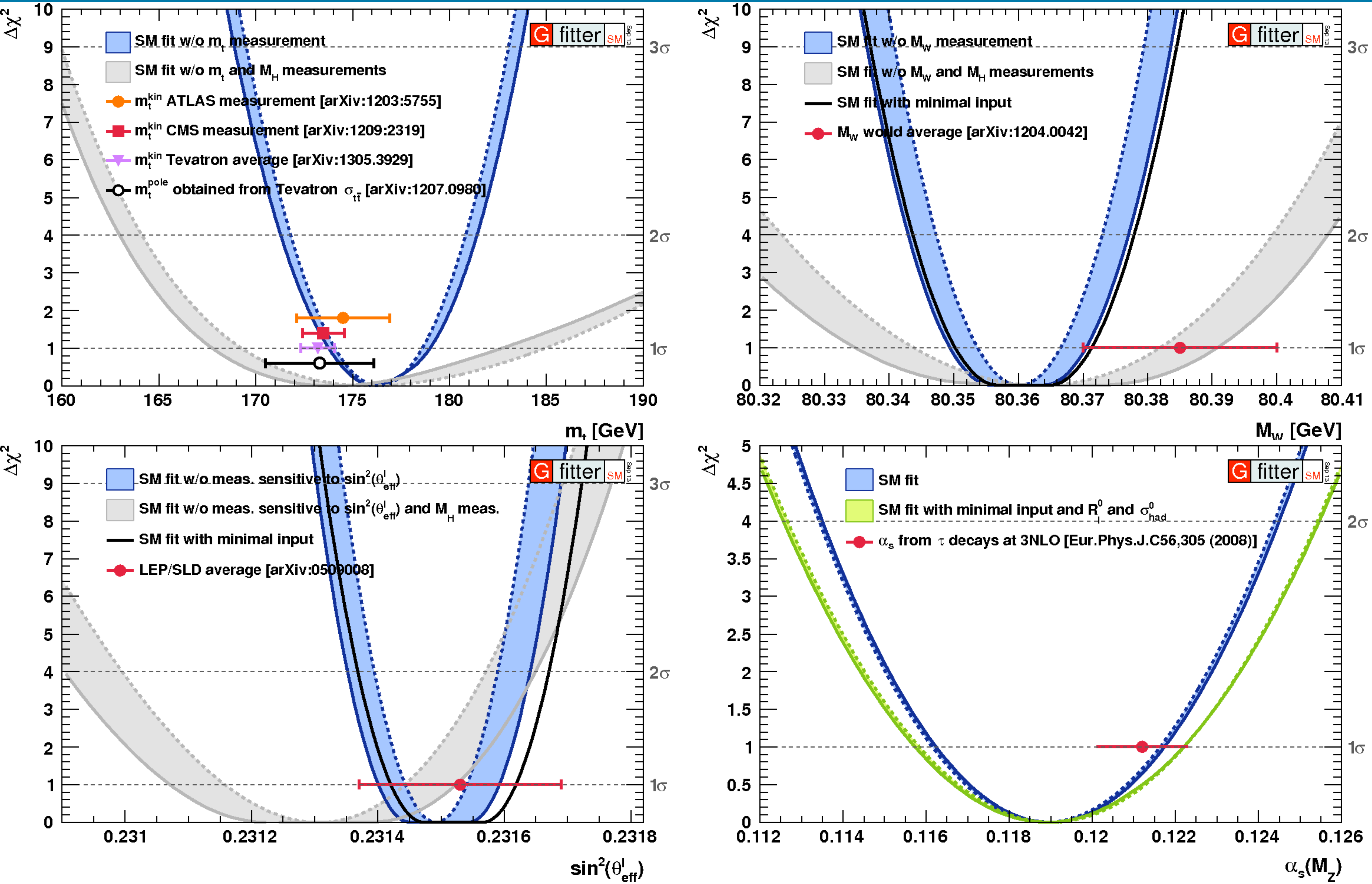


Fit result
Indirect determination
Measurement
G fitter SM
Sep 13
M_H
M_W
Γ_W
M_Z
Γ_Z
σ^0_{had}
R^0_{lep}
$A^{0,l}_{FB}$
A_l(LEP)
A_l(SLD)
$\sin^2\Theta^{lept}_{eff}(Q_{FB})$
A_c
A_b
$A^{0,c}_{FB}$
$A^{0,b}_{FB}$
R^0_c
R^0_b
m_t
$\alpha_s(M^2_Z)$
$\Delta\alpha^{(5)}_{had}(M^2_Z)$
-3 -2 -1 0 1 2 3
$(O - O_{indirect}) / \sigma_{tot}$

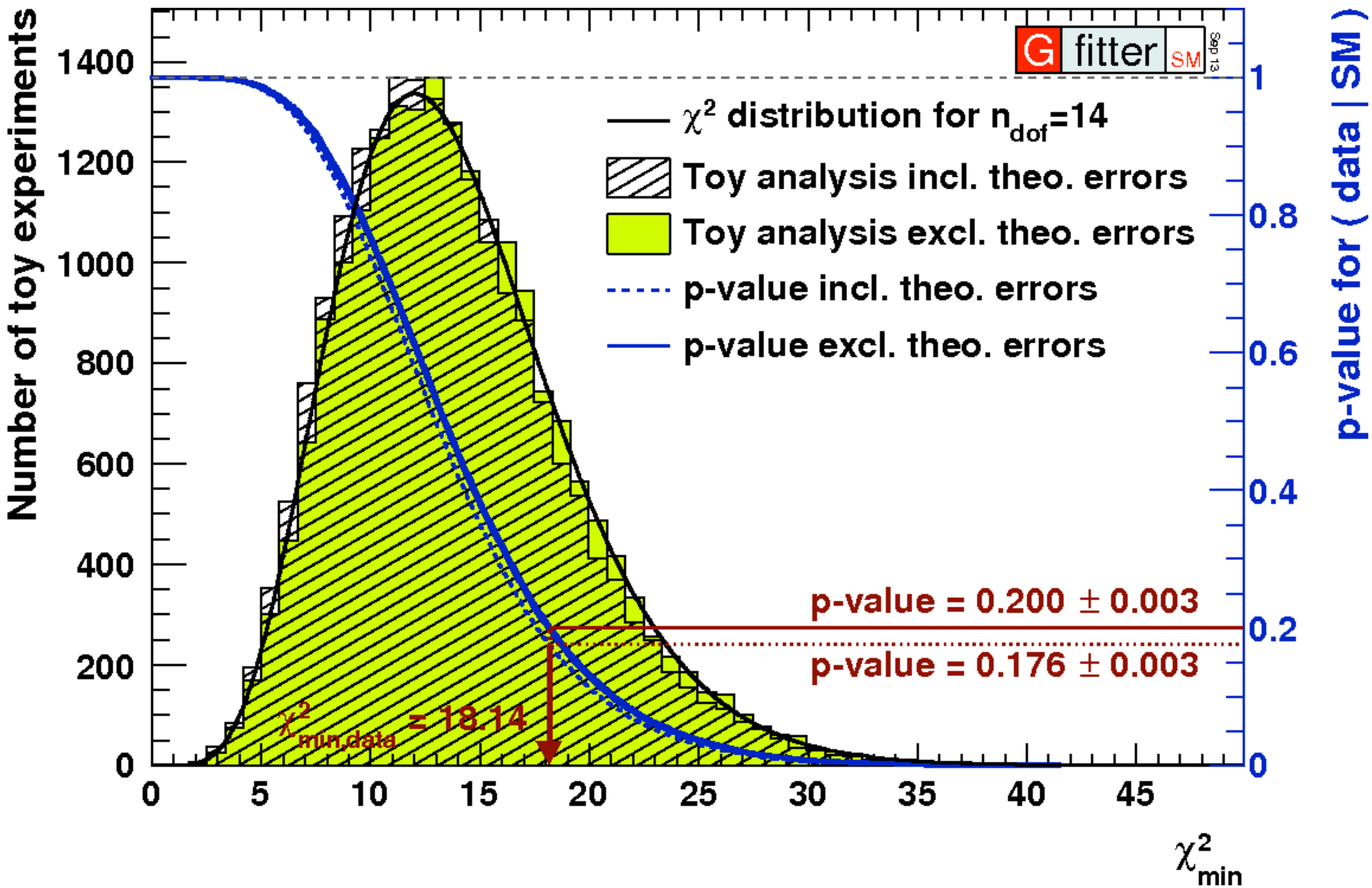


with M_H measurement
w/o M_H measurement
G fitter SM
Sep 13
M_H 0.0 (-1.4)
M_W -1.2 (-0.3)
Γ_W 0.2 (0.2)
M_Z 0.2 (0.0)
Γ_Z 0.0 (0.3)
σ^0_{had} -1.6 (-1.7)
R^0_{lep} -1.1 (-1.0)
$A^{0,l}_{FB}$ -0.8 (-0.7)
A_l(LEP) 0.2 (0.4)
A_l(SLD) -2.0 (-1.7)
$\sin^2\Theta^{lept}_{eff}(Q_{FB})$ -0.7 (-0.8)
$A^{0,c}_{FB}$ 0.9 (1.0)
$A^{0,b}_{FB}$ 2.5 (2.7)
A_c 0.0 (0.0)
A_b 0.6 (0.6)
R^0_c 0.0 (0.0)
R^0_b -1.2 (-1.2)
$\overline{m}_c$ 0.0 (0.0)
$\overline{m}_b$ 0.0 (0.0)
m_t 0.4 (0.0)
$\Delta\alpha^{(5)}_{had}(M^2_Z)$ -0.1 (0.0)
-3 -2 -1 0 1 2 3
$(O_{fit} - O_{meas}) / \sigma_{meas}$
Plot inspired by Eberhardt et al. [arXiv:1209.1101]

Measurements/Predictions



The overall fit consistency



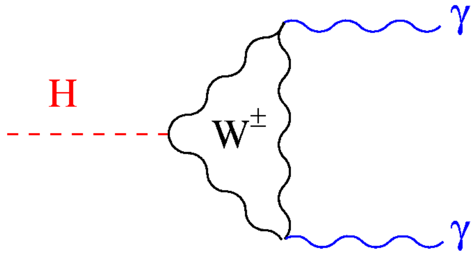
Result of the MC toy analysis of the SM fit. Shown are the χ^2_{min} distribution of a toy MC simulation (open histogram), the corresponding distribution for a fit ignoring theoretical errors (shaded/green histogram), an ideal χ^2 distribution assuming a Gaussian case with n_{dof}=14 (black line) and the p-value as a function of the χ^2_{min} of the global fit.

Early Searches for the Standard Model Higgs boson

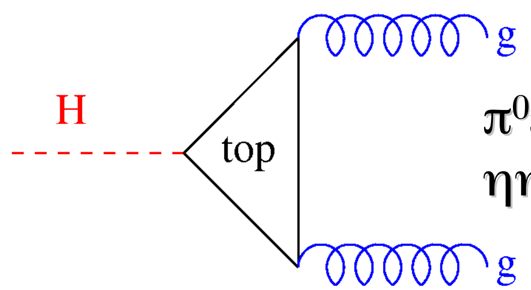
Now, we'll discuss the early direct experimental/phenomenological searches for the Standard Model Higgs boson, where early refers to the period before LEP. In general, in this period the searches were constrained in the "very low" mH region, i.e. ≲ 5-10 GeV

The decay branching ratios depend only on m_H:

- ❑ $m_H < 2m_e$: $H \to \gamma\gamma$ + large lifetime;

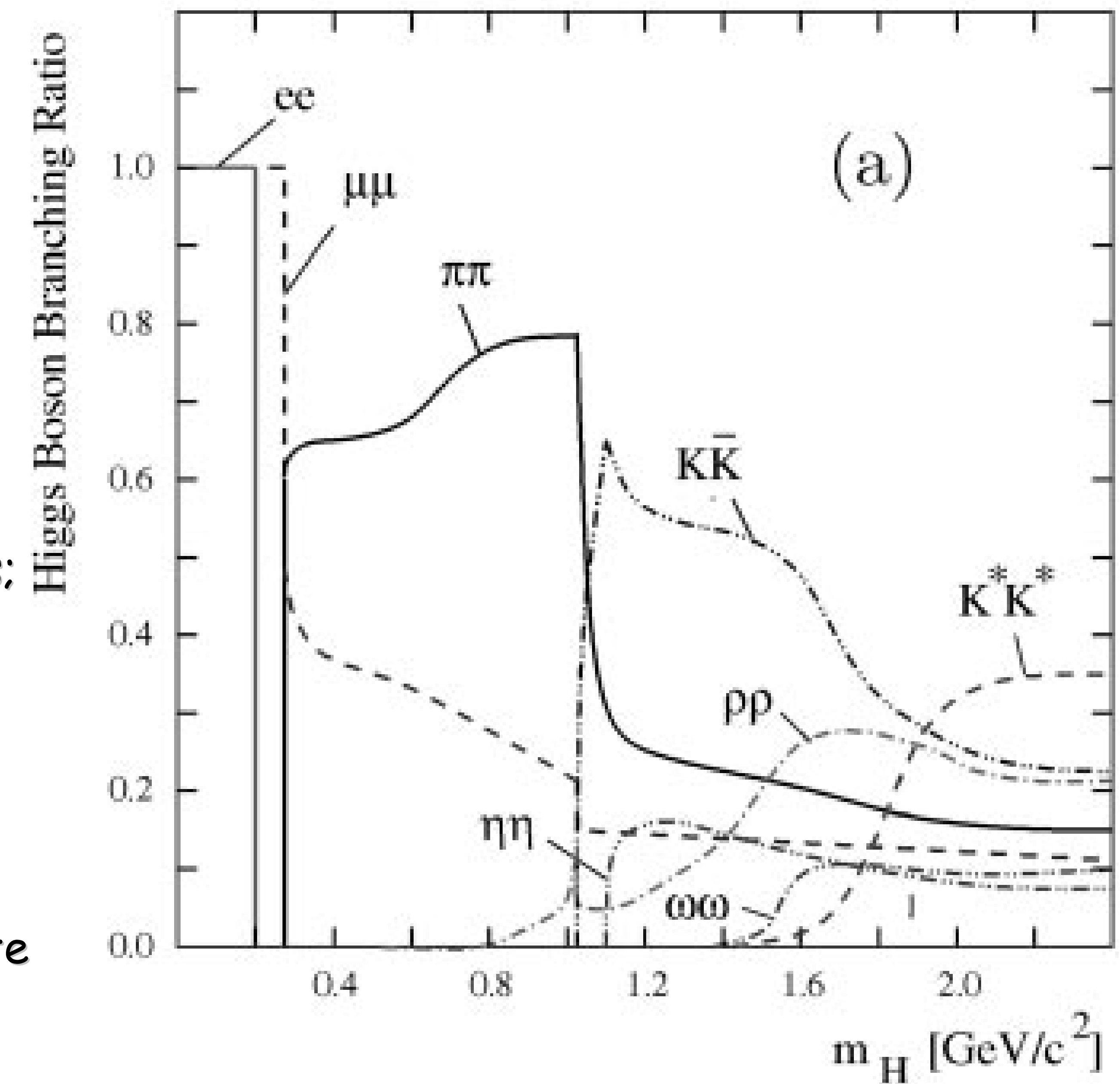


- ❑ $m_H < 2m_\mu$: $H \to e^+e^-$ dominates;
- ❑ $m_H < 2m_\pi$: $H \to \mu^+\mu^-$ dominates;
- ❑ $m_H < 3 - 4$ GeV: $H \to gg$ dominates;



$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, … etc

- ❑ $m_H < 2m_b$: $H \to \tau^+\tau^-$ and $c\bar{c}$ dominate



Astrophysical Constraints on m_H

- Effect on Cosmic Microwave background $0.1\ \text{eV} < m_H < 100\ \text{eV}$

(Sato and Sato, 1975)

- Emission from stars: $m_H > 0.7\ m_e$

(Sato and Sato, 1975)

Prog. Theor. Phys. Vol. 54 (1975), Sept.

Primordial Higgs Mesons and Cosmic Background Radiations

Katsuhiko SATO and Humitaka SATO

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May 12, 1975

The unified theory of weak and electro-magnetic interactions, proposed by Weinberg and Salam, has become a reliable one by the discovery of neutral currents in CERN and NAL. On the other hand, in this theory, the presence of neutral scalar meson, "Higgs meson", is also inevitable but its mass m_ϕ, is arbitrary in this theory. Recently Kohler et al.[1] showed that Higgs meson cannot have a mass in the range $1.030\ \text{MeV} < m_\phi < 18.2\ \text{MeV}$ by the experiment of 0^+ to 0^+ transition of ^{4}He. However the present day experiments, except for the above one, cannot rule out any range of mass, even a very small mass like 1 keV as discussed by Jackiw and Weinberg[2] and Resnick et al.[3]

Here, we will discuss a role of Higgs meson in the big-bang universe without such a speculative hypothesis and will give a constraint on its mass range derived from the observed cosmic background radiation.

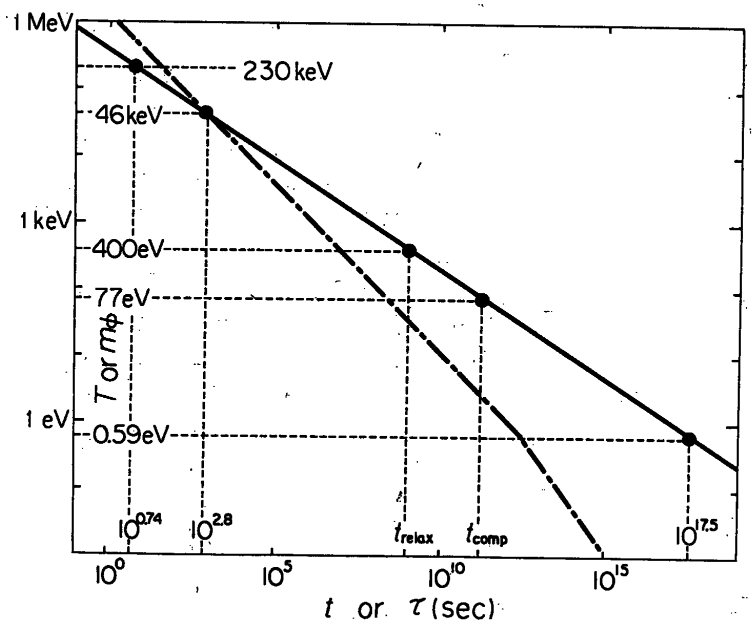

Fig. 1. Higgs meson mass (m_ϕ) versus decay life (τ) relation in a solid line and cosmic temperature (T) versus cosmic time (t) relation in a dot-dashed line. t_{relax} shows the end times of "free-free and Compton stage" where the spectrum always relaxes into the Planck one.

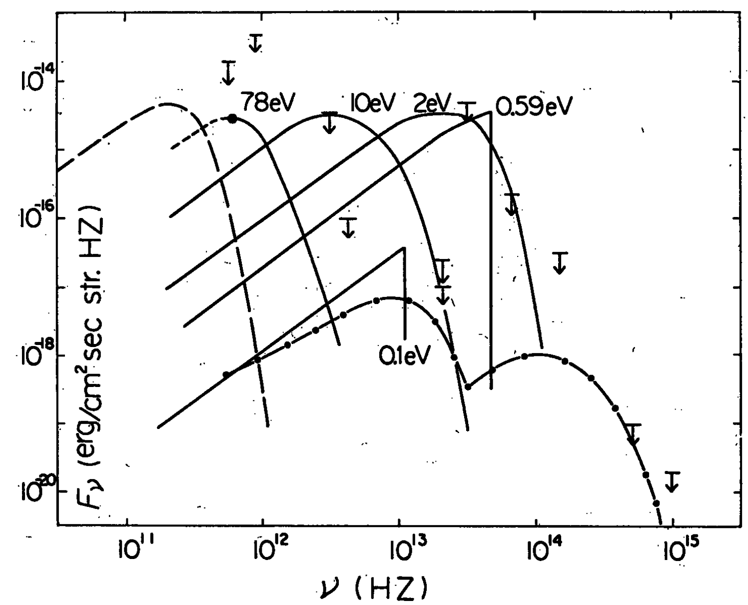

Fig. 2. Energy spectrum of the background radiation created by Higgs meson decay. The dashed curve represents the 2.7°K black body radiation. The observational upper limits of the flux are shown by the arrows and the theoretical estimations by Longair and Sunyaev[6] is shown by dot-dashed line.

Prog. Theor. Phys. Vol. 54 (1975), Nov.

Higgs Meson Emission from a Star and a Constraint on Its Mass

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July 3, 1975

In the unified theory of weak and electromagnetic interaction,[1] a presence of Higgs meson is inevitable but its mass, m_ϕ, is arbitrary. In our previous paper,[2] we discussed the effect of the primordial Higgs mesons to the cosmic background radiation and obtained the constraint that the mass cannot be in the range $0.1\ \text{eV} < m_\phi < 100\ \text{eV}$. Here we discuss the Higgs meson emission from stars and it is argued that such a low mass range as $m_\phi < 0.7 \times$ (electron mass) should be ruled out, otherwise this emission process would affect the evolution of stars drastically.

In the first paper, the effect of the φ→γγ decays from the primordial Higgs bosons on the cosmic microwave background spectrum are estimated, and conclusions on the excluded Higgs boson masses are drawn based on the limits on the fluxes in the CMB spectrum

In the second paper, the process γ+e→φ+e is considered and the effect to the star lifetime due to the energy loss are estimated (plus the non-observation of a γ-line from Higgs decays)

Searches for the Higgs boson in Nuclear Physics

The beginning of the 1970s started of with great excitement!

Two groups observed deviations in the X-ray spectrum of muonic atoms wrt QED expectations.

Dixit et al., Experimental test of the theory of muonic atoms, Phys.Rev.Lett. 27 (1971) 878-881

Walter et al., Test of quantum-electrodynamical corrections in muonic atoms, Phys.Lett. B40 (1972) 197-199

VOLUME 27, NUMBER 13 PHYSICAL REVIEW LETTERS 27 SEPTEMBER 1971

Experimental Test of the Theory of Muonic Atoms*†

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and

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(Received 28 June 1971)

We have measured muonic x rays in the energy region 150 to 440 keV in nine elements with an absolute precision of 15 to 21 eV for transitions with small nuclear effects. Calculated transition energies were found to be consistently larger than those measured by an amount that varied from 15±16 eV at 157 keV to 137±22 eV at 438 keV. For these transitions, the principal correction to the Dirac energy is the vacuum polarization. The discrepancy, however, lies outside the expected validity of quantum-electrodynamic calculations and we are unable, at present, to offer an explanation for this effect.

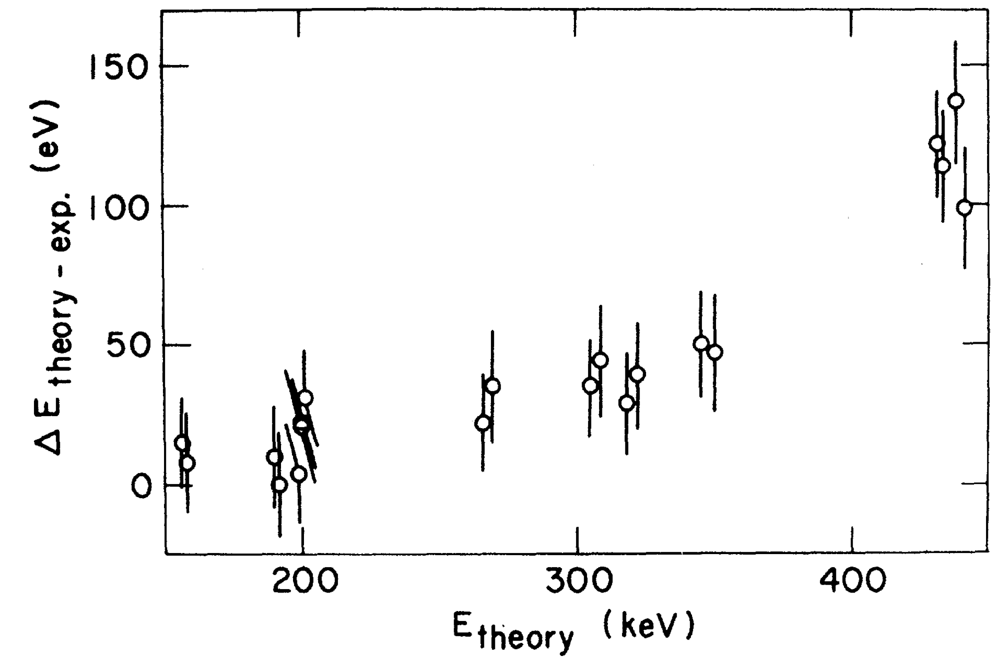


FIG. 1. The discrepancy $\Delta E_{\text{theo - expt}}$ (eV) plotted against the theoretical transition energies for 20 muonic x-ray transitions.

As expected a number of theory papers followed discussing potential sources of this effect, one being the production of a low mass Higgs boson, m_H~20 MeV

[1]S. Weinberg, Phys. Rev. Lett. 27, 1688 (1971).
[2]R. Jakiw and S. Weinberg, Phys. Rev. D 5, 2396 (1972).
[3]L. Resnick, M. K. Sundaresan, and P. J. S. Watson, Phys. Rev. D 8, 172 (1973).
[4]M. K. Sundaresan and P. J. S. Watson, Phys. Rev. Lett. 29, 15 (1972).

Searches for the Higgs boson in Nuclear Physics (II)

Rafelski, Muller, Soff and Greiner,
Critical Discussion of the Vacuum Polarization Measurements with Muonic Atoms,
Annals Phys.88(1974) 419

Before comparing theory and experiment, one has further to consider a number of smaller effects like self-energy, electron screening, recoil, finite size, and polarization of the nucleus; furthermore, higher-order vacuum polarization. We shall discuss all these effects in the subsequent sections. The "raison d'être" of the great recent interest in the muonic atoms experiments is the fact that systematic differences between the present theory and experiment have been observed. Dixit *et al.* [3] and Walter *et al.* [4] have measured energies of the $5g_{9/2}$–$4f_{7/2}$ and $5g_{7/2}$–$4f_{5/2}$ transitions in Pb, Hg, Tl, Ba, and other transitions in lighter elements which are almost unaffected by the finite size of the nucleus. Dixit's comparison of theory and experiment showed very severe discrepancies between theoretical and expetimental values. He used some previously published results [5] for higher order vacuum polarization corrections which were later recalculated by Sundaresan and Watson [6], Blomquist [7], and Bell [8]. The discrepancy has been reduced considerably in the new calculations. However, a difference of about 2 standard deviations between theory and experiment of Dixit *et al.* [3] in Pb and Ba and of Walter *et al.* [4] in Hg, Tl remains.

Searches for the Higgs boson in Nuclear Physics (III)

Flurry of experimental work on the topic:

- Neutron-electron/Deuteron-electron scattering: $m_H > 0.6$ MeV

Adler, Dashen and Treiman, Comments on Proposed Explanations for the mu - Mesic Atom X-Ray Discrepancy Phys.Rev. D10 (1974) 3728

- Neutron-nucleus scattering: $m_H > 13$ MeV

Barbieri and Ericson, Evidence Against the Existence of a Low Mass Scalar Boson from Neutron-Nucleus Scattering, Phys.Lett. B57 (1975) 270

- Nuclear $^{16}O(6.05$ MeV$)$ and $^{4}He(20.2$ MeV$)$ to ground state ($0^+ \rightarrow 0^+$) transitions (can occur through Higgs emission): $m_H > 18$ MeV

Kohler, Watson and Becker, Experimental Search for a Low-Mass Scalar Boson, Phys.Rev.Lett. 33 (1974) 1628-1631

The experiment on the $^{16}O(6.05$ MeV$)$ state will be described first. The φ should, according to the Weinberg theory, decay via the weak interaction into an electron-positron pair provided that $m_\varphi \geq 1.022$ MeV. The lifetime[3] for the decay ranges from approximately 0.7 nsec near $m_\varphi = 6.05$ MeV to many microseconds near $m_\varphi = 1.022$ MeV (below 1.022 MeV only the two-photon decay mode is available with a lifetime expected[3] to be $\gtrsim 10^{-4}$ sec). Since the particle possesses only the weak interactions, it would readily penetrate[3] matter much as does the neutrino. A heavily shielded scintillation detector placed near a target in which the $^{16}O(6.05$ MeV$)$ state is produced should suffice to detect φ's which decayed within the volume of the detector; the signal from such a decay would approximate that of a 6.05-MeV γ ray.

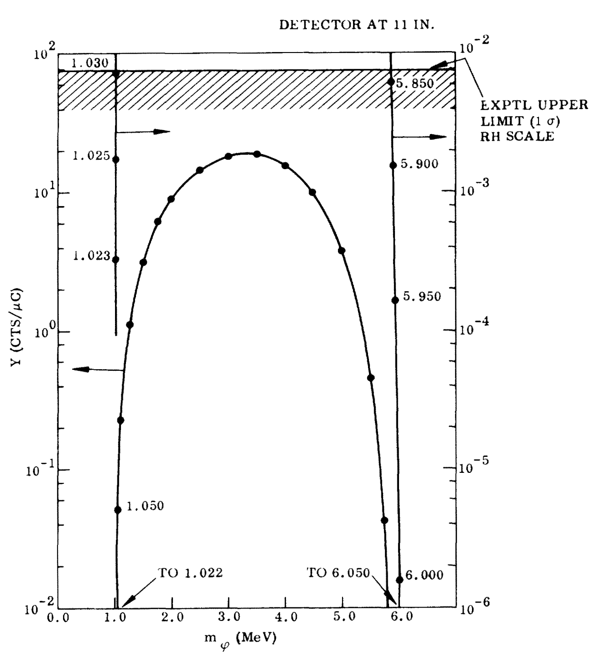


FIG. 1. Theoretical yield (counts/μC of proton beam) of detected φ's from the reaction $^{19}F(p,\alpha)^{16}O(6.05$ MeV$) \rightarrow {}^{16}O(g.s.) + \varphi$ versus assumed m_φ. (Note the separate parts of the yield curve and corresponding scales.) Also shown is the measured upper limit to the yield of detected φ's as a horizontal line with hatching crossing the lower wings of the yield curve (right-hand scale only).

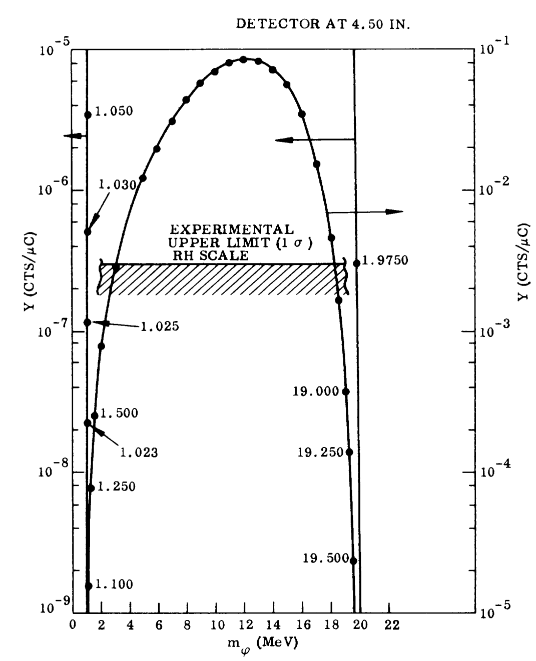


FIG. 2. Theoretical yield (counts/μC of proton beam) of detected φ's from the reaction $^{3}H(p)^{4}He(20.2$ MeV$) \rightarrow {}^{4}He(g.s.) + \varphi$ versus assumed m_φ. (Note the separate parts of the yield curve and corresponding scales.) Also shown is the measured upper limit to the yield of detected φ's as a horizontal line with hatching crossing the central portion of the yield curve (right-hand scale only).

These two experiments taken together then show that the scalar particle of Sundaresan and Watson,[4] if it exists at all, cannot have a mass in the range 1.030 MeV $\leq m_\varphi \leq 18.2$ MeV. The total range of masses judged acceptable by Resnick, Sundaresan, and Watson[3] was $0 \leq m_\varphi \leq 22$ MeV (masses $\leq 10^{-4}$ eV could already be excluded by an argument[3] relating to measurements of the gravitional constant, G). Thus the major portion of the total proposed mass range can now be excluded, suggesting a relatively low probability for the correctness of the Sundaresan and Watson proposal. This observation should perhaps be tempered by the realization that there are ~10 orders of magnitude between the 1-MeV upper limit from this work and the 10^{-4}-eV limit from the gravitational-constant measurements.

Searches in particle decays

- SINDRUM Collaboration measured $\pi+ \to e^+ \nu e^+ e^-$ and searched for $H \to e^+ e^-$

[excluded 10 MeV < M_H < 110 MeV]
SINDRUM spectrometer experiment at the Paul Scherrer Institute (PSI) 590 MeV proton cyclotron.
Measurement of the Decay π+→e+ve+e- and Search for a Light Higgs Boson
SINDRUM Collaboration (S. Egli (Zurich U.) et al.), Phys.Lett. B**222** (1989) 533

- CUSB Collaboration $Y \to H\gamma$

[excluded $2m_\mu$ <M_H < 5-6 GeV]
Investigated the radiative decay dependent on high order corrections of various states of the Y into a Higgs boson.
The search for a monochromatic photon sample from the decay $Y \to \gamma + X$.
It turned out that first order QCD corrections reduce the lowest order calculation by about 50%, and the effects of higher order corrections or relativistic corrections were not known.
CUSB also searched for Y decays to a photon plus a massless, invisible scalar.

- Crystal Ball collaboration looked for $J/\psi \to \gamma +$ massless scalar

The data were collected with the Crystal Ball Detector at the Stanford Linear Accelerator Center e'e storage ring facility SPEAR at the peak of the J/ψ resonance

[Edwards et al, Upper Limit for J/ψ → γ+Axion, Phys.Rev.Lett. 48 (1982) 903]
These two results CUSB and Crystal Ball together excluded a massless and very light Higgs, which is also subject to radiative correction uncertainties

- CERN-Edinburgh-Orsay-Mainz-Pisa-Siegen (NA31) $K^0 L \to \pi^0 H (\to ee)$

[excluded M_H < 50 MeV]
The NA31 experiment at the CERN Super Proton Synchrotron (SPS) searched for Higgs boson decays in e^+e^- in the decay $K^0_L \to \pi^0 H$.
These searches severely constrain the Higgs boson mass in the domain below 50 MeV by conferring an upper limit on the product of the branching ratios Br(K0L →π0H)×Br(H →e+e−) of approximately 2×10^{-8}
Search for a Neutral Higgs Particle in the Decay Sequence K0L →π0H and $H \to e^+ e$
NA31 Collaboration (G.D. Barr (CERN) et al.), Phys.Lett. B235 (1990) 356

Searches in particle decays (II)

Searches were performed also at PETRA (or the Positron-Electron Tandem Ring Accelerator) at DESY which operated between 1978 and 1986.

MARK-J Collaboration (Adeva et al.) Search for Top Quark and a Test of Models Without Top Quark at the Highest PETRA Energies,Phys.Rev.Lett. 50 (1983) 799

JADE Collaboration (W. Bartel et al.), A Search for Flavor Changing Neutral Currents in b Decay at PETRA Phys.Lett. B132 (1983) 241

TASSO Collaboration (Althoff et al.), Production and Muonic Decay of Heavy Quarks in e+ e- Annihilation at 34.5-GeV,Z.Phys. C22 (1984) 219

Also the CLEO experiment at the Cornell Electron Positron Storage Ring (CESR) searched for decays of the Higgs boson into a pair of muons, pions, and kaons produced through the FCNC decay B→HK$^{0(*)}$, with H(→ μμ,ππ,KK) and through the inclusive decay B → H X using the H → μμ decay. A limit, excluding the mass range 0.2-3.6 GeV [2m$_{\pi}$, 2m$_{\tau}$] was set. This exclusion relies on the estimate for B→H decay, which is subject to large theoretical uncertainties. The data sample consisted of about 487000 B-meson decays, from an integrated luminosity of 212 pb^{-1} at the Y(4S) resosance.

[CLEO Collaboration (M.S. Alam et al.).Search for a Neutral Higgs Boson in B-Meson Decay Phys.Rev. D40 (1989) 712-720, Erratum-ibid. D40 (1989) 3790]

TABLE I. The range of sensitivity in H^0 mass and the detection efficiency ϵ for exclusive two-bodv decays $B \to H^0\kappa$ with various H^0 decay modes and strange mesons κ. The detection efficiencies a averaged over the H^0 mass range and include the $K^0 \to \pi^+\pi^-$ and $K^* \to K\pi^\pm$ branching fractions.

H^0 decay	$\mu^+\mu^-$	$\pi^+\pi^-$	K^+K^-	$K^+\bar{K}^{*-}$	$K^0\bar{K}^{*0}$	$K^{*0}\bar{K}$
M_H (GeV)	0.2–3.6	0.3–3.6	1.0–3.6	1.4–3.6	1.4–3.6	1.8–3.
$\epsilon(H^0K^\pm)$	0.21	0.33	0.35	0.032	0.035	0.04
$\epsilon(H^0K^0)$	0.063	0.071	0.08			
$\epsilon(H^0K^{*\pm})$	0.025	0.041	0.03			
$\epsilon(H^0K^{*0})$	0.10	0.14	0.18	0.015	0.017	0.02

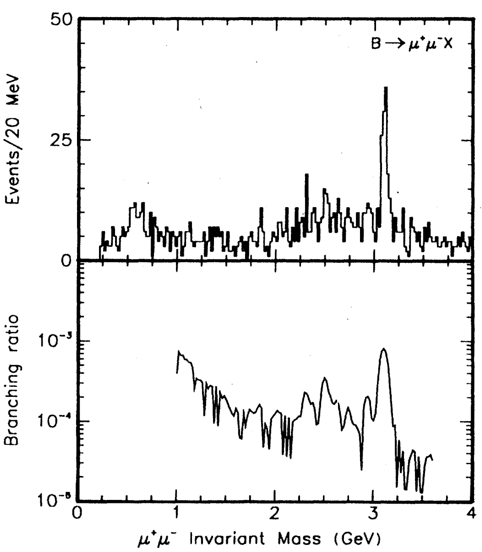
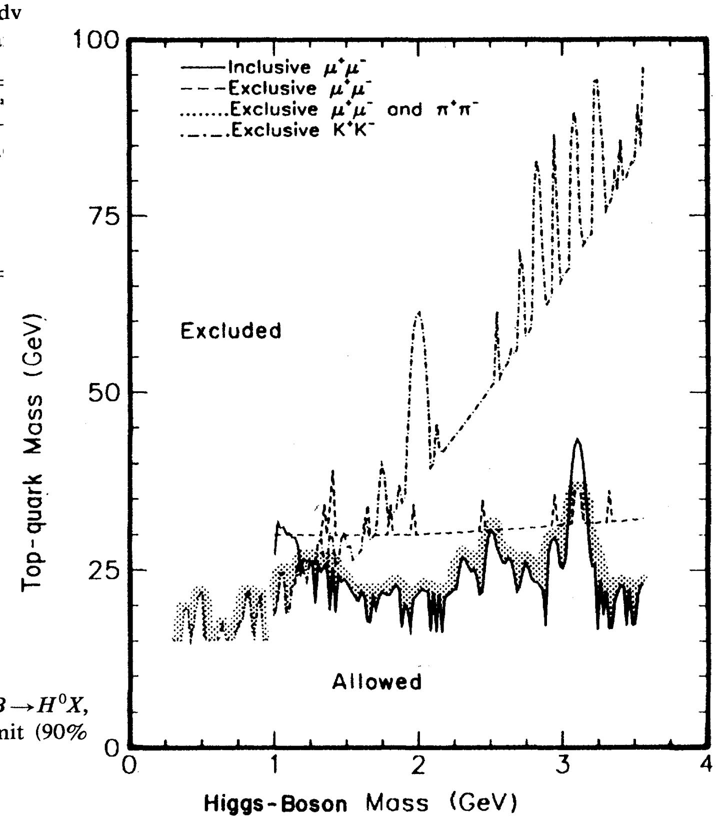


FIG. 6. Top: observed number of candidates for $B \to H^0X$, $H^0 \to \mu^+\mu^-$ as a function of M_H. Bottom: upper limit (90% confidence level) for $B(B\to H^0X)B(H^0\to\mu^+\mu^-)$.

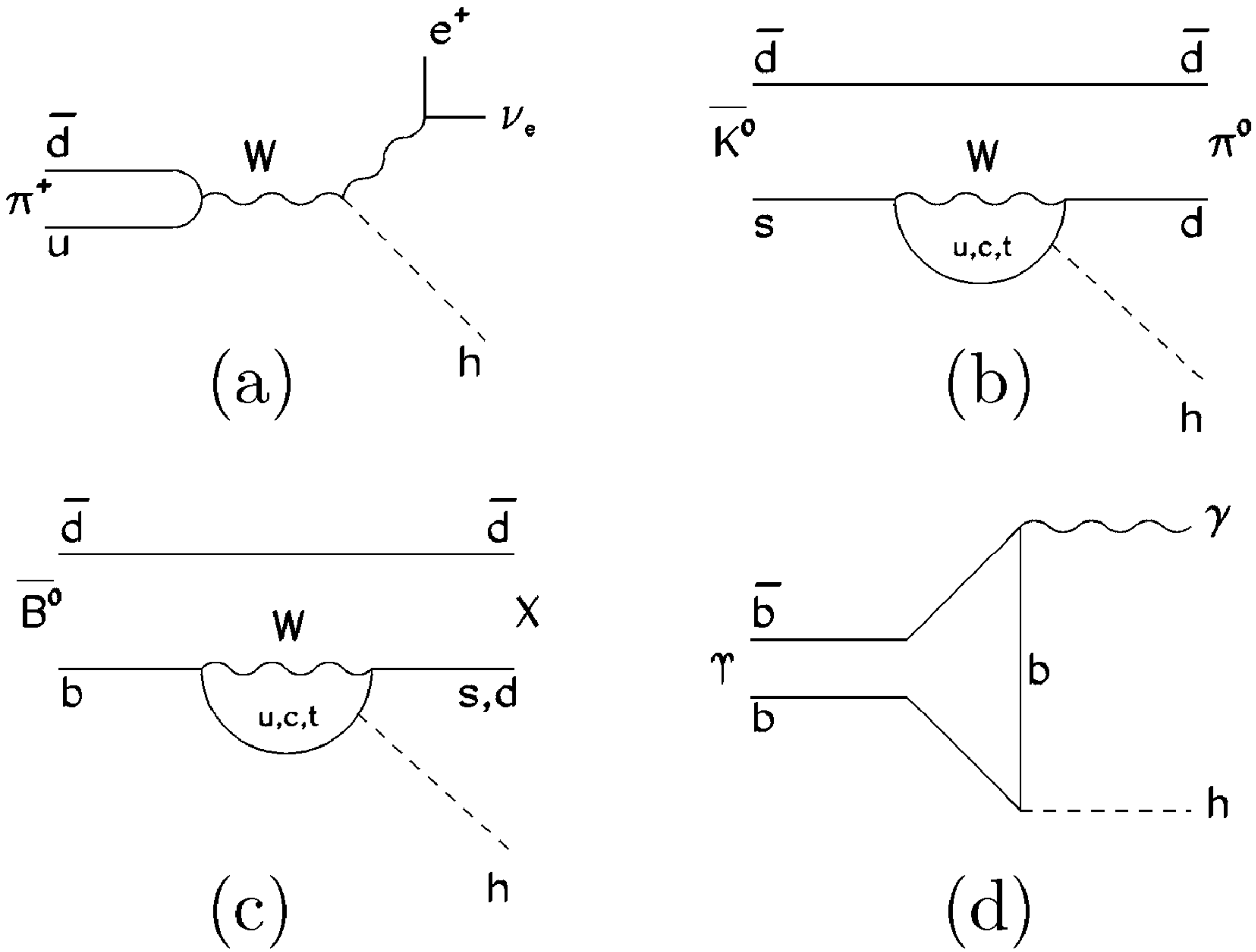


Phys.Rev. D40 (1989) 712

VI. CONCLUSION

Our conclusion is that if the Willey and Yu formula does not overestimate the B-to-Higgs-boson branching ratio and if the model assumptions used in obtaining the limits in Fig. 14 do not overestimate our experimental sensitivity to Higgs-boson decays, then a minimal neutral Higgs boson of mass between 0.2 and 3.6 GeV is excluded, provided that the top-quark mass is at least 30 GeV. For Higgs-boson masses near the Ψ mass (3.1±0.1 GeV) the minimum top-quark mass required to exclude the Higgs boson increases to 36 GeV. In light of the experimental lower limit of 28 GeV on the top-quark mass[25] and the various pieces of evidence[26] that the top-quark mass is greater than 44 GeV, we can, therefore, exclude the neutral-Higgs-boson mass from the 0.2-to-3.6-GeV range with considerable margin for error[27] in the theoretical models used to interpret the data.

Pre-LEP searches



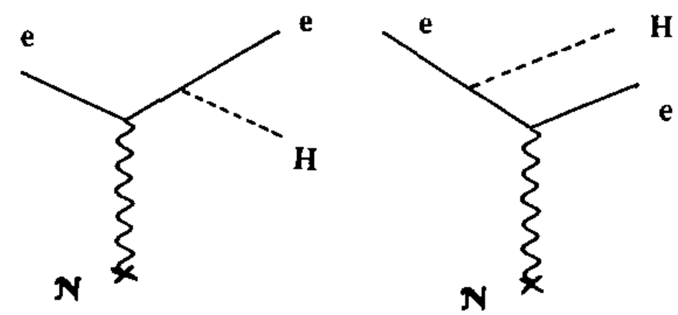
The issue with these searches was that the estimates on the SM Higgs boson production cross sections are potentially sensitive to large QCD corrections.
As a result, it is difficult to draw unambiguous conclusions.

Electron Beam Dump Experiment at LAL, Orsay

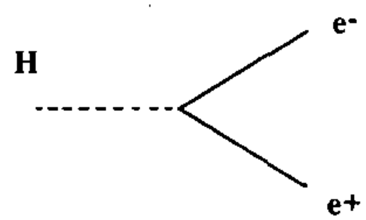
Phys.Lett. B**229** (1989) 150

1. Introduction

Among all the untested features of the electroweak standard model, it is annoying that the Higgs mechanism for the generation of mass is still not directly confirmed. Although indirect evidence for the existence of weak-isospin doublets of scalar fields has been obtained through the measurements of W and Z masses [1], the direct finding of the corresponding spin-0 particles would be the most welcome and definitive proof of this important phenomenon. On theoretical grounds the mass of the Higgs boson is little constrained. The only fact that it cannot be very heavy – less than a few TeV [2] – leaves open a wide field of experimental investigation which, but for a very small part, has not yet been attacked for lack of suitable processes. This state of affairs is expected to change shortly with the exploitation of LEP and SLC machines [3].



Higgs Bremsstrahlung



Higgs decay

This search is performed in the 1 - 50 MeV range.
The Br(H→γγ) < 2% thus only $H \to e^+e^-$ considered.

Advantage of this experiment: both production and decay are controlled by a unique coupling constant, totally specified by the SM and its simple extensions.
Also no hadronic matrix elements in theory calculations.

For $m_H \gg 2m_e$ the cross-section is independent whether H is 0^+ or 0^- [use formulae from Axion bremsstrahlung].
Higgs boson angular distirbution peaks at small angles with respect to the incident electron ($\sim m_H/E_0/4$)

$$z = E_H/E_0$$

$$\frac{d\sigma}{dz} \simeq \frac{2\alpha^2 \alpha_H Z^2}{m^2} \frac{z(1+\frac{2}{3}f)}{(1+f)^2} F$$

with

$$f = \frac{m_H^2(1-z)}{m^2 z^2}, \quad \alpha_H = \frac{g^2_{He\bar{e}}}{4\pi} = \frac{m^2 G_F \sqrt{2}}{4\pi},$$

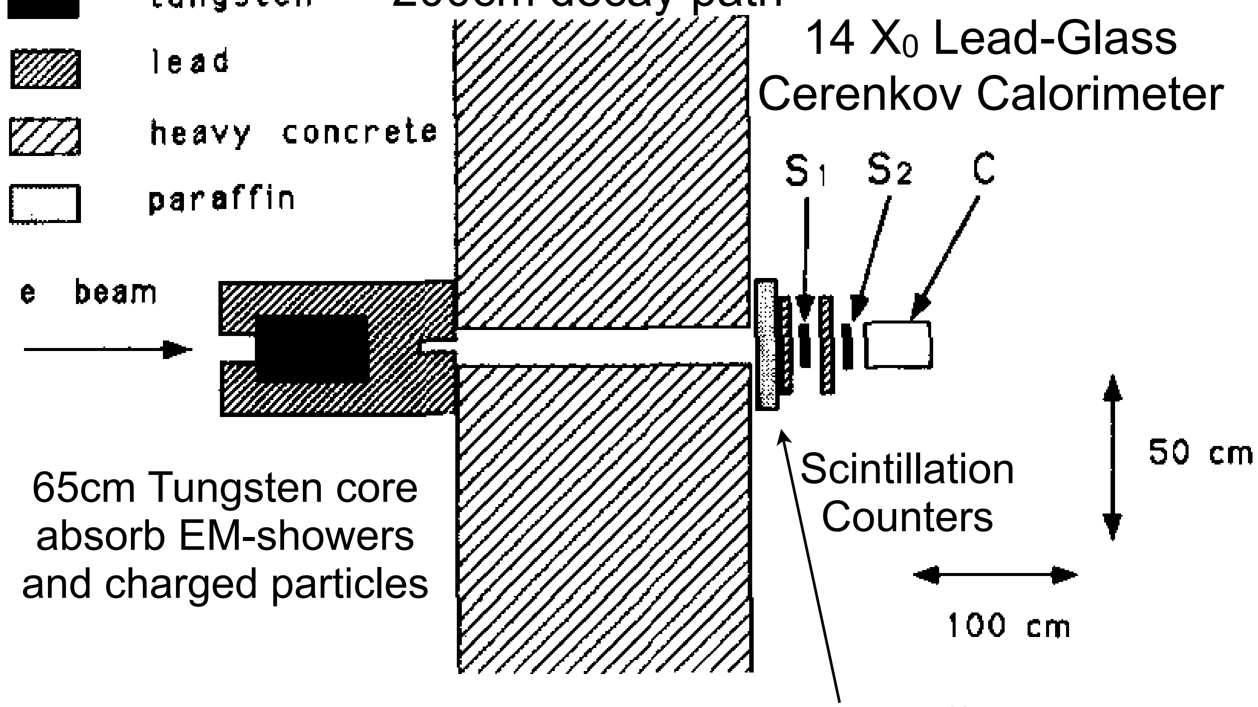
$$F = \ln(184 Z^{-1/3}) \quad \text{complete screening [14],}$$

$$= \ln \frac{2E_0(1-z)}{mz\sqrt{1+f}} - \frac{1}{2} \quad \text{no screening [15].}$$

$$\tau_H^{-1} = \frac{1}{2}\alpha_H m_H \left(1 - \frac{4m^2}{m_H^2}\right)^{3/2}$$

dσ/dz peaks at z~1 (in contrast to photon-bremsstrahlung)
distinct experimental signature

Electron Beam Dump Experiment at LAL, Orsay



Phys.Lett. B**229** (1989) 150

Cross-section falls slightly faster than m_H^{-2}

Life time decreases as m_H^{-1}

<u>Limiting Factors for this experiment:</u>

"Low Mass" Higgs boson decays outside fiducial volume [for E_0=1.6GeV: 5MeV Higgs boson travels 80m, 50MeV Higgs boson travels 75cm]

"High Mass" Higgs boson decays in the dump and small cross-section

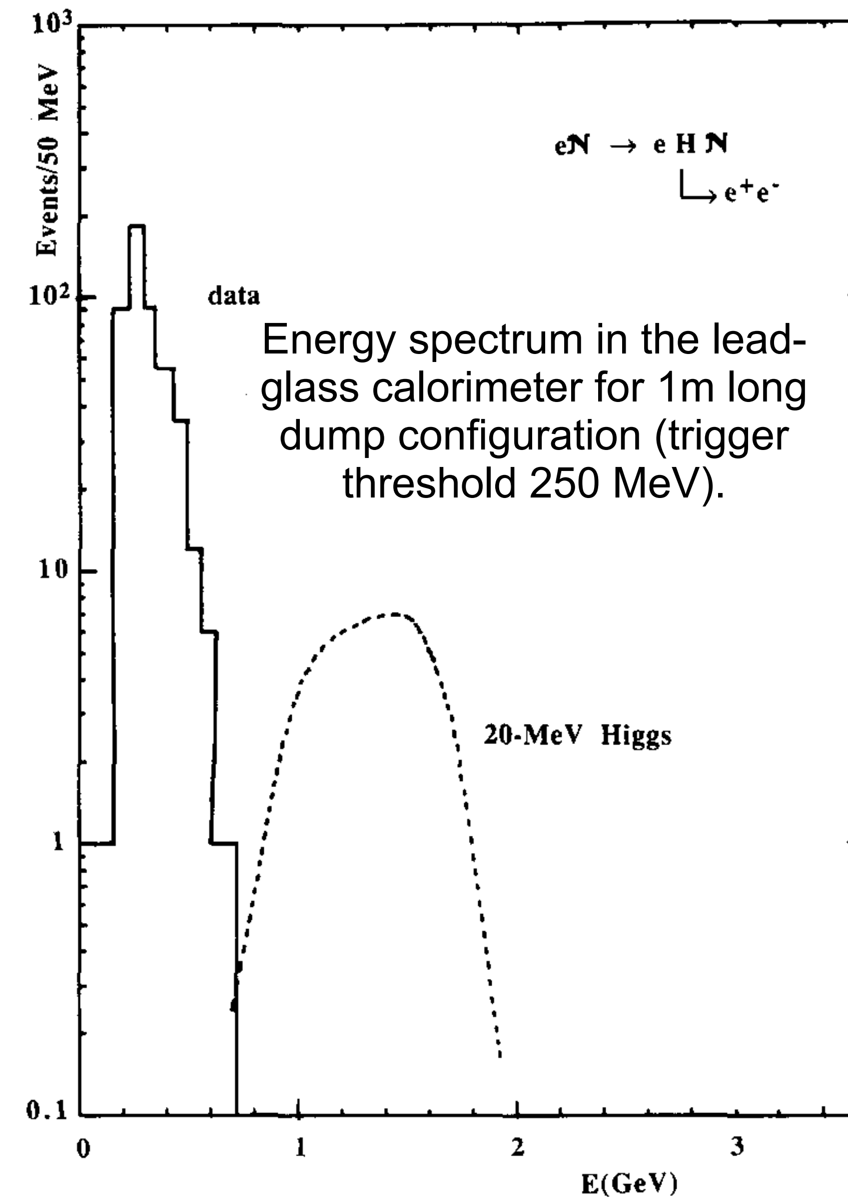
E_0=1.6GeV 15μs pulses @ 50 Hz

average intensity limited to $2\cdot 10^{12}$e/s to avoid pile-up

Cherenkov threshold of 250MeV, coincidence rate 1count/min

Calibration using 1.2GeV e-beam on the calorimeter

σE=10.7%sqrt(E[GeV])



<u>"A total of 2 1016 electrons was dumped during the data-taking part of the experiment which lasted only a few hours."</u>

No events observed above 750 MeV for the 1m-long dump configuration and above 1.1 GeV for the 1.2m-long dump configuration

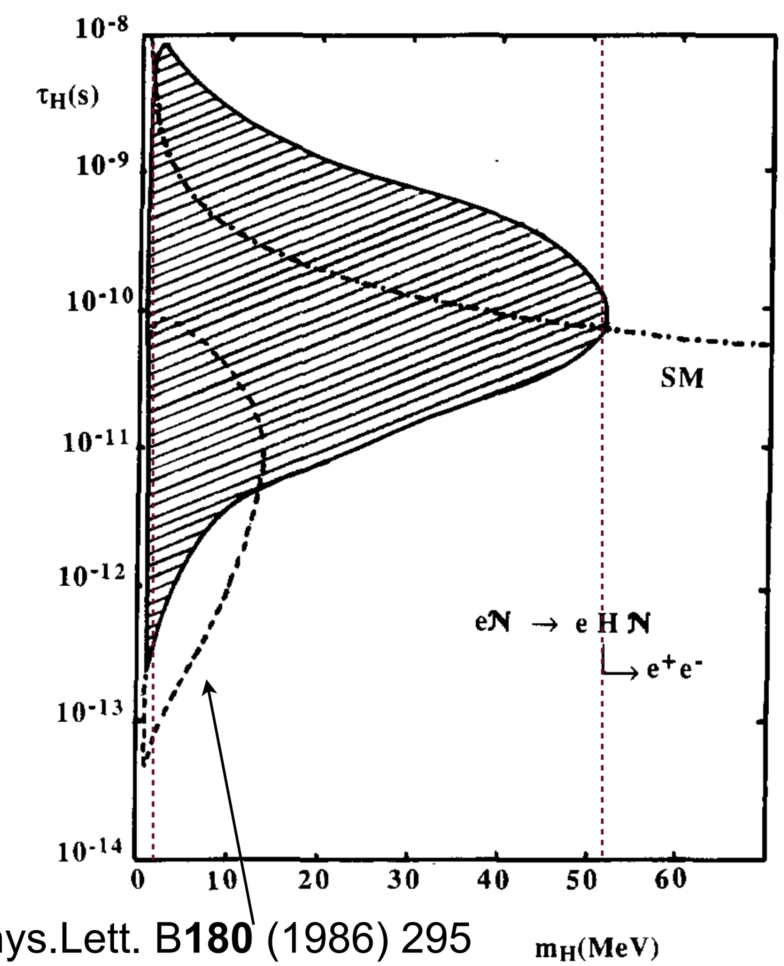
To quote mass limits one needs to estimate the efficiencies

Electron Beam Dump Experiment at LAL, Orsay

Phys.Lett. B**229** (1989) 150

The cross section for Higgs bremsstrahlung has been folded with the electron shower distribution in the dump and the efficiency for detecting a Higgs boson of a given mass was determined in our set-up. The trigger requirements could be satisfied by one or both of the decay particles (e^+e^-). For masses considered in this experiment, the geometrical acceptance for the decay products was always very close to one; however, a large reduction occurred for small and large lifetime values due to the finite lengths of the dump and of the decay region. Together with the energy cut defined above in order to remove the background, the overall efficiency to detect a Higgs boson produced in our dump had a maximum value of 37% for a mass near 30 MeV and decreased on either side because of decays. At low mass, the limitation arises from the fixed length of the decay region and at high mass, most produced Higgs would decay in the dump and escape detection. As an example, at 50 MeV, the overall efficiency has fallen to 11%. At any rate, the efficiency remains rather high and it is well understood by a few simple geometrical factors. As an illustration of the expected signal, we show in fig. 3 the energy spectrum which would be associated with the production of a 20 MeV Higgs boson: if that were the case, about 80 events would have been observed in this experiment above our energy cuts where we in fact observe none.

90% CL excluded region for scalar (or pseudoscalar) particles on the (m_H,τ_H) plane



Phys.Lett. B**180** (1986) 295

5. Conclusions

A very simple beam-dump experiment was designed to look for light Higgs bosons. The sensitivity of the method together with the fact that bremsstrahlung from electrons is a well controlled and calculable process only dependent on the existence of the coupling of Higgs to electrons, enabled us to exclude in a definitive way the mass range from 1.2 to 52 MeV for a standard Higgs.

We have also considered the supersymmetry-inspired minimal extension of the standard model and we have excluded a significant domain of masses and couplings for light scalar and pseudoscalar Higgs bosons. To our knowledge, these are the first results to constrain such models, for admittedly low, yet possible masses.

Higgs Boson Searches at LEP

Summarizing the situation at the dawn of LEP:
A Higgs boson lighter than 5-6 GeV is considered to be very unlikely,
subject mostly to theoretical uncertainties.
A massless Higgs boson or with mass between 1.2–100 MeV Higgs had been probably excluded.

Therefore, a final, unambiguous, answer on light Higgs bosons
was an important mission of the LEP experiments.
This is especially true if we consider some extension of the Standard Model.
For heavier Higgs bosons, LEP was unrivaled by any other experiment.

But there are important things to be kept in mind:
1) Higgs boson searches were already a hot topic in the 1970s and 1980s
[i.e. already after the discovery of the neutral currents]
2) Exclusion of hypotheses have a lot to do with the signal
[discoveries have to do mostly with the background]
3) Ingenuity