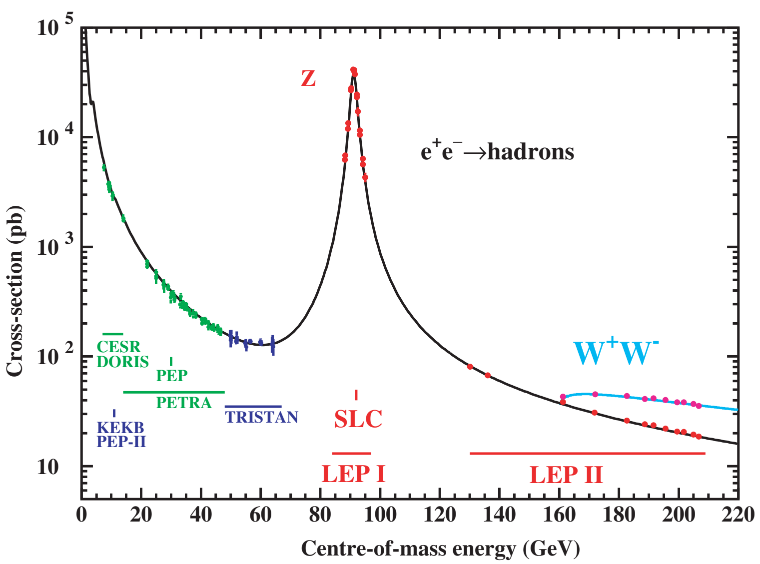
The global electroweak fit after the discovery of a new boson at the LHC

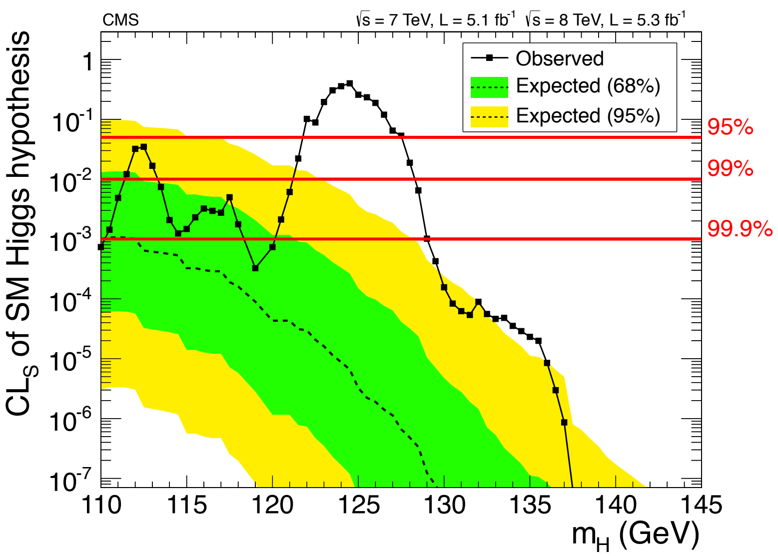


Roman Kogler
(University of Hamburg)

for the Gfitter group

HECAP Seminar

ICTP, Trieste, Nov 26, 2012

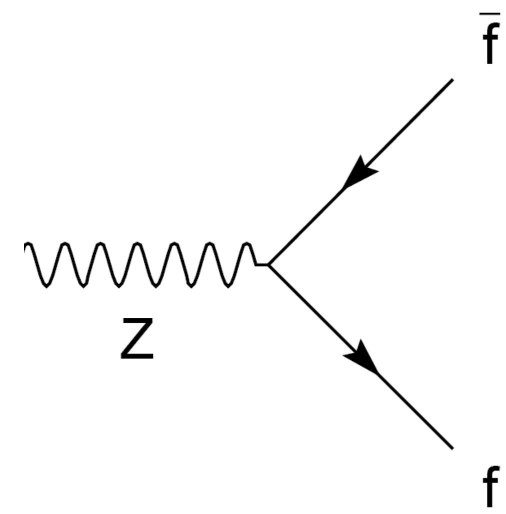


The Gfitter group: M. Baak (CERN), M. Goebel (DESY), J. Haller (Univ. Hamburg), A. Höcker (CERN), D. Kennedy (DESY), R. K. (Univ. Hamburg), K. Mönig (DESY), M. Schott (CERN) J. Stelzer (DESY)

Predictive Power of the SM

Tree level relations for Z → f $\bar{\text{f}}$

$$g_{V,f}^{(0)} \equiv g_{L,f}^{(0)} + g_{R,f}^{(0)} = I_3^f - 2Q^f \sin^2\theta_W$$
$$g_{A,f}^{(0)} \equiv g_{L,f}^{(0)} - g_{R,f}^{(0)} = I_3^f \,,$$



$$i\bar{f}\gamma^\mu\left(g_{V,f} - g_{A,f}\gamma_5\right) f Z_\mu$$

with the weak mixing angle:

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

Electroweak unification connects the electromagnetic and the weak coupling strengths

$$G_F = \frac{\pi\alpha}{\sqrt{2}(M_W^{(0)})^2\left(1 - \frac{(M_W^{(0)})^2}{M_Z^2}\right)}$$

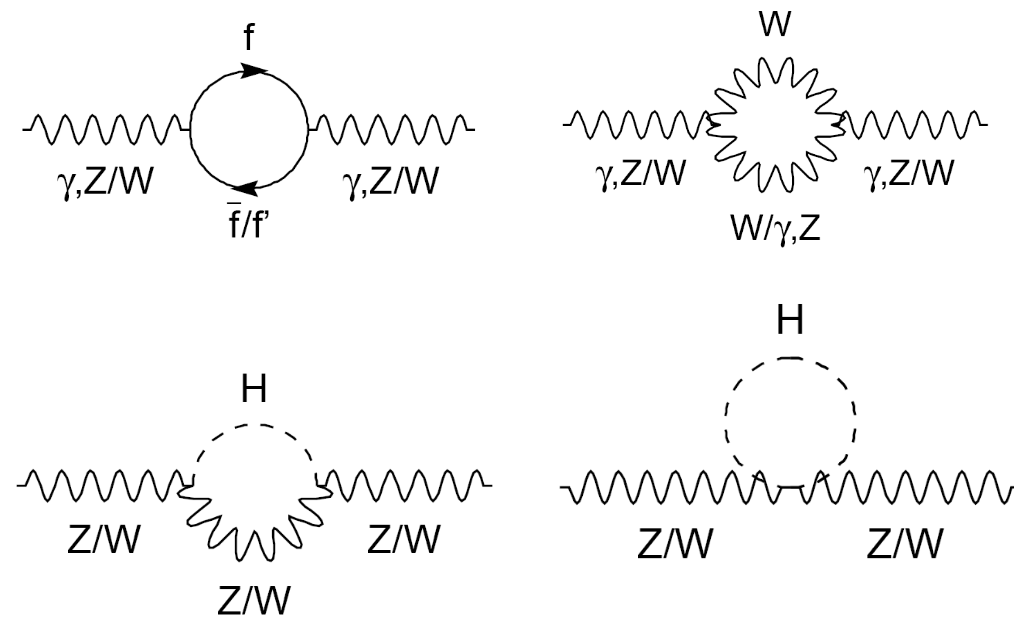
...and M_W can be expressed in terms of M_Z and G_F

$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$

Electroweak sector of SM is given by three free parameters, for example α, G_F and M_Z

Radiative Corrections

Modification of propagators and vertices

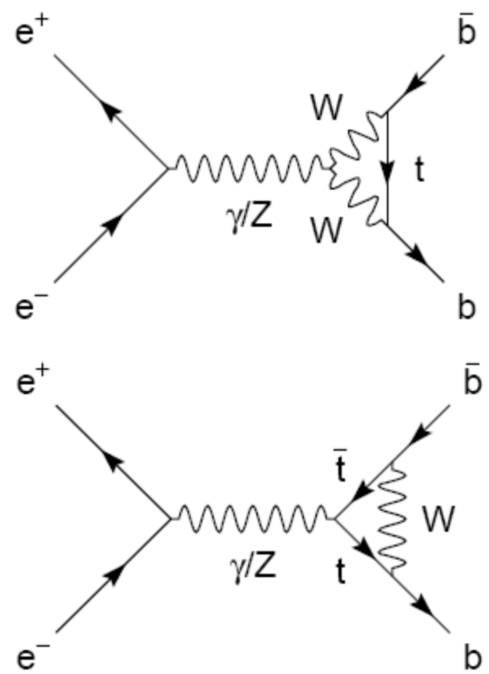


- Parametrisation of radiative corrections: electroweak form factors ρ, κ, Δr
- Effective couplings at the Z-pole:

$$g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\mathrm{eff}}^f\right)$$

$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$

$$\sin^2\theta_{\mathrm{eff}}^f = \kappa_Z^f \sin^2\theta_W$$



- Mass of the W boson:

$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

- ρ, κ, Δr depend nearly quadratically on m_t and logarithmically on M_H

Precision tests and constraints of the SM

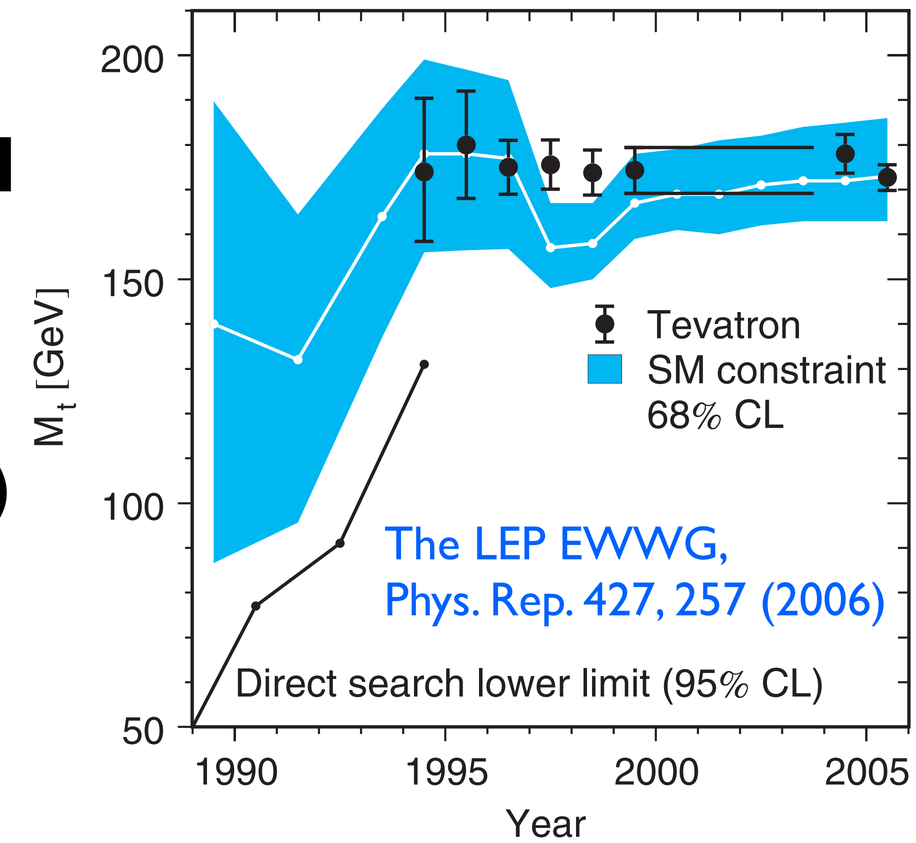
Electroweak Fits

Electroweak Fits to precision data have a long tradition

- Huge amount of work to precisely understand loop corrections in the SM - can only outline a few of the recent results here
- Most observables known at least in two-loop order, sometimes leading order terms of higher order corrections available
- Parametrisation of computationally intensive results used in fits
- Precision measurements crucial, after the LEP/SLC era results from Tevatron and LHC become available

Electroweak Fits routinely performed by many groups

- TOPAZ0 (G. Passarino et al.)
- LEP EWWG, using ZFITTER (D. Bardin et al.)
- GAPP (J. Erler)
- Gfitter (M. Baak et al.)
- ...

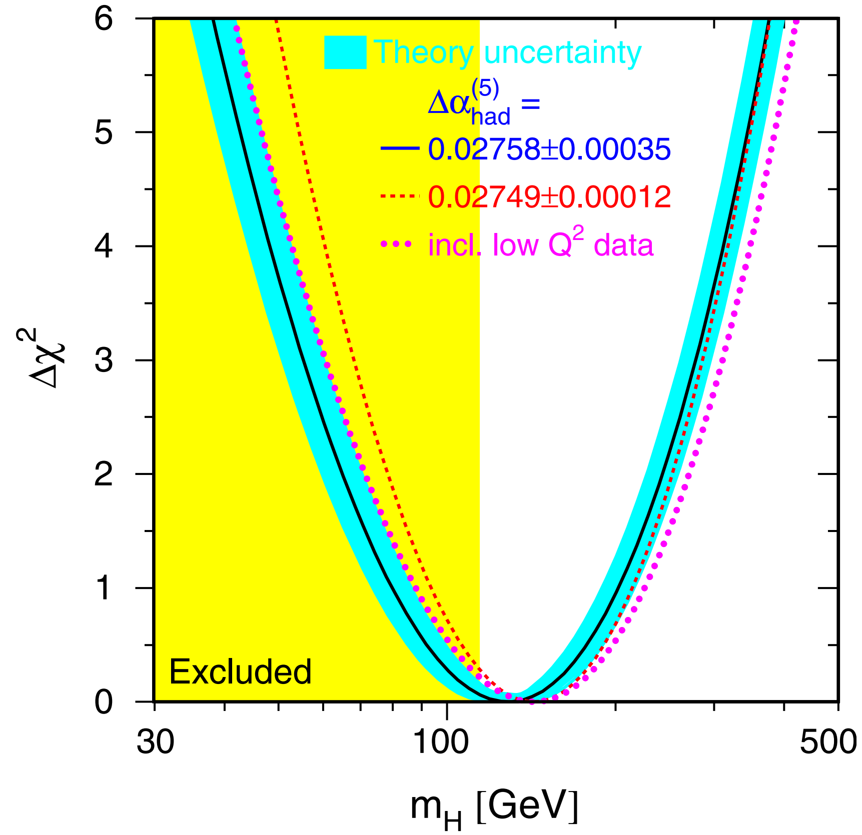


EW Fits and the Higgs Boson

Closing in on the Higgs Boson

- Final word from LEP/SLC in 2006
- Precision data at the Z-pole
- Direct limits: $M_H > 114.4$ GeV (LEP-II)
- Indirect determination:
  $M_H = 129^{+74}_{-49}$ GeV

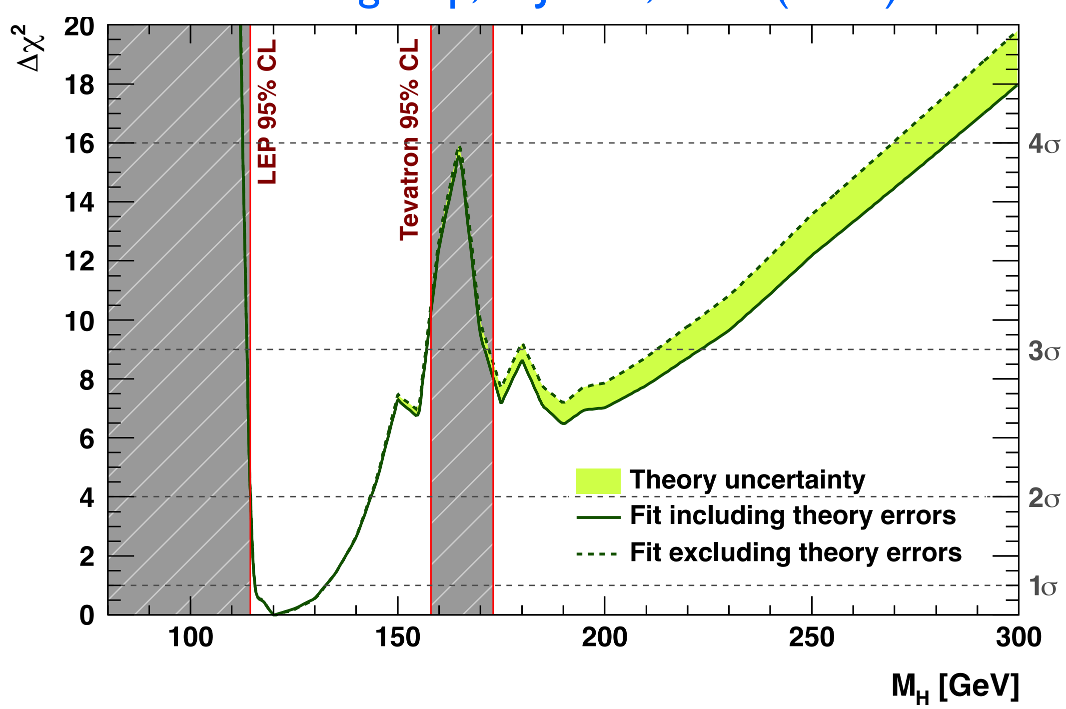
The LEP EWWG, Phys. Rep. 427, 257 (2006)



Experimental Limits at high values of M_H become available

- First exclusion limits from the Tevatron
- Limits incorporated in EW fits
- Indirect determination:
  $M_H = 120^{+12}_{-5}$ GeV

Gfitter group, EPJC 72, 2003 (2012)



The Gfitter Project

G fitter **A Generic Fitter Project for HEP Model Testing**

www.cern.ch/gfitter

Gfitter Software

- Modular framework based on C++, xml, python and ROOT
- Core packages for data handling, fitting and statistics tools

Gfitter Features

- Consistent treatment of statistical, systematic and theoretical uncertainties
  - correlations and inter-parameter dependencies taken into account
  - theoretical uncertainties handled with Rfit prescription: included in χ^2 estimator with flat likelihood in allowed ranges
- Several fitting tools available
  - Minuit, genetic minimisation, simulated annealing... (via TMVA)
- Full statistical analysis possible
  - parameter scans, p-values, MC tests, goodness-of-fit...

[The Gfitter group, EPJ C60, 543 (2009), EPJC 72, 2003 (2012)]

The Gfitter SM Package

A Gfitter package for the global electroweak fit

- Implementation of SM predictions of all available precision observables
- State of the art calculations used
  parametrisations: considerable speed improvement, agreement with exact calculations to high accuracy
  - The mass of the W boson M_W [M. Awramik et al., Phys. Rev. D69, 053006 (2004)]
  - The effective weak mixing angle $\sin^2\theta^l_{\mathrm{eff}}$ [M. Awramik et al., JHEP 11, 048 (2006), M. Awramik et al., Nucl.Phys.B813:174-187 (2009)]
  - Partial and total widths of the Z, total width of the W [Cho et. al, arXiv:1104.1769]
  - hadronic Z width [P.A. Baikov et al., arXiv:1201.5804]
  - Electroweak two-loop corrections to Rb [Freitas et al., arXiv:1205.0299]
- Free fit parameters: M_Z, M_H, $\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, $\overline{m}_c$, $\overline{m}_b$, m_t
- Scale parameters for theoretical uncertainties: ΔM_W, $\Delta\sin^2\theta^l_{\mathrm{eff}}$

www.cern.ch/gfitter

Observables and Calculations

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong."

(Richard P. Feynman)

Measurements at the Z-Pole

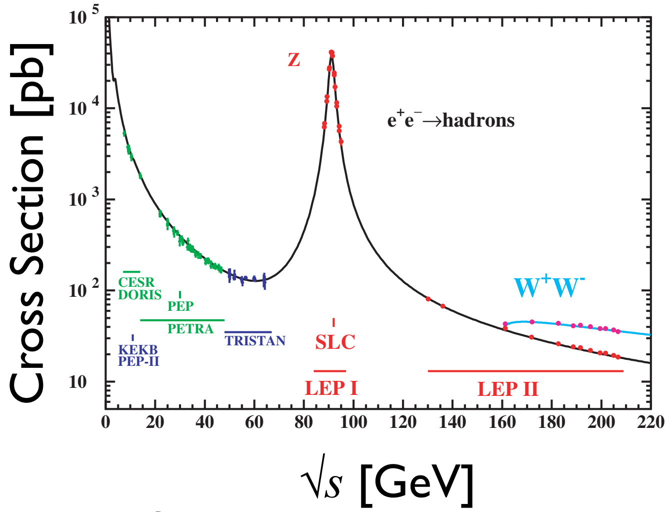
Total cross section

- Express in terms of partial decay width of initial and final state

$$\sigma^Z_{f\bar{f}} = \sigma^0_{f\bar{f}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} \frac{1}{R_{\mathrm{QED}}} \quad \text{with} \quad \sigma^0_{f\bar{f}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

Corrected for QED radiation

- Full width: $\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\mathrm{had}} + \Gamma_{\mathrm{inv}}$
- Highly correlated set of parameters



Less correlated set of parameters

- Z mass and width: M_Z, Γ_Z
- Hadronic pole cross section $\sigma^0_{\mathrm{had}} = 12\pi/M_Z^2 \cdot \Gamma_{ee}\Gamma_{\mathrm{had}}/\Gamma_Z^2$
- Three leptonic ratios (lepton univ.) $R^0_\ell = R^0_e = \Gamma_{\mathrm{had}}/\Gamma_{ee}\ (= R^0_\mu = R^0_\tau)$
- Hadronic width ratios R^0_b, R^0_c

Measurements at the Z-Pole

Definition of Asymmetry

- Distinguish axial and axial-vector couplings of the Z

$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = \frac{2 g_{V,f}\, g_{A,f}}{g_{V,f}^2 + g_{A,f}^2}$$

- Directly related to $\sin^2\theta_{\mathrm{eff}}^{f\bar{f}} = \frac{1}{4Q_f}\left(1 + \mathcal{R}e\left(\frac{g_{V,f}}{g_{A,f}}\right)\right)$

Observables

- In case of no beam polarisation (LEP) use final state angular distribution to define forward/backward asymmetry

$$A_{FB}^f = \frac{N_F^f - N_B^f}{N_F^f + N_B^f} \qquad A_{FB}^{0,f} = \frac{3}{4} A_e A_f$$

- Polarised beams (SLC): define left/right asymmetry

$$A_{LR}^f = \frac{N_L^f - N_R^f}{N_L^f + N_R^f}\frac{1}{\langle |P|_e \rangle} \qquad A_{LR}^0 = A_e$$

- Measurements: $A_{FB}^{0,\ell}$, $A_{FB}^{0,c}$, $A_{FB}^{0,b}$, A_ℓ, A_c, A_b

The Electromagnetic Coupling

Running of the EM coupling

- The EW fit requires precise knowledge of $\alpha(M_Z)$ (better than 1%)
- Conventionally parametrised as ($\alpha(0)$ = fine structure constant)

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)}$$

- Evolution with renormalisation scale

$$\Delta\alpha(s) = \Delta\alpha_{\mathrm{lep}}(s) + \Delta\alpha^{(5)}_{\mathrm{had}}(s) + \Delta\alpha_{\mathrm{top}}(s)$$

- Leptonic term known up to three loops for $q^2 \gg m_l$ [M. Steinhauser, Phys. Lett. B429, 158 (1998)]
- Top quark contribution known up to two loops, small: $-0.7 \cdot 10^{-4}$
- Hadronic contribution difficult, cannot be obtained from pQCD alone
  - analysis of low energy e^+e^- data
  - usage of pQCD if lack of data

$$\Delta\alpha_{\mathrm{had}}(M_Z^2) = (274.2 \pm 1.0) \cdot 10^{-4}$$

[M. Davier et al., Eur. Phys. J. C71, 1515 (2011)]

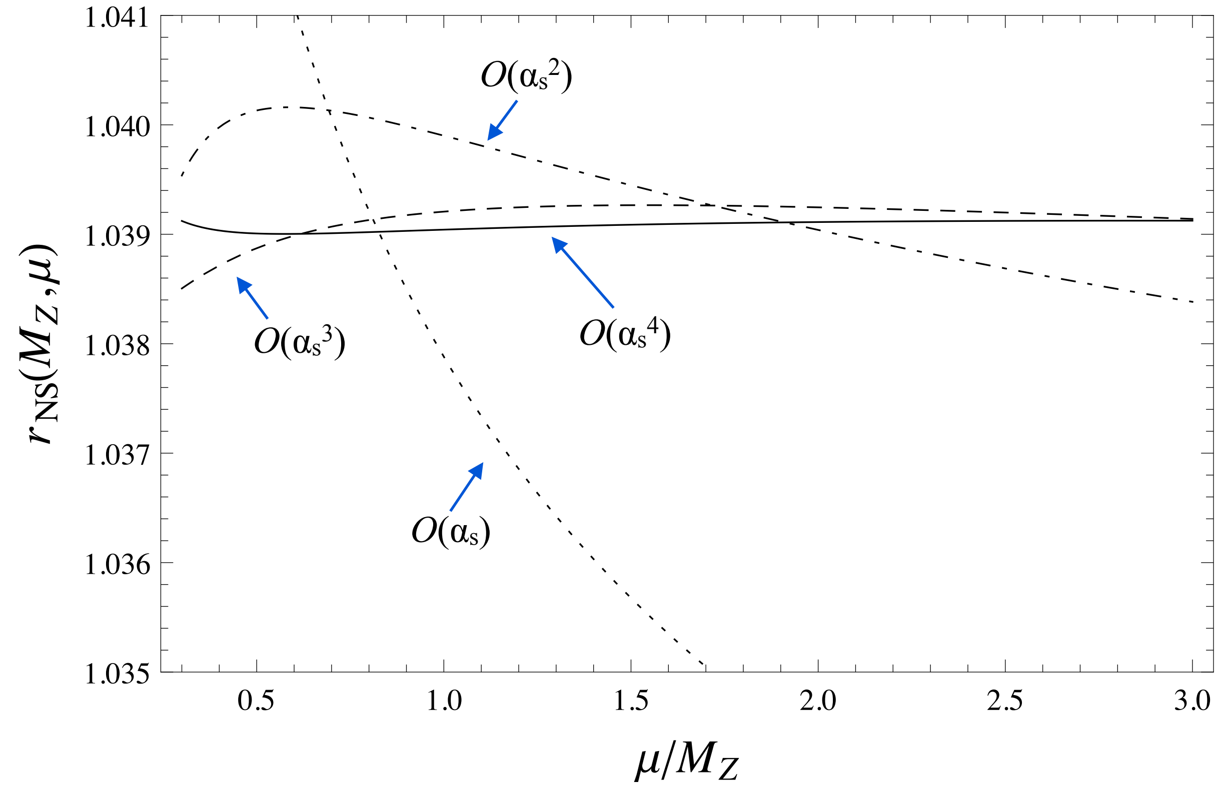
Radiator Functions

- Partial widths are defined inclusively: they contain QCD and QED contributions
- Corrections can be expressed as radiator functions $R_{A,f}$ and $R_{V,f}$

$$\Gamma_{f\bar{f}} = N_c^f \frac{G_F M_Z^3}{6\sqrt{2}\pi} \left(|g_{A,f}|^2 R_{A,f} + |g_{V,f}|^2 R_{V,f} \right)^2$$

[D. Bardin, G. Passarino, "The Standard Model in the Making", Clarendon Press (1999)]

- High sensitivity to the strong coupling α_s
- Recently full four-loop calculation of QCD Adler function became available (N³LO)
- Much reduced scale dependence
- Theoretical uncertainty of 0.1 MeV, compare to experimental uncertainty of 2.0 MeV



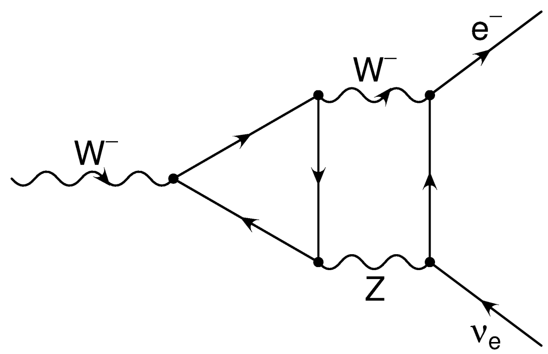
[P. Baikov et al., Phys. Rev. Lett. 108, 222003 (2012)]
[P. Baikov et al Phys. Rev. Lett. 104, 132004 (2010)]

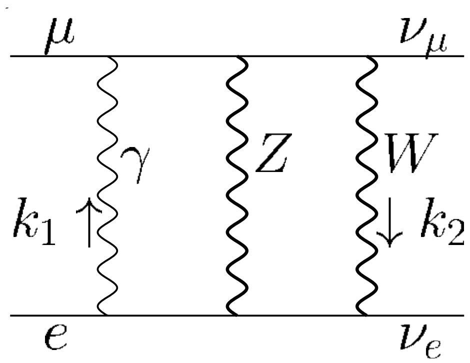
Calculation of M_W

- Full EW one- and two-loop calculation of fermionic and bosonic contributions
- One- and two-loop QCD corrections and leading terms of higher order corrections
- Results for Δr include terms of order $O(\alpha)$, $O(\alpha\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^2_{\text{ferm}})$, $O(\alpha^2_{\text{bos}})$, $O(\alpha^2\alpha_s m_t^4)$, $O(\alpha^3 m_t^6)$
- Uncertainty estimate:
  - missing terms of order $O(\alpha^2\alpha_s)$: about 3 MeV (from $O(\alpha^2\alpha_s m_t^4)$)
  - electroweak three-loop correction $O(\alpha^3)$: < 2 MeV
  - three-loop QCD corrections $O(\alpha\alpha_s^3)$: < 2 MeV
  - Total: $\delta M_W \approx 4$ MeV

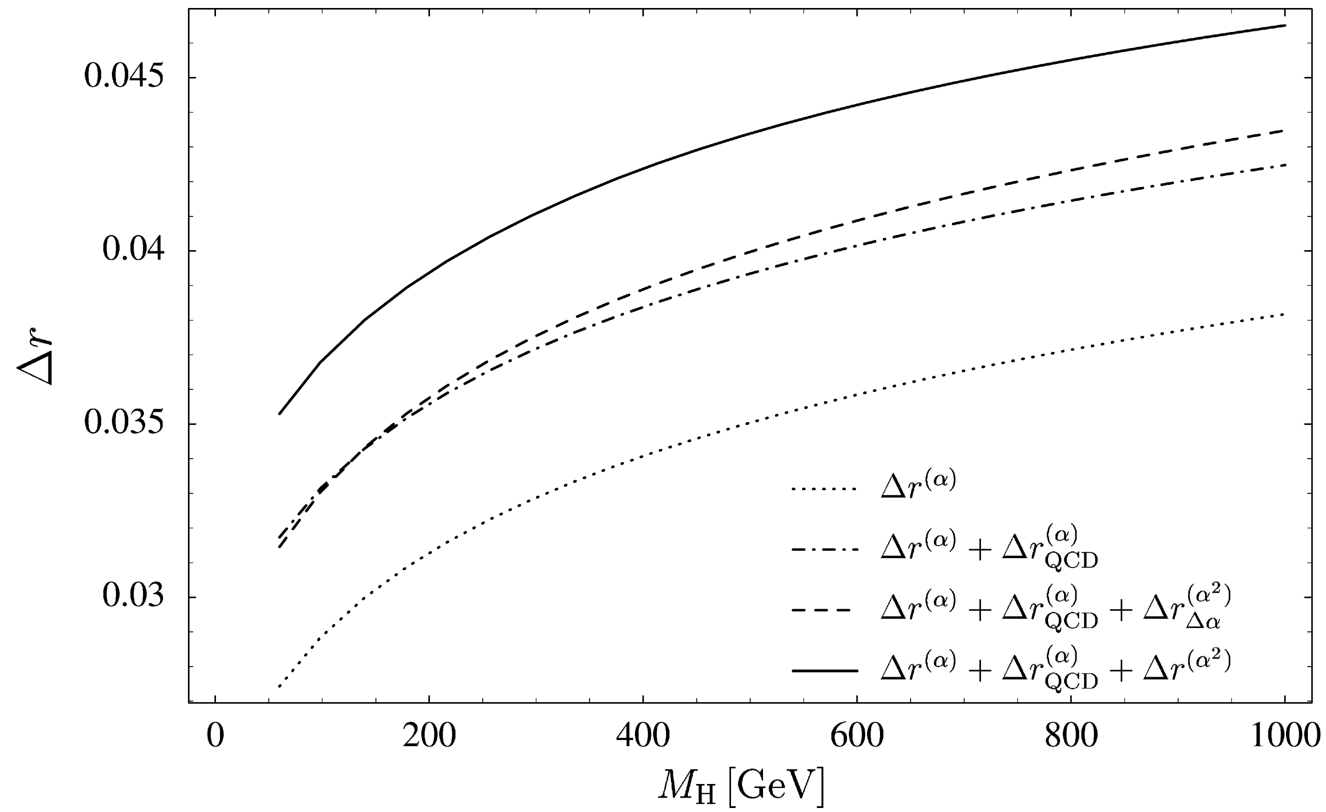
[M Awramik et al., Phys. Rev. D69, 053006 (2004)]

[M Awramik et al., Phys. Rev. Lett. 89, 241801 (2002)]





A Freitas et al., Phys. Lett. B495, 338 (2000)]



Calculation of $\sin^2(\theta^l_{eff})$

[M Awramik et al, Phys. Rev. Lett. 93, 201805 (2004)]
[M Awramik et al., JHEP 11, 048 (2006)]

- Effective mixing angle:

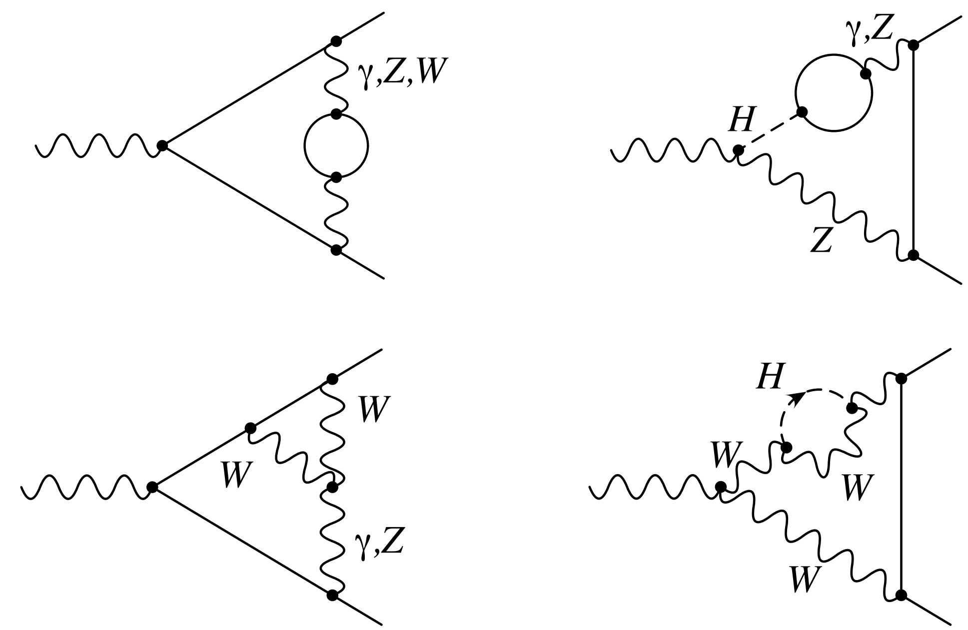
$$\sin^2\theta_{\rm eff}^{\rm lept} = \left(1 - M_{\rm W}^2/M_{\rm Z}^2\right)(1+\Delta\kappa)$$

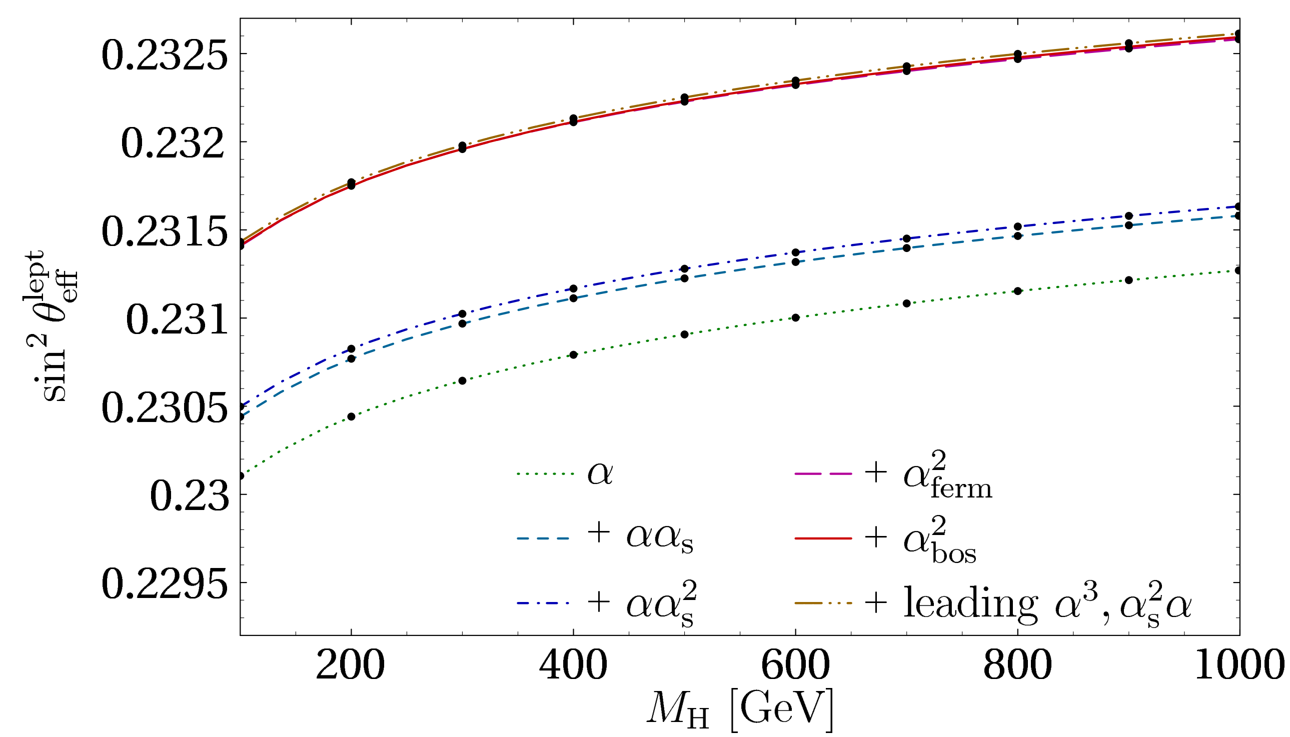
- Two-loop EW and QCD correction to $\Delta\kappa$ known, leading terms of higher order QCD corrections
- fermionic two-loop correction about 10^{-3}, whereas bosonic one 10^{-5}
- Uncertainty estimate obtained with different methods, geometric progression:

$$\mathcal{O}(\alpha^2\alpha_{\rm s}) = \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}\,\mathcal{O}(\alpha\alpha_{\rm s}).$$

$\mathcal{O}(\alpha^2\alpha_{\rm s})$ beyond leading $m_{\rm t}^4$	$3.3\ldots2.8\times10^{-5}$
$\mathcal{O}(\alpha\alpha_{\rm s}^3)$	$1.5\ldots1.4$
$\mathcal{O}(\alpha^3)$ beyond leading $m_{\rm t}^6$	$2.5\ldots3.5$

Total: $\delta\sin^2\theta^l_{\rm eff} \approx 4.7\ 10^{-5}$



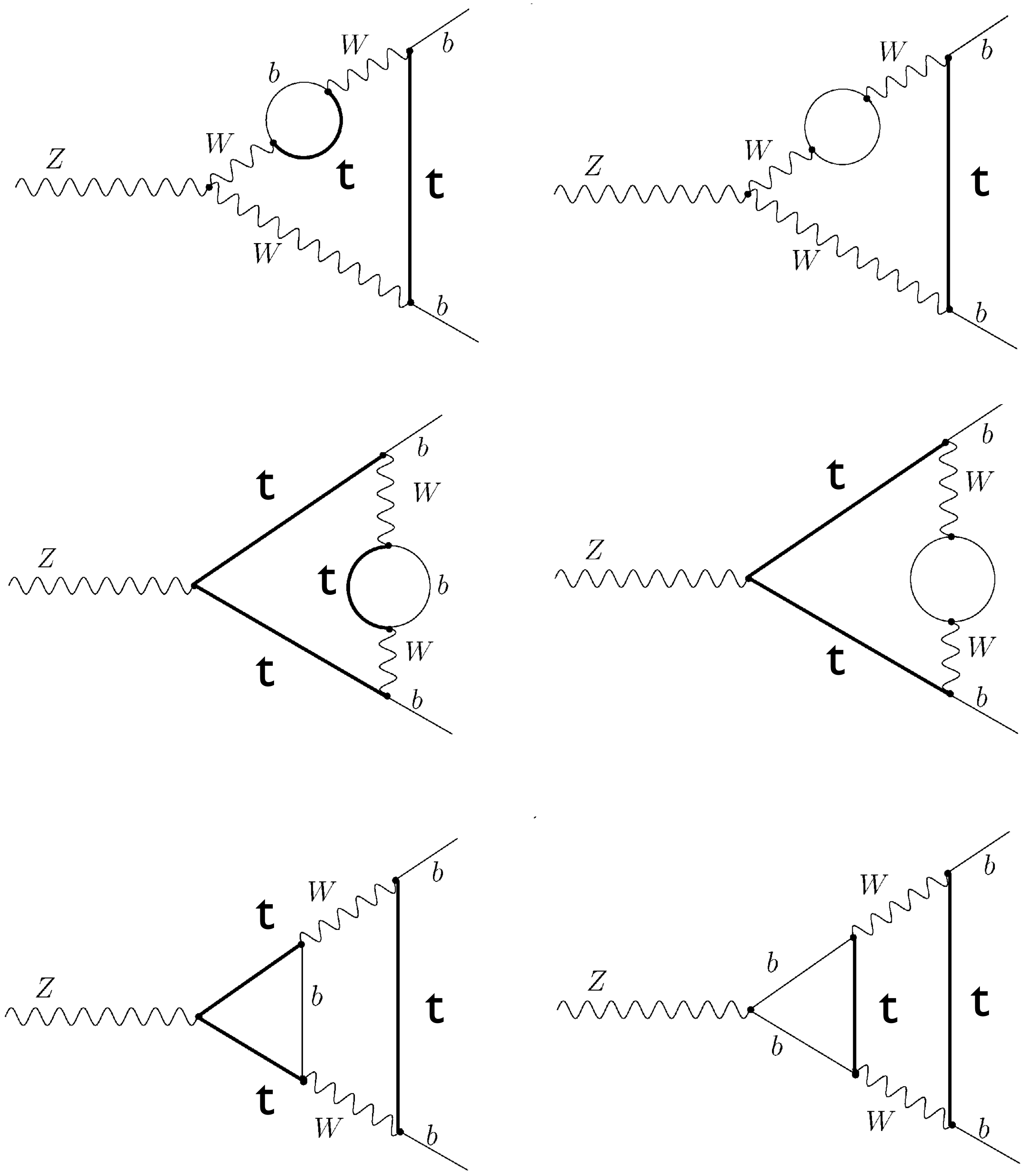


New Calculation of $\sin^2(\theta^{bb}_{eff})$

[M Awramik et al, Nucl. Phys. B813, 174 (2009)]

- Calculation of $\sin^2\theta_{eff}$ for b-quarks more involved, because of top quark propagators in the $Z \rightarrow b\bar{b}$ vertex
- Investigation of known discrepancy between $\sin^2\theta_{eff}$ from leptonic and hadronic asymmetry measurements
- Two-loop EW correction only recently completed, effect of $O(10^{-4})$
- Now $\sin^2\theta^{bb}_{eff}$ known at the same order as $\sin^2\theta_{eff}$ for leptons and light quarks
- Uncertainty assumed to be of same size as for $\sin^2\theta_{eff}$:

$\delta\sin^2\theta^{bb}_{eff} \approx 4.7\ 10^{-5}$



New Calculation of R^0_b

[A. Freitas et al., JHEP 1208, 050 (2012)]

Full two-loop calculation of $Z \to b\bar{b}$

- The branching ratio $R^0{}_b$: partial decay width of $Z \to b\bar{b}$ and $Z \to q\bar{q}$

$$R_b \equiv \frac{\Gamma_b}{\Gamma_{\rm had}} = \frac{\Gamma_b}{\Gamma_d + \Gamma_u + \Gamma_s + \Gamma_c + \Gamma_b} = \frac{1}{1 + 2(\Gamma_d + \Gamma_u)/\Gamma_b}$$

- Contribution of same terms as in the calculation of $\sin^2\theta^{bb}{}_{\rm eff}$
  → cross-check the two results, found good agreement
- Two-loop corrections are comparable to experimental uncertainty ($6.6 \cdot 10^{-4}$)

	1-loop EW and QCD correction to FSR	2-loop EW correction	2-loop EW and 2+3-loop QCD correction to FSR	1+2-loop QCD correction to gauge boson selfenergies
$M_{\rm H}$ [GeV]	$\mathcal{O}(\alpha) + {\rm FSR}_{1-{\rm loop}}$ $[10^{-3}]$	$\mathcal{O}(\alpha^2_{\rm ferm})$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\rm ferm}) + {\rm FSR}_{>1-{\rm loop}}$ $[10^{-4}]$	$\mathcal{O}(\alpha\alpha_{\rm s}, \alpha\alpha^2_{\rm s})$ $[10^{-4}]$
100	-3.632	-6.569	-9.333	-0.404
200	-3.651	-6.573	-9.332	-0.404
400	-3.675	-6.581	-9.331	-0.404

The Global EW Fit with Gfitter

"There's two possible outcomes: if the result confirms the hypothesis, then you've made a discovery. If the result is contrary to the hypothesis, then you've made a discovery."

(Enrico Fermi)

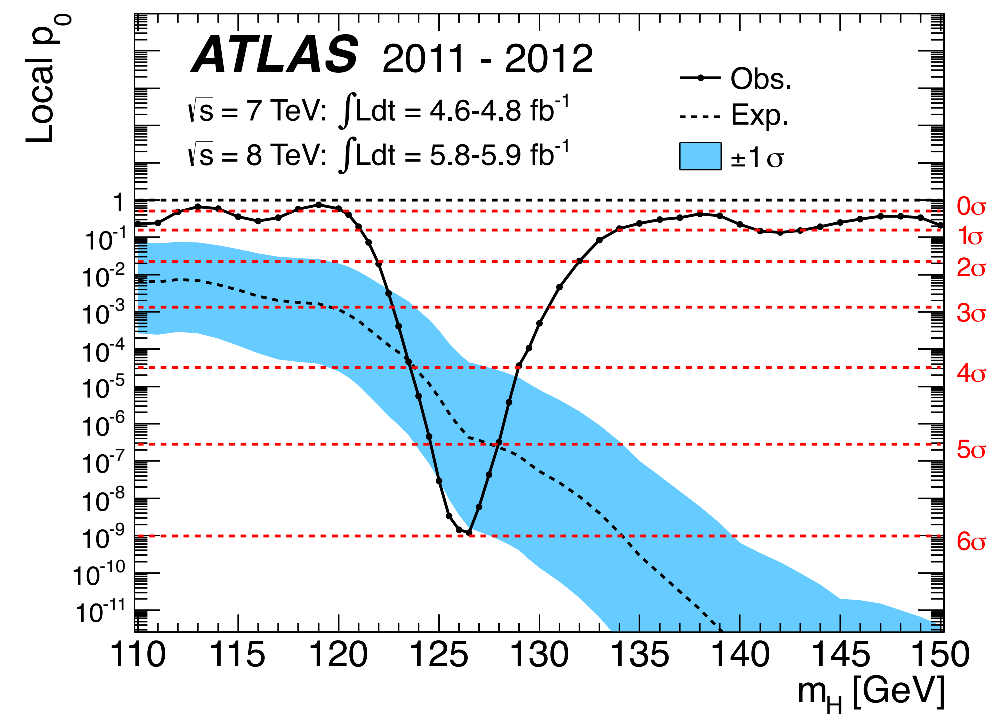
This Year's Discovery

ATLAS and CMS have reported the discovery of a new boson

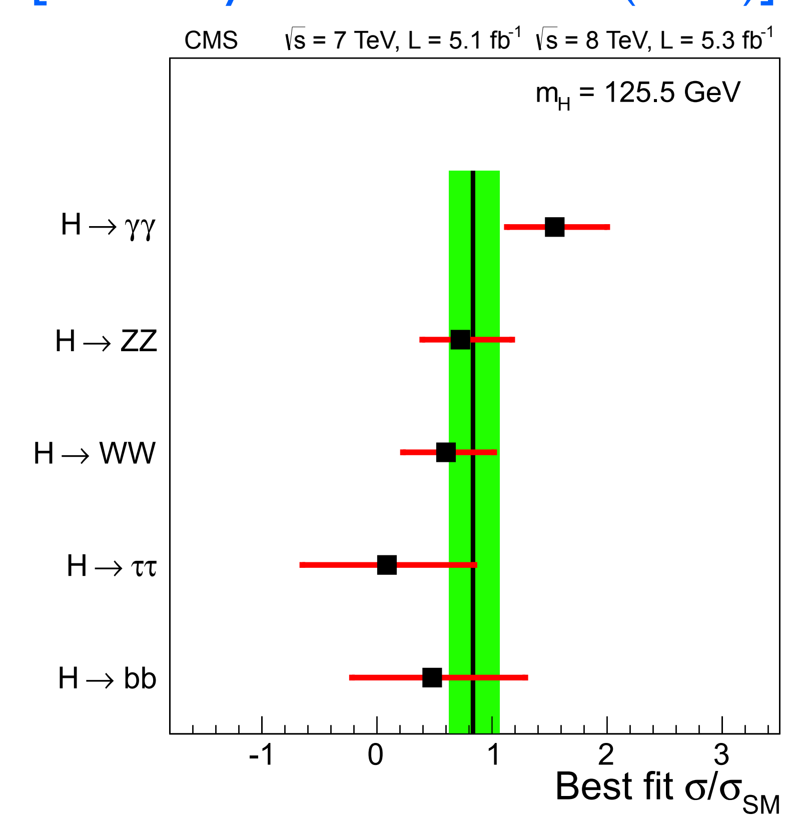
- The cross section and branching ratios are compatible with the SM Higgs boson
- Measured mass:
  ATLAS: 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV
  CMS: 125.3 ± 0.4 (stat) ± 0.4 (sys) GeV
- Assume that it is the Higgs boson, then M_H = 125.7 ± 0.4 GeV
- Difference between fully uncorrelated and fully correlated systematic uncertainties: uncertainty on M_H 0.4 → 0.5 GeV

The SM is for the first time fully overconstrained → test its consistency

[ATLAS, Phys. Lett. B, 761, 1 (2012)]



[CMS, Phys. Lett. B, 761, 30 (2012)]



Experimental Input

Observables:

- Z-pole observables: LEP/SLD results
  [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
- M_W and Γ_W: LEP/Tevatron [arXiv:1204:0042]
- m_t : Tevatron [arXiv:1207:1069]
- $\Delta\alpha_{had}^{(5)}(M_Z)$ [M. Davier et al., EPJC 71, 1515 (2011)]
- $\overline{m}_c$, $\overline{m}_b$: world averages
  [PDG, J. Phys. G33, 1 (2006)]
- M_H : LHC [arXiv:1207.7214 , arXiv:1207.7235]

Free fit parameters:

- M_Z, M_H, $\Delta\alpha_{had}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, $\overline{m}_c$, $\overline{m}_b$, m_t
- Scale parameters for theoretical uncertainties
  δM_W (4 MeV), $\delta\sin^2\theta^l_{eff}$ ($4.7 \cdot 10^{-5}$)

M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	Tevatron
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP / SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	SLC
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP / SLC
R^0_b	0.21629 ± 0.00066	LEP / SLC
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.18 ± 0.94	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\nabla)}$	2757 ± 10	

[The Gfitter Group, arXiv:1209.2716]

Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	94^{+25}_{-22}	94^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0116
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01627 ± 0.0002	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	0.1477 ± 0.0009	$0.1468 \pm 0.0005^{(\dagger)}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23148^{+0.00011}_{-0.00007}$	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6680^{+0.00025}_{-0.00038}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00004}_{-0.00007}$	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	0.0740 ± 0.0005	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	0.1036 ± 0.0007	0.1034 ± 0.0004
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	0.21475 ± 0.00003	0.21473 ± 0.00003
$\overline{m}_c$ [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]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\triangle\nabla)}$	2757 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M^2_Z)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-1.4	4.7	–

[The Gfitter Group, arXiv:1209.2716]

Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	94^{+25}_{-22}	94^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0116
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01627 ± 0.0002	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	0.1477 ± 0.0009	$0.1468 \pm 0.0005^{(\dagger)}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23148^{+0.00011}_{-0.00007}$	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6680^{+0.00025}_{-0.00038}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00004}_{-0.00007}$	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	0.0740 ± 0.0005	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	0.1036 ± 0.0007	0.1034 ± 0.0004
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	0.21475 ± 0.00003	0.21473 ± 0.00003
$\overline{m}_c$ [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]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\triangledown)}$	2757 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-1.4	4.7	–

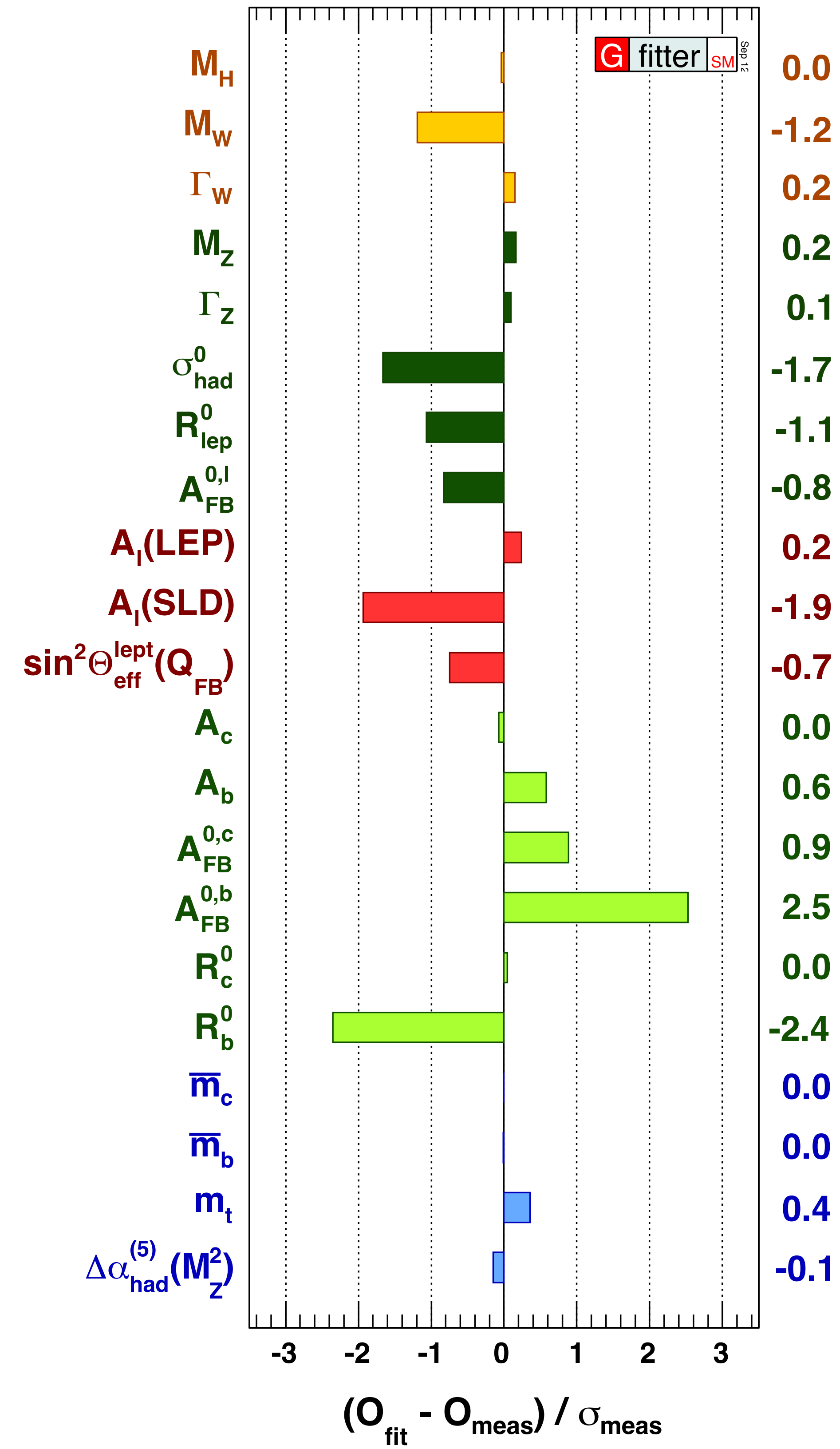
Global Fit: Results

χ^2_{min}/ndf = 21.8/14 → p-value = 0.08

- large value of χ^2_{min} not due to inclusion of M_H measurement
- without M_H measurement: χ^2_{min} /ndf = 20.3/13 → naive p-value = 0.09

Pull values after the fit

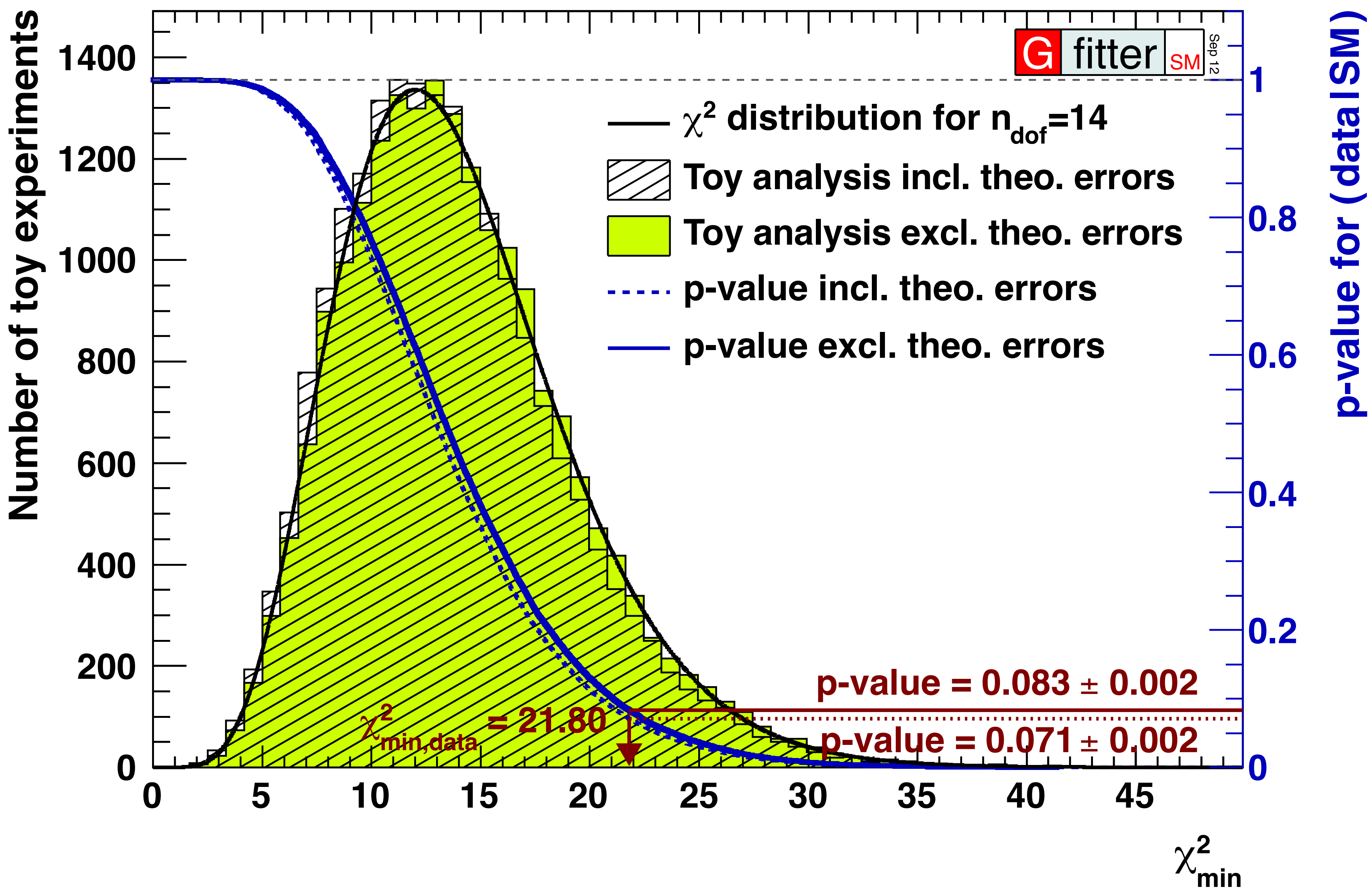
- Pull defined as $P = \dfrac{O_{\rm fit} - O_{\rm meas}}{\sigma_{\rm meas}}$
- No pull value exceeds deviations of more than 3σ (good consistency of SM)
- Small values for M_H, A_c, $R^0{}_c$, m_c and m_b indicate that their input accuracies exceed the fit requirements
- Largest deviations in the b-sector: $A^{0,b}{}_{FB}$ and $R^0{}_b$ with 2.5σ and -2.4σ



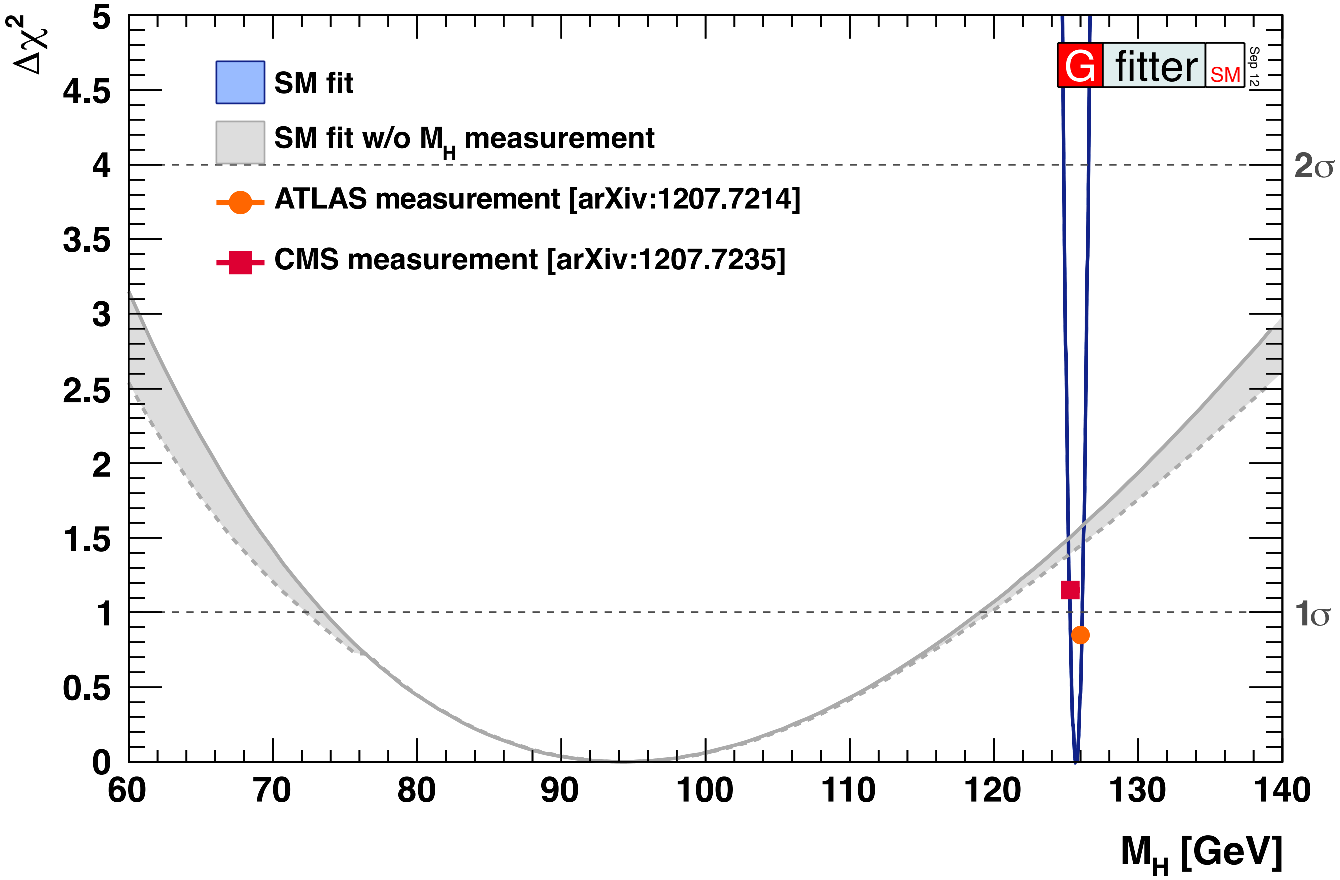
Goodness of Fit

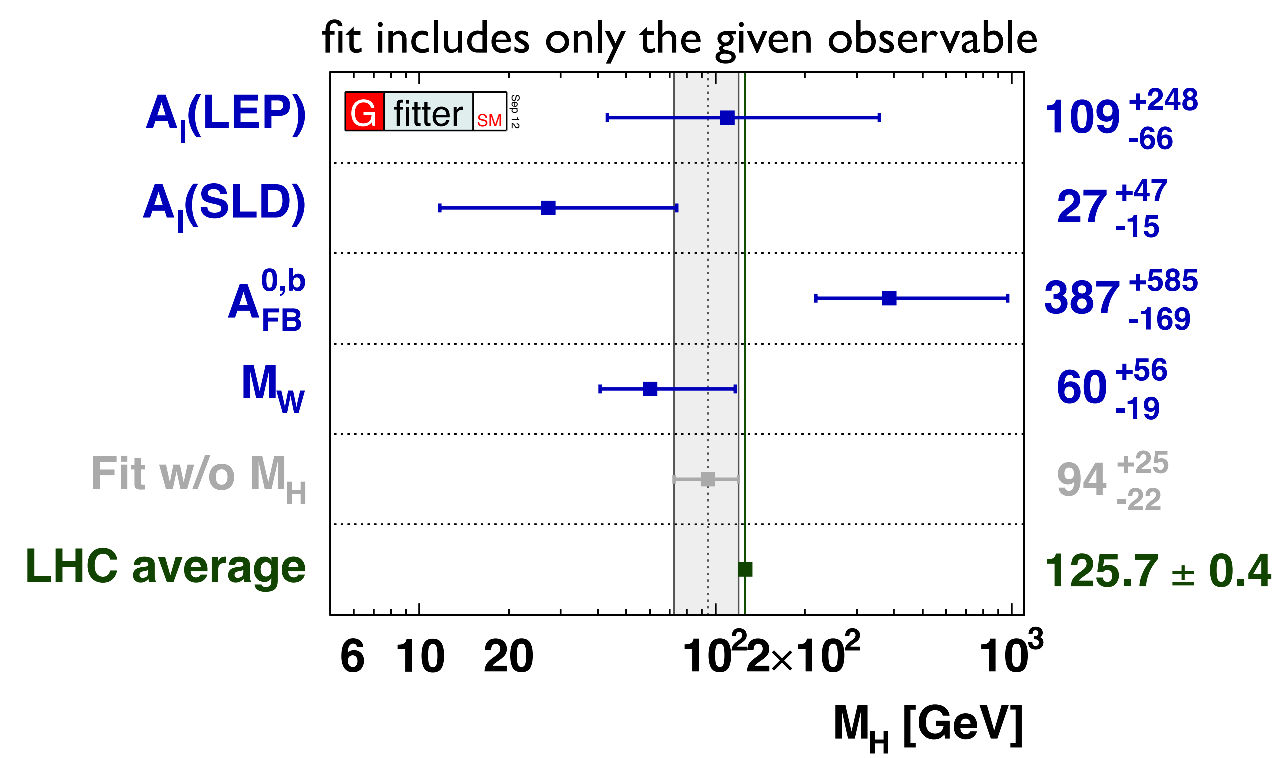
Toy analysis with 20000 toy experiments

- p-value: probability for getting $\chi^2_{min, toy}$ larger than χ^2_{min} from data
- p-value: probability for wrongly rejecting the SM: 0.07 ± 0.01 (theo)



Global Fit: Results





Scan of the $\Delta\chi^2$ profile versus M_H

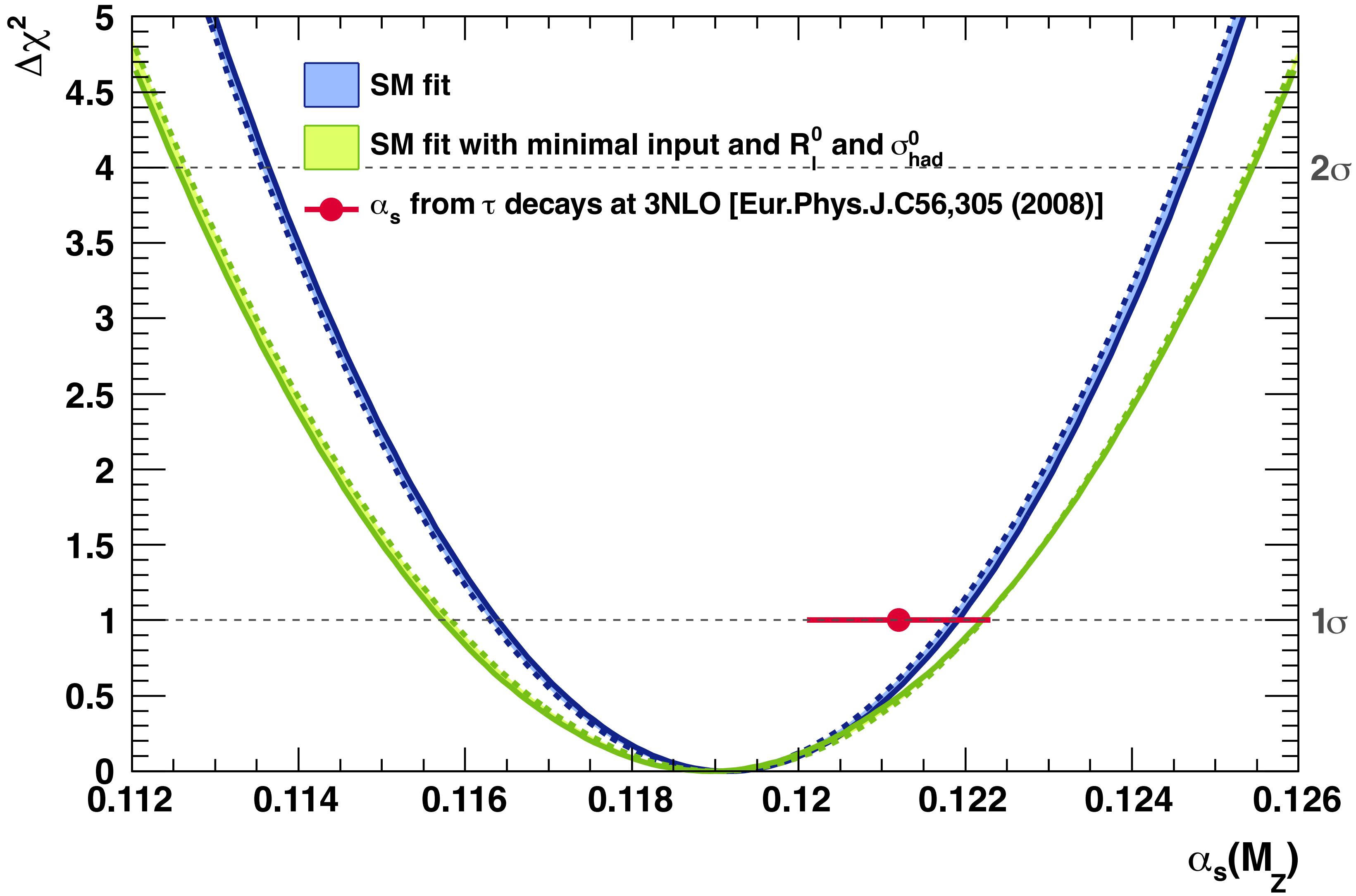
- blue line: full SM fit
- grey band: fit without M_H measurement
- fit without M_H input gives
  $M_H = 94\,^{+25}_{-22}$ GeV
- consistent within 1.3σ with measurement

Determination of M_H removing all sensitive observables except the given one:

Tension (2.5σ) between $A^{0,b}{}_{FB}$, $A_{\rm lep}$(SLD) and M_W visible

$\alpha_s(M_Z)$ from Z→hadrons

- Determination of α_s at NNNLO
- most sensitivity through total hadronic cross section σ^0_{had} and the partial leptonic width R^0_l
- Theory uncertainty obtained by scale variation, per-mille level



$$\alpha_s(M_Z) = 0.1191 \pm 0.0028\,(\text{exp.}) \pm 0.0001\,(\text{theo.})$$

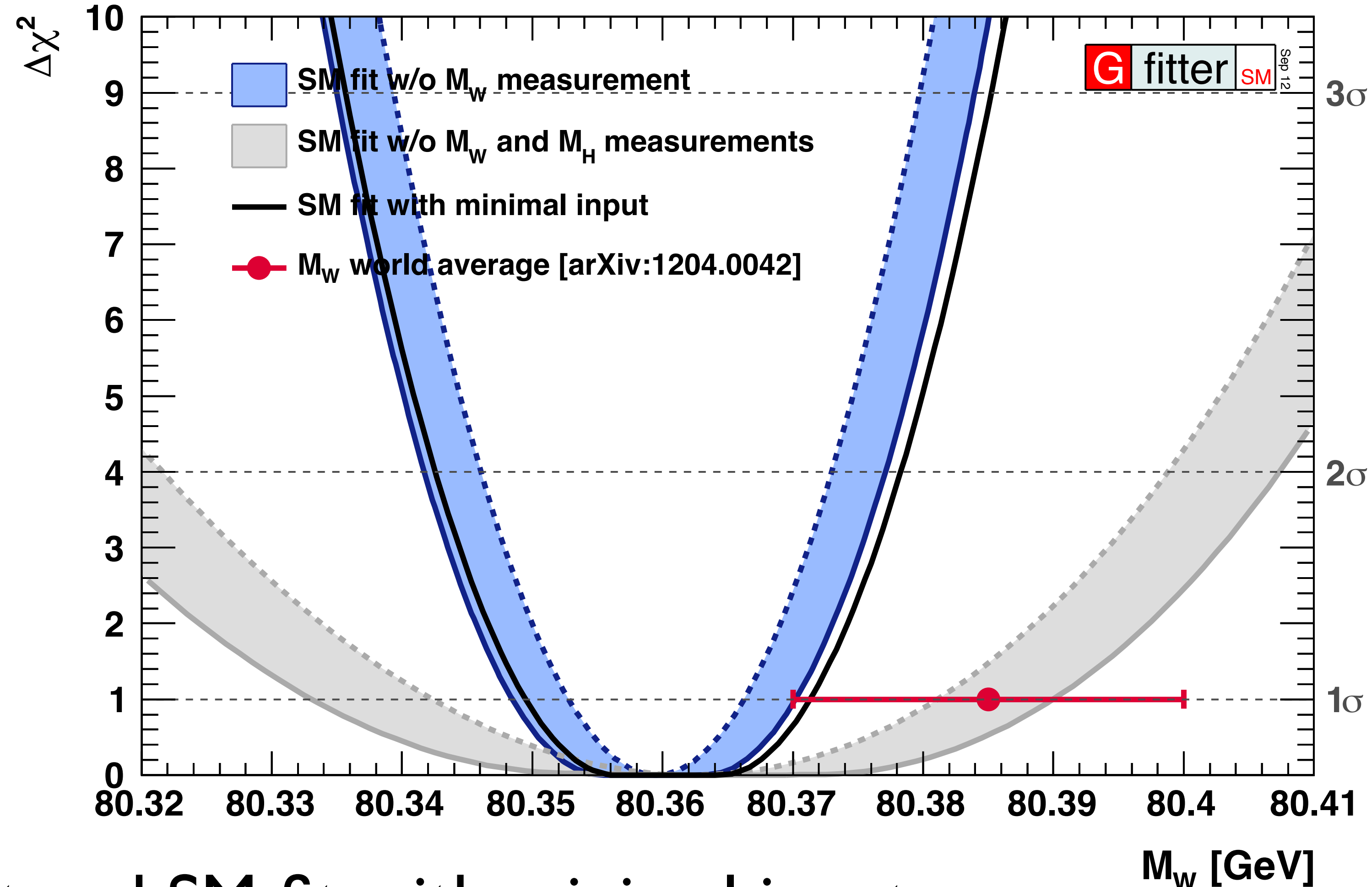
- Good agreement with value from τ decays, also at N^3LO

Improvement in precision only with ILC/GigaZ expected

Indirect Determination: W Mass

Scan of the $\Delta\chi^2$ profile versus Mw

- M_H measurement allows for precise constraint of M_W
- also shown: SM fit with minimal input: M_Z, G_F, $\Delta\alpha_{had}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, M_H, $\overline{m}_c$, $\overline{m}_b$, m_t



- Consistency between total fit and SM fit with minimal input
- Fit result for the indirect determination of M_W:

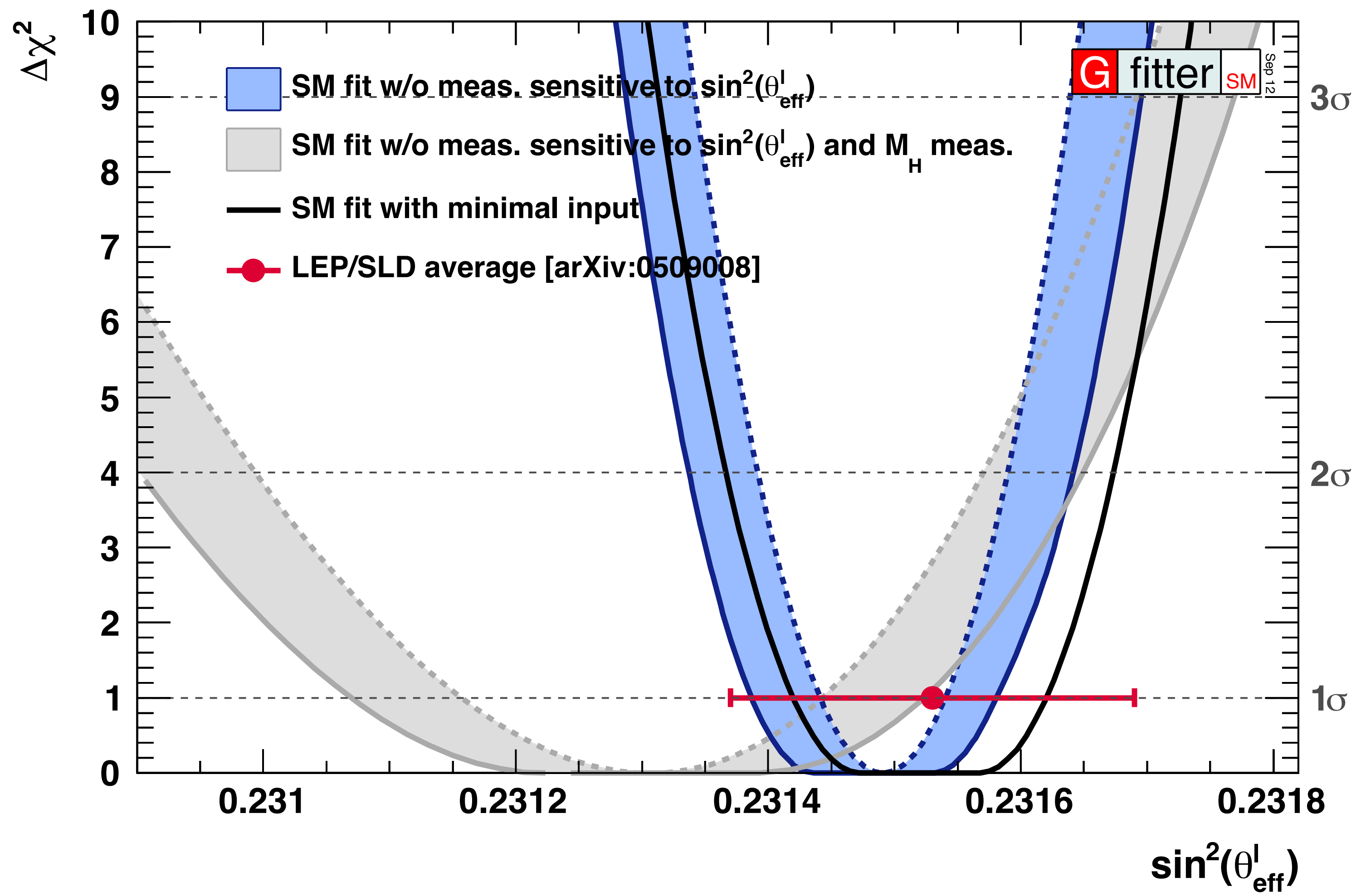
$$\begin{aligned} M_W &= 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\ &\quad \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\rm theo}\,, \\ &= 80.359 \pm 0.011_{\rm tot}\,, \end{aligned}$$

More precise than the direct measurements

The Effective Weak Mixing

Scan of the $\Delta\chi^2$ profile versus $\sin^2\theta^l_{eff}$

- all observables sensitive to $\sin^2\theta^l_{eff}$ removed from fit
- M_H measurement allows for precise constraint of $\sin^2\theta^l_{eff}$
- also shown: SM fit with minimal input

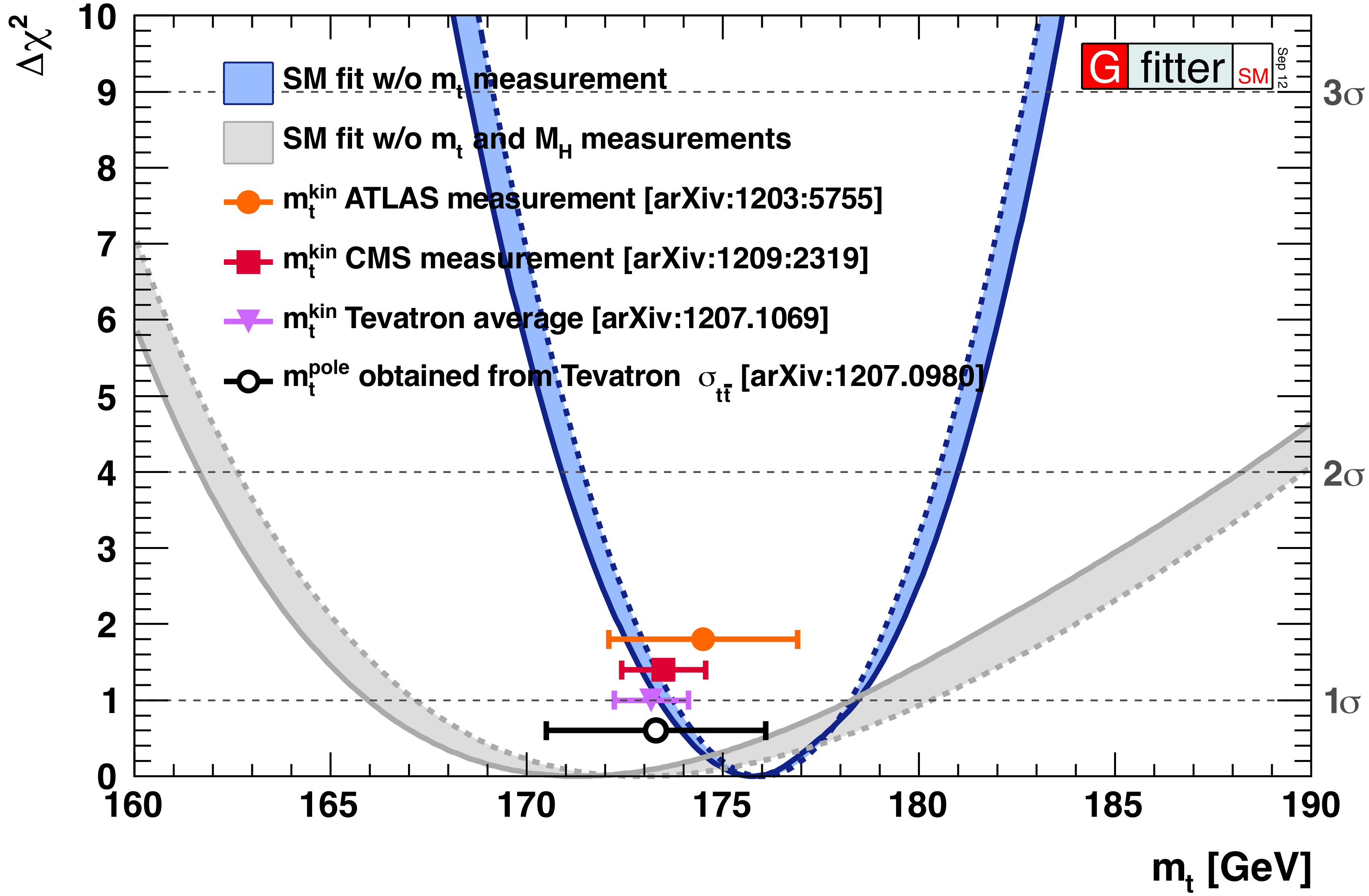


$$\sin^2\theta^\ell_{\rm eff} = 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}} \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\rm theo}\,,$$

$$= 0.23150 \pm 0.00010_{\rm tot}\,,$$

More precise than the direct determination from LEP/SLD measurements

Indirect Determination: Top Mass

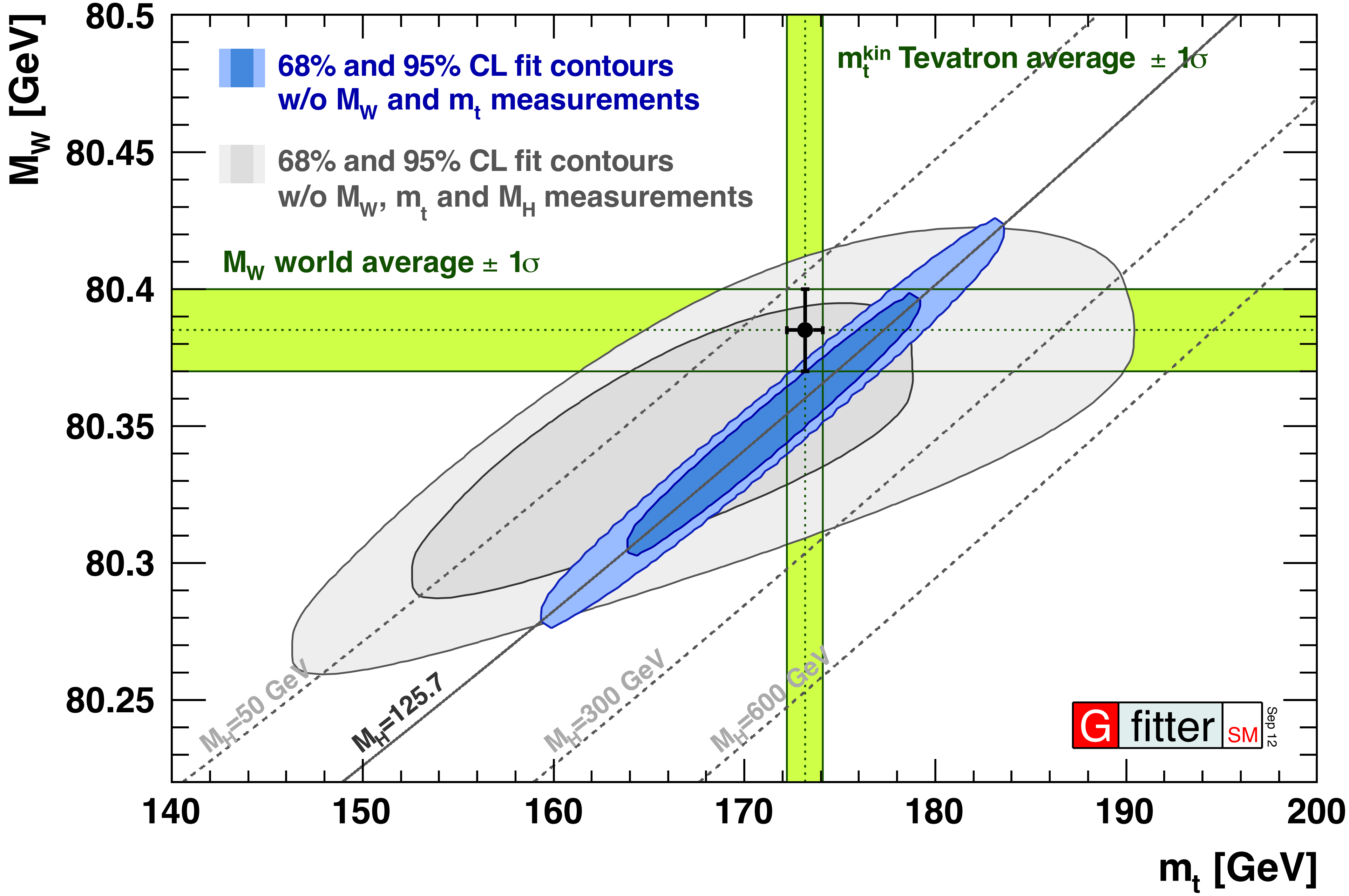


Scan of the $\Delta\chi^2$ profile versus m_t

- consistency with direct measurements
- M_H measurement allows for better constraint of m_t

$m_t = 175.8\,^{+2.7}_{-2.4}\,\mathrm{GeV}$ (Tevatron average: m_t = 173.2 ± 0.9 GeV)

W and Top Mass



68% and 95% CL contours of fit without using M_W, m_t (and M_H)

- Impressive consistency of the SM

Oblique Parameters

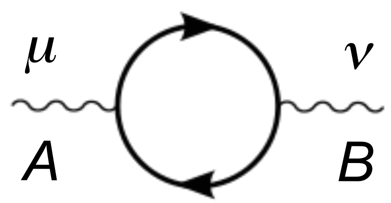
"A man should look for what is, and not for what he thinks should be."

(Albert Einstein)

Beyond the SM

At low energies, BSM physics appears dominantly through vacuum polarisation

- Aka, *oblique corrections*



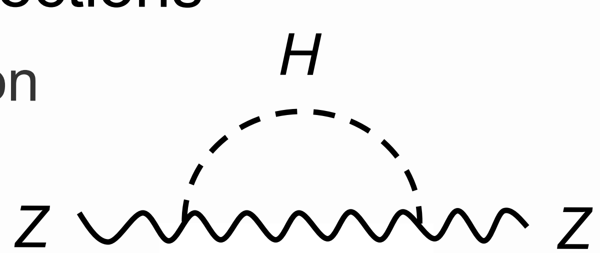
$$= i\Pi^{\mu\nu}_{AB=\{W,Z,\gamma\}}(q)$$

- Direct corrections (vertex, box, bremsstrahlung) generally suppressed by m_f / Λ

Oblique corrections reabsorbed into electroweak parameters $\Delta\rho$, $\Delta\kappa$, Δr

Electroweak fit sensitive to BSM physics through oblique corrections

- In direct competition with Higgs loop corrections



- Oblique corrections from New Physics described through ***STU* parameters**
  [Peskin-Takeuchi, Phys. Rev. D46, 381 (1992)]

$$O_{\text{meas}} = O_{\text{SM,ref}}(M_H, m_t) + c_S \boldsymbol{S} + c_T \boldsymbol{T} + c_U \boldsymbol{U}$$

S : (*S*+*U*) New Physics contributions to neutral (charged) currents

T : Difference between neutral and charged current processes – sensitive to weak isospin violation

U : Constrained by M_W and Γ_W. Usually very small in NP models (often: U=0)

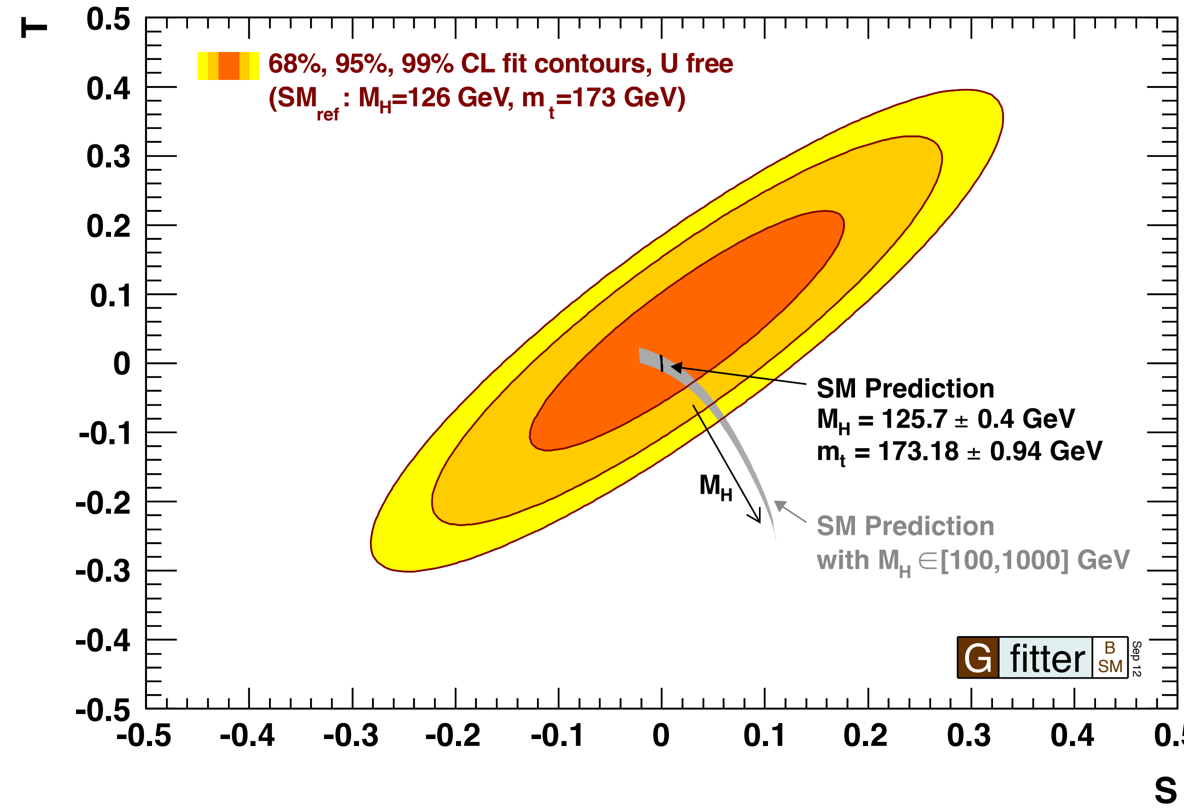
- Also considered: correction to $Z \to bb$ coupling, and extended parameters (*VWX*)
  [Burgess et al., PLB 326, 276 (1994), PRD 49, 6115 (1994)]

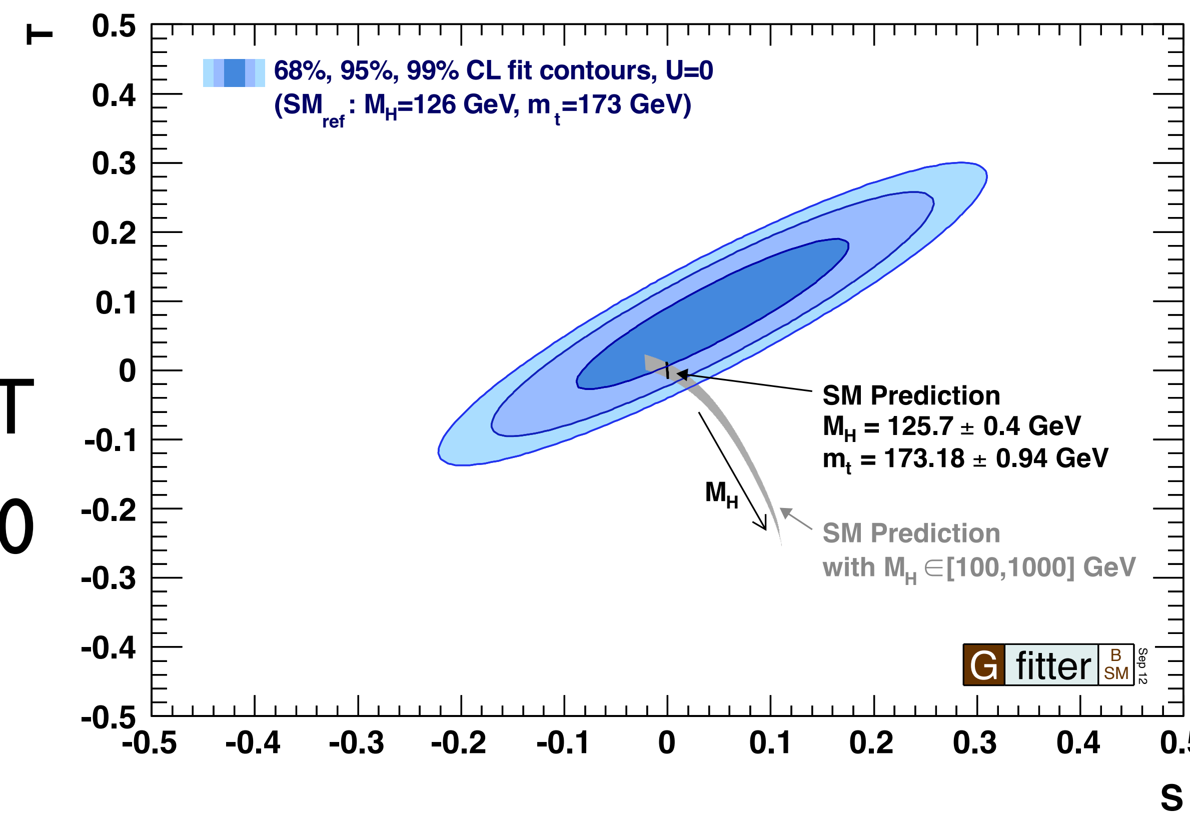
Constraints on S, T and U

S, T, U obtained by fit to EW observables

- SM reference chosen to be
  $M_{H,\text{ref}}$ = 126 GeV
  $m_{t,\text{ref}}$ = 173 GeV
  - this defines (0, 0, 0)
  - S,T depend logarithmically on M_H
- Fit result:
  S = 0.03 ± 0.10
  T = 0.05 ± 0.12
  U = 0.03 ± 0.10
  with large correlation between S and T
- Stronger constraints from fit with U=0

No indication of new physics





The Future

“Prediction is very difficult, especially if it concerns the future.”

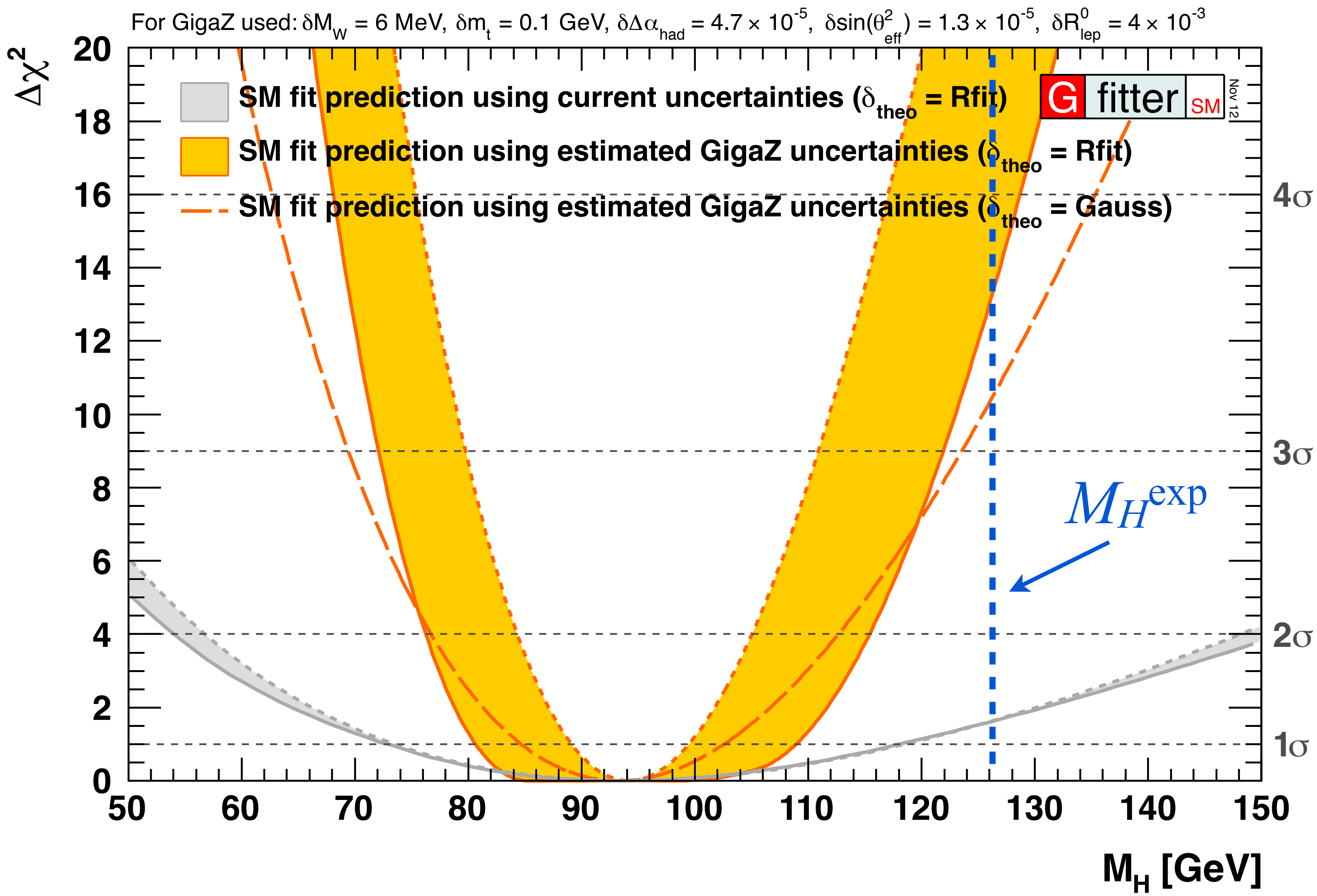
(Niels Bohr)

ILC with GigaZ

A future linear collider would tremendously improve the precision of electroweak observables

- Z peak measurements
  - polarised beams, uncertainty $\delta A^{0,f}_{LR}$: $10^{-3} \rightarrow 10^{-4}$ translates to $\delta \sin^2\theta^{l}_{\rm eff}$: $10^{-4} \rightarrow 1.3 \cdot 10^{-5}$
  - high statistics: 10^9 Z decays: $\delta R^0_{\rm lep}$: $2.5 \cdot 10^{-2} \rightarrow 4 \cdot 10^{-3}$
- $t\bar{t}$ threshold
  - obtain m_t indirectly from production cross section: $\delta m_t = 1 \rightarrow 0.1$ GeV
- WW threshold
  - from threshold scan: $\delta M_W = 15 \rightarrow 6$ MeV
- Low energy data
  - $\Delta\alpha_{\rm had}$: more precise cross section data for low energy ($\sqrt{s} < 1.8$ GeV) and around $c\bar{c}$ resonance (BES-III), improved α_s, improvements in theory: $10^{-4} \rightarrow 4.7 \cdot 10^{-5}$

Prospects for ILC with GigaZ



- no theory uncertainty: $M_H = 94.2\,^{+5.3}_{-5.0}\,(^{+22.7}_{-18.7})$ GeV
- Rfit scheme: $M_H = 92.3\,^{+16.6}_{-11.6}\,(^{+36.3}_{-23.3})$ GeV

in brackets the 4σ values

- strong coupling: $\alpha_s(M_Z) = 0.1190 \pm 0.0005(\text{exp}) \pm 0.0001(\text{theo})$

Summary

Assuming the newly discovered boson is the SM Higgs

- all fundamental parameters of the SM are known
- possibility to overconstrain the SM at the electroweak scale
- global EW fit has been redone, with a p-value of 0.07
- small p-value comes mostly from R^0_b and $A^{0,b}_{FB}$

Knowledge of M_H allows for precision determinations of

- W mass, top mass, effective weak mixing angle $\sin^2\theta^l_{\mathrm{eff}}$
- detailed information in arXiv:1209.2716 and updates on www.cern.ch/gfitter

EW Fit allows to constrain many BSM models

- no signs of new physics from oblique parameters
- stay tuned for more results