



Helmholtz Alliance
'Physics at the Terascale'
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**The global electroweak Fit:
now and during the LHC era**

paper submitted to Eur. Phys. J. C, (arXiv:0811.0009)

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The Gfitter Project



- Gfitter: A **Generic Fitter** Project for HEP Model Testing
- aim: provide a reliable framework for involved fitting problems in the LHC era (and beyond).
- software:
 - abstract object-oriented code in C++ using ROOT functionality
 - core package:
 - tools for data handling, fitting, statistical analyses
 - physics: plug-in packages
 - **GSM**: Library for the Standard Model fit to the electroweak precision data
 - **G2HDM**: Library for the 2HDM extension of the SM
 - **GSUSY**: Library for supersymmetric extensions of the SM (in preparation)

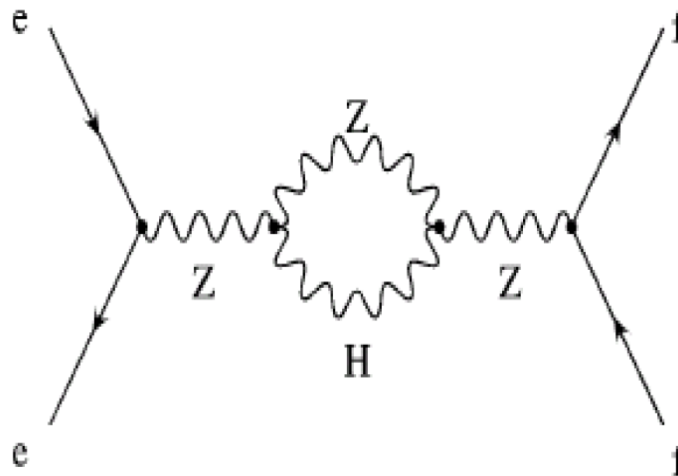


The Gfitter Project



- Gfitter features:
 - consistent treatment of statistical, systematic and theoretical errors, correlations, and inter-parameter dependencies
 - theoretical uncertainties: Rfit prescription [A Höcker et al., EPJ C21, 225 (2002)]
 - theory uncertainties included in χ^2 estimator with flat likelihood in allowed ranges
 - fitting:
 - several minimization algorithms available, e.g. TMinuit, genetic minimisation algorithm
 - caching of computation results between fit steps
 - only theory predictions are recalculated that depend on modified parameters
 - substantial speed improvement
 - advanced statistical analyses (frequentist approach):
 - e.g. parameter scans, contours, MC toy analyses, goodness-of-fit, p-value, etc.

- first theoretical library implemented in Gfitter framework: SM predictions of electroweak precision observables
- state-of-the art calculations (OMS scheme); in particular:
 - M_W and $\sin^2\theta_{\text{eff}}^f$: full two-loop + leading beyond-two-loop correction
 [M. Awramik et al., Phys. Rev D69, 053006 (2004) and ref.][M. Awramik et al., JHEP 11, 048 (2006) and refs.]
 - **radiator functions**: N³LO of the massless QCD Adler function
 [P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]



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 - **radiator functions**: N³LO of the massless QCD Adler function
[P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]
- calculations thoroughly cross-checked against ZFitter (Fortran) package → excellent agreement
- free fit parameters:
 - $M_Z, M_H, m_{t^*}, \Delta\alpha_{\text{had}}^{(5)}(M_Z^2), \alpha_S(M_Z^2), \bar{m}_c, \bar{m}_b$
 - parameters for theoretical uncertainties on M_W ($\delta M_W = 4-6\text{GeV}$), $\sin^2\theta_{\text{eff}}^l$ ($\delta\sin^2\theta_{\text{eff}}^l = 4.7 \cdot 10^{-5}$) (and the electroweak form factors ρ_Z^f, κ_Z^f)

Parameter	Input value	Free in fit
M_Z [GeV]	91.1875 ± 0.0021	yes
Γ_Z [GeV]	2.4952 ± 0.0023	-
σ_{had}^0 [nb]	41.540 ± 0.037	-
R_ℓ^0	20.767 ± 0.025	-
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	-
$A_\ell^{(*)}$	0.1499 ± 0.0018	-
A_c	0.670 ± 0.027	-
A_b	0.923 ± 0.020	-
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	-
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	-
R_c^0	0.1721 ± 0.0030	-
R_b^0	0.21629 ± 0.00066	-
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	0.2324 ± 0.0012	-
M_H [GeV] ^(*)	Likelihood ratios	yes
M_W [GeV]	80.398 ± 0.025	-
Γ_W [GeV]	2.106 ± 0.050	-
\overline{m}_c [GeV]	1.25 ± 0.09	yes
\overline{m}_b [GeV]	4.20 ± 0.07	yes
m_t [GeV]	172.4 ± 1.2	yes
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ ($\dagger\Delta$)	2769 ± 22	yes
$\alpha_s(M_Z^2)$	-	yes
$\delta_{\text{th}} M_W$ [MeV]	$[-4, 4]_{\text{theo}}$	yes
$\delta_{\text{th}} \sin^2\theta_{\text{eff}}^\ell$ (\dagger)	$[-4.7, 4.7]_{\text{theo}}$	yes
$\delta_{\text{th}} \rho_Z^f$ (\dagger)	$[-2, 2]_{\text{theo}}$	yes
$\delta_{\text{th}} \kappa_Z^f$ (\dagger)	$[-2, 2]_{\text{theo}}$	yes

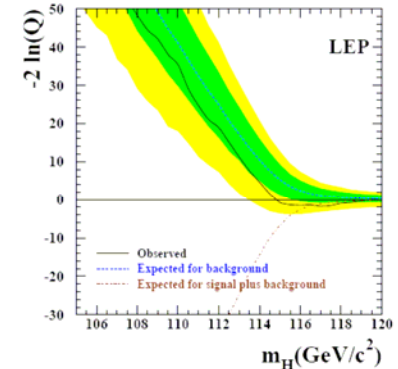
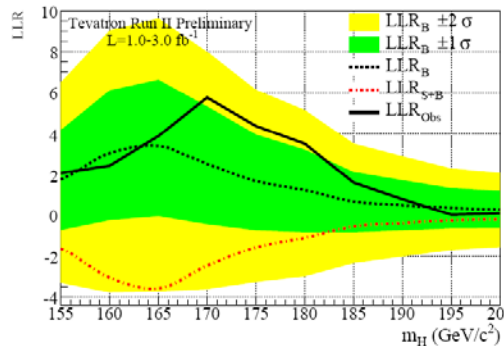
\dagger in units of 10^{-5}

- usage of latest experimental results:

- **Z-pole observables:** LEP/SLD results [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
- **M_W and Γ_W :** LEP + Tevatron [ADLO, hep-ex/0612034] [CDF, Phys Rev. D77, 112001 (2008)] [CDF, Phys. Rev. Lett. 100, 071801 (2008)] [CDF+D0, Phys. Rev. D 70, 092008 (2004)]
- $\overline{m}_c, \overline{m}_b$: world averages [PDG, J. Phys. G33,1 (2006)]
- m_t : **latest Tevatron average** [arXiv:0808.1089 [hep-ex]]
- $\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$: [K. Hagiwara et al., Phys. Lett. B649, 173 (2007)] + Gfitter rescaling mechanism to account for α_s -dependency

- fits are performed in two versions:

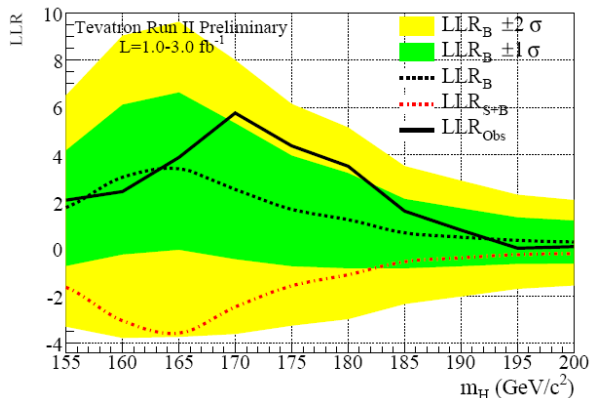
- **Standard fit:** all data except results from direct Higgs searches
- **Complete fit:** all data including results from direct Higgs searches at LEP [ADLO: Phys. Lett. B565, 61 (2003)] and Tevatron [CDF+D0: arXiv:0804.3423, CDF+D0: arXiv:0808.0534]



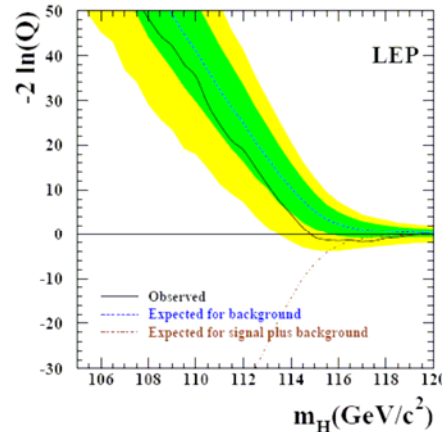
- Usage of CL_{S+B} :
 - describe probability of upwards fluctuations of the test statistics (LLR, $-2\ln Q$)
 - transform one-sided CL_{S+B} into a two-sided CL
 - contribution to χ^2 estimator obtained via inverse error function

$$\delta\chi^2 = \text{Erf}^{-1}(1 - CL_{S+B}^{2\text{-sided}})$$

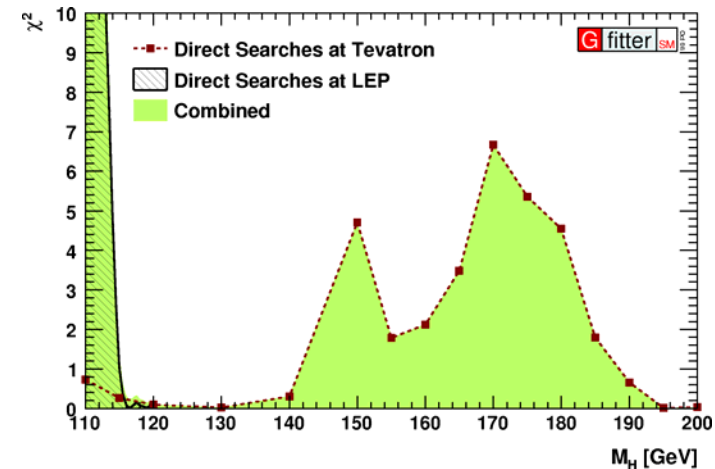
Tevatron

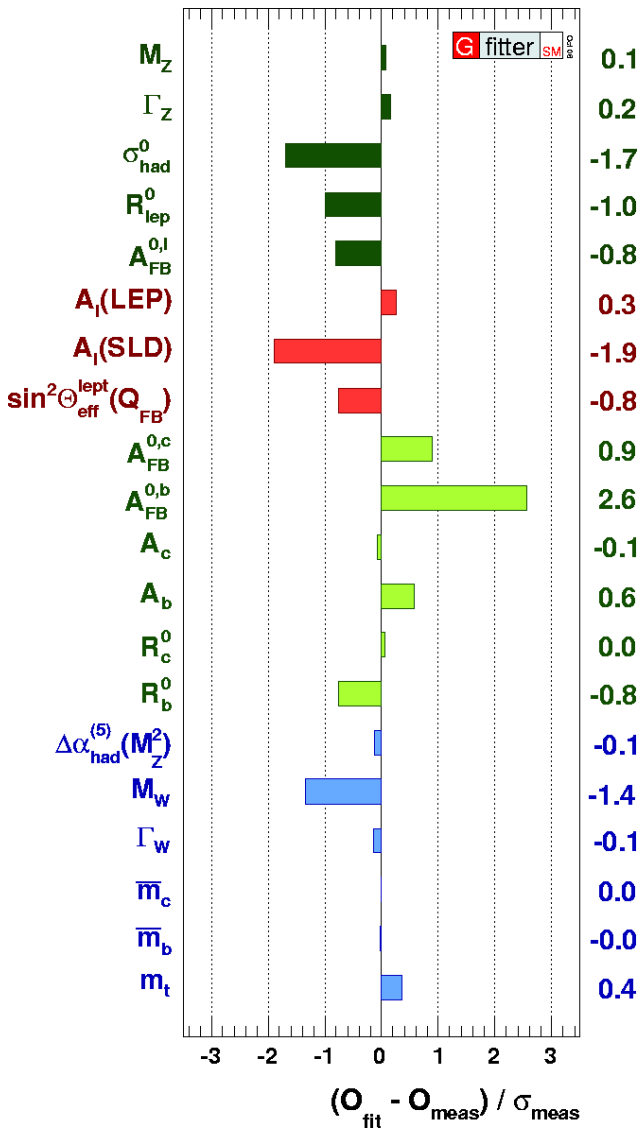


LEP



contribution to χ^2 estimator





- convergence and naïve p-values:
 - *standard fit*: $\chi^2_{min} = 16.4 \rightarrow \text{Prob}(\chi^2_{min}, 13) = 0.23$
 - *complete fit*: $\chi^2_{min} = 18.0 \rightarrow \text{Prob}(\chi^2_{min}, 14) = 0.21$

- α_S from *complete fit*: $\alpha_S(M_Z^2) = 0.1193_{-0.0027}^{+0.0028} \pm 0.0001$
 - first error is experimental fit error
 - second error due to missing QCD orders:
 - incl. variation of renorm. scale from $M_Z/2$ to $2M_Z$ and massless terms of order/beyond $\alpha_S^5(M_Z)$ and massive terms of order/beyond $\alpha_S^4(M_Z)$
 - excellent agreement with recent N³LO result from τ decay [M. Davier et al., arXiv:0803.0979]

$$\alpha_S(M_Z^2) = 0.1212 \pm 0.0011$$

- pull values of *complete fit*
 - no value exceeds 3σ
 - FB asymmetry of bottom quarks \rightarrow largest contribution to χ^2

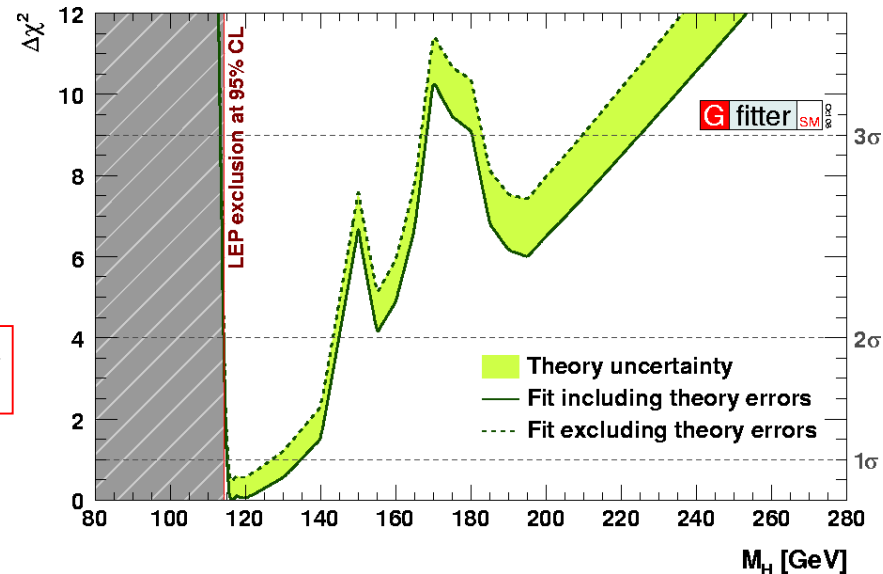
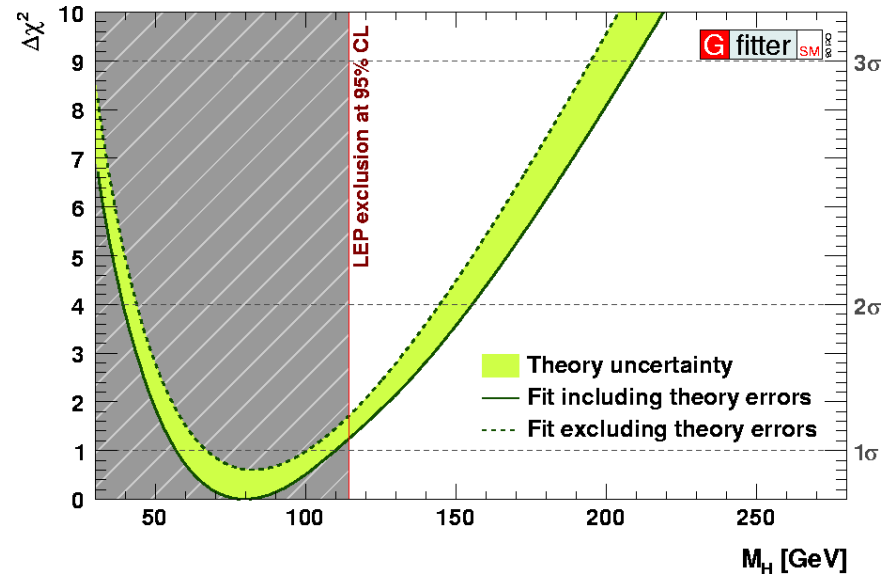
- M_H from *standard fit*:

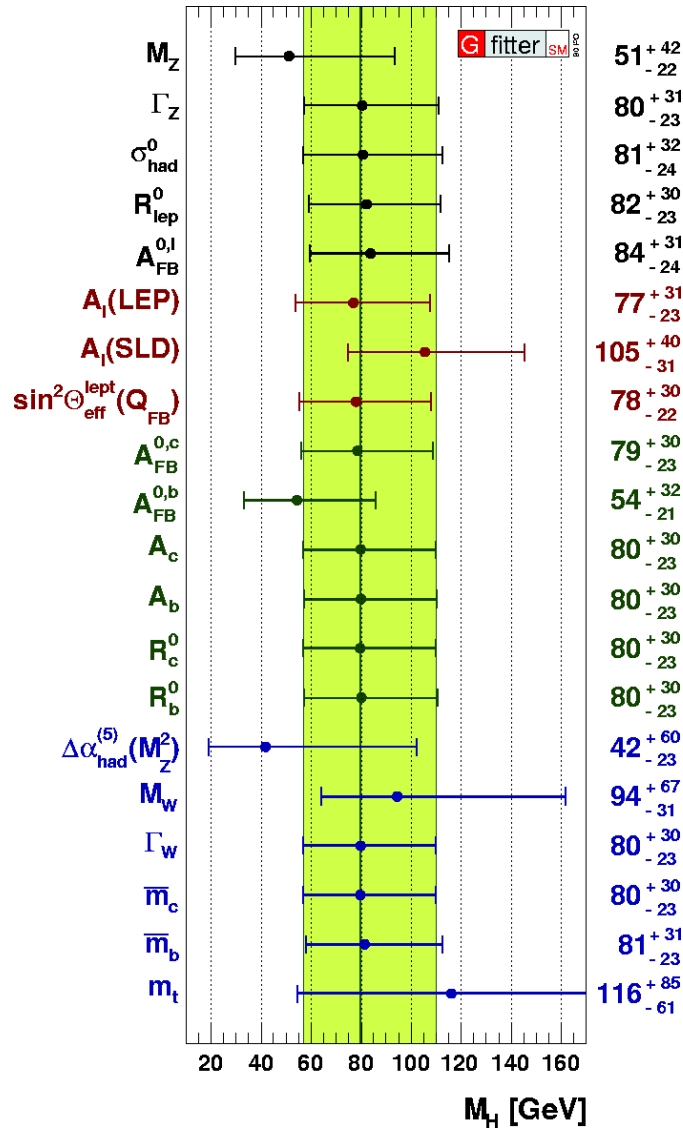
- central value $\pm 1\sigma$: $M_H = 80^{+30}_{-23} \text{ GeV}$
- 2σ interval: [39, 155] GeV
- 3σ interval: [26, 209] GeV

green band due to Rfit treatment of theory errors, fixed errors lead to larger χ^2

- M_H from *complete fit* (i.e. incl. direct Higgs searches):

- central value $\pm 1\sigma$: $M_H = 116.4^{+18.3}_{-1.3} \text{ GeV}$
- 2σ interval: [114, 145] GeV

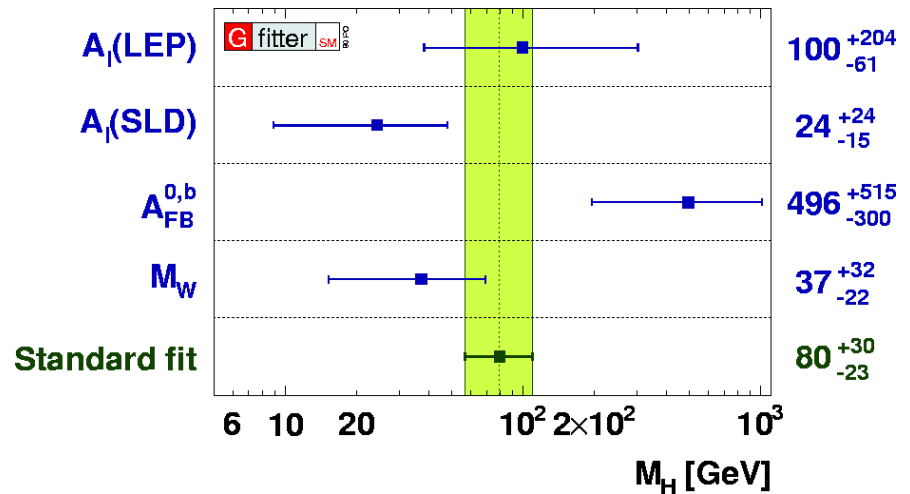




■ M_H from fits excluding respective measurements

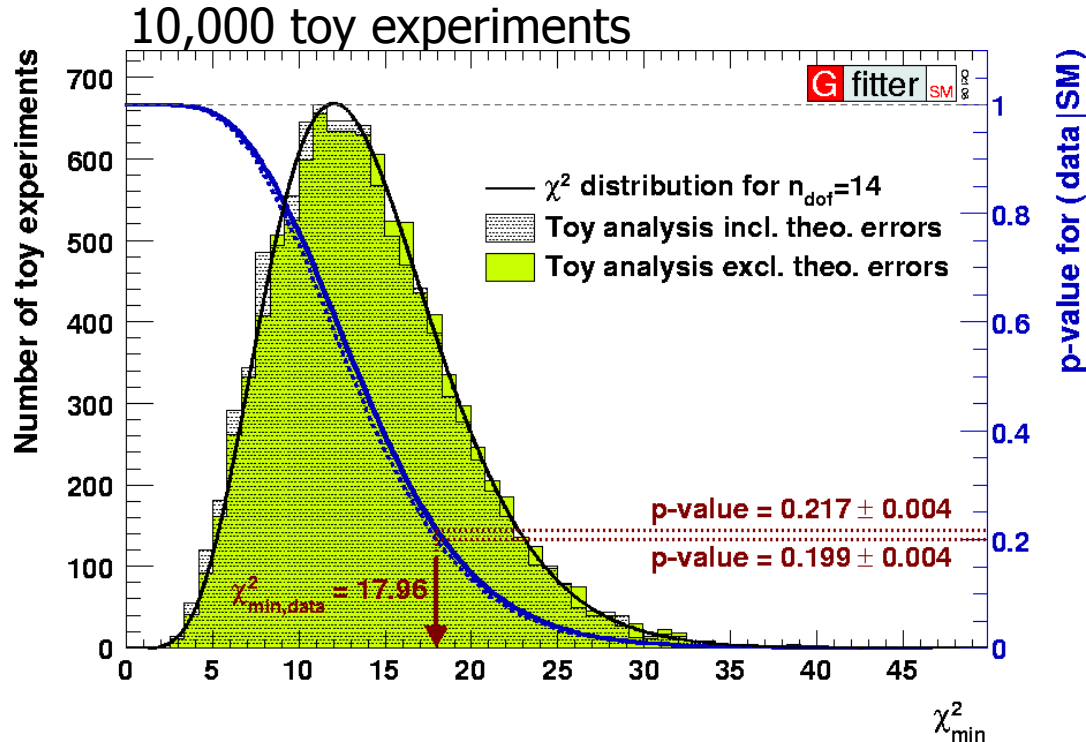
- excluding $A_1(SLD)$ => significantly larger M_H
- tension between W mass, $A_1(SLD)$, and FB asymmetry of bottom quarks
- toy analysis ("look-elsewhere-effect")
 - 1.4% (2.5 σ) of toys show a result worse than the observed values

M_H determined only with one sensitive observable



by using toy analysis

- execute the SM fit
- generate toy sample by random sampling from Gaussian distributions around initial fit results (Correlations are taken into account)
- refit with new values for observables, achieve a new χ^2



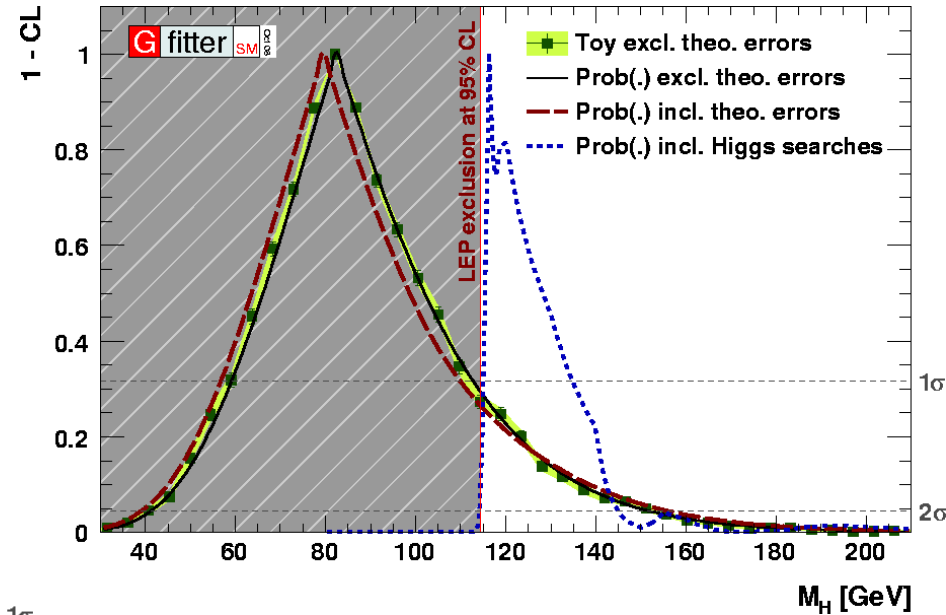
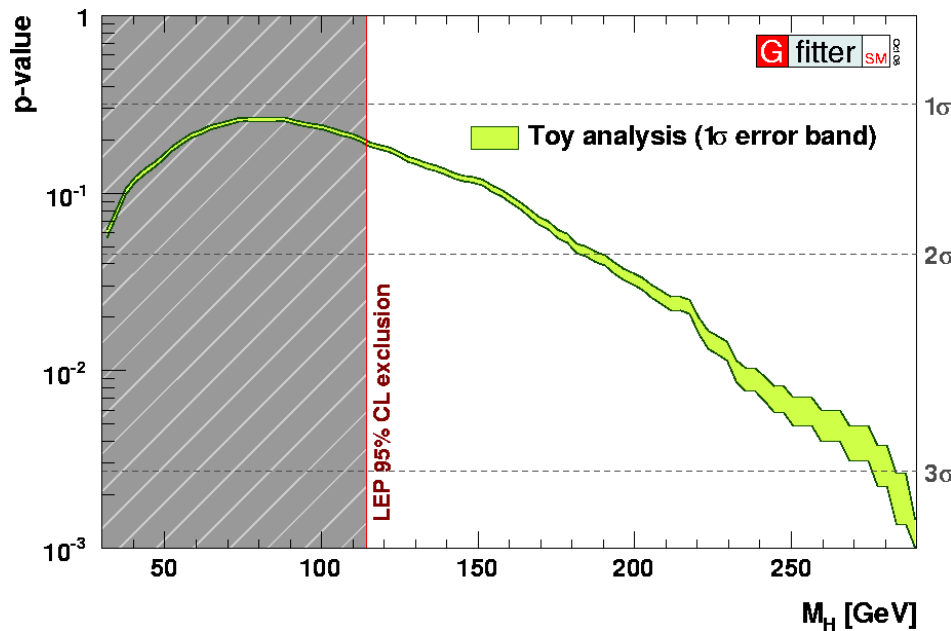
Testing the SM

p-value: Probability

- for wrongly rejecting the SM
- for getting a χ^2 larger than the χ^2 of the fit

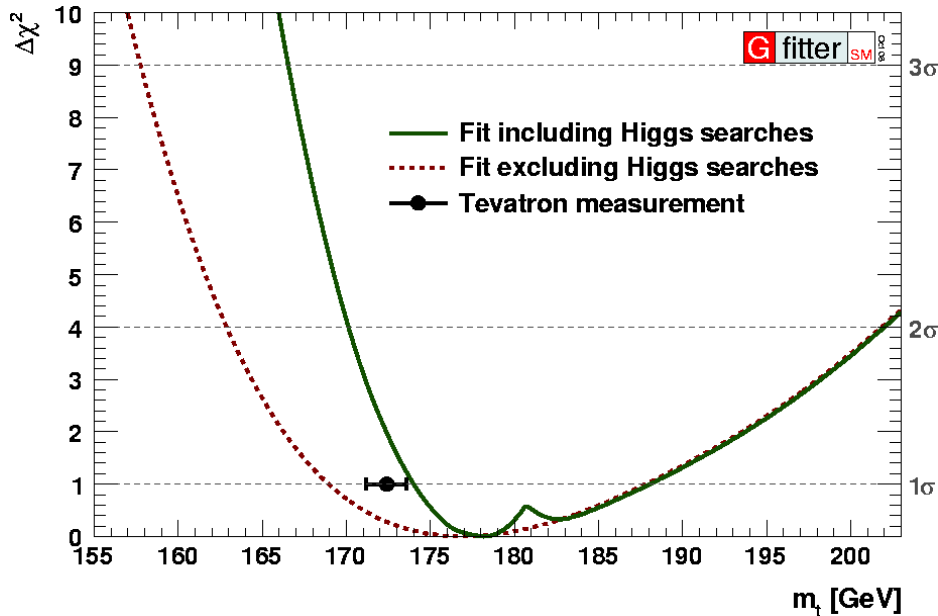
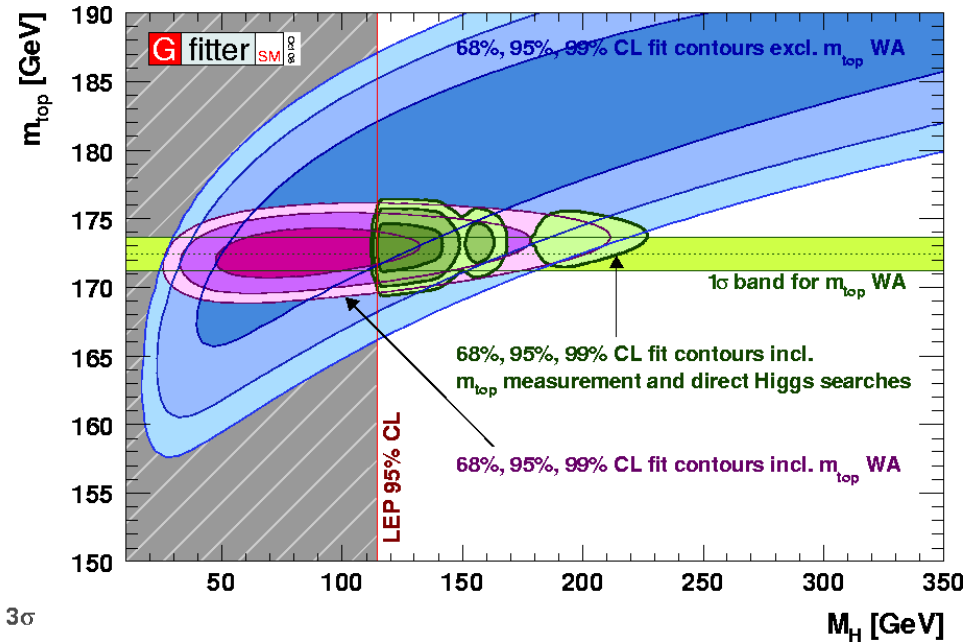
p-value = $(21.7 \pm 0.4)\%$
 No strong requirement for new physics

- Gfitter allows statistical analysis of fit results
- example: study of the Gaussian properties of the $\Delta\chi^2$ estimator
 - good agreement of CL from MC toy with Gaussian approximation using Prob().



- p-values for fixed Higgs masses using toy experiment
- here: p-value is larger than for fit with free Higgs mass
 - Higgs mass fixed
 - n_{dof} increased by one

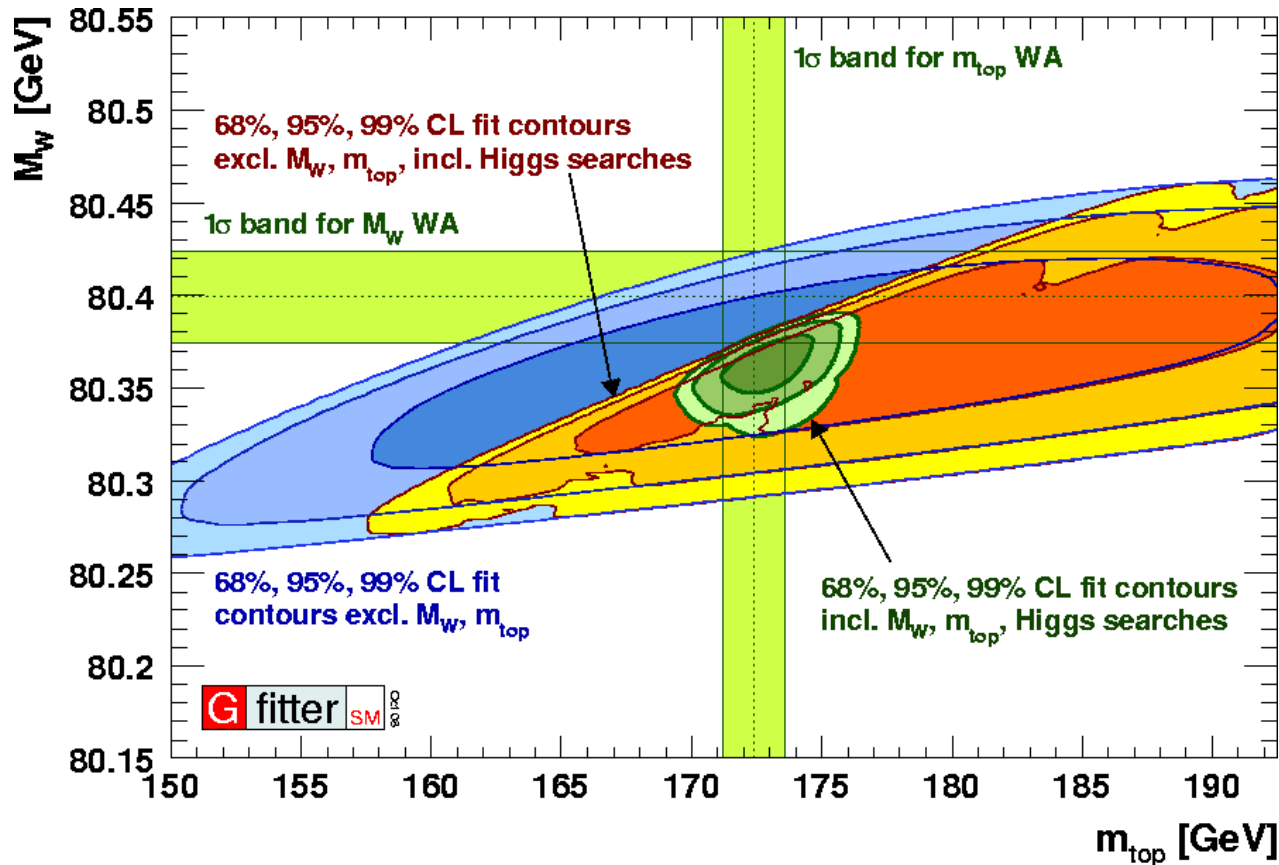
- positive correlation value between m_{top} and M_H
- inclusion of m_{top} measurement reduce allowed region



- Indirect determination of m_{top}
 - w Higgs search: $m_{top} = 178.2^{+9.8}_{-4.2} \text{ GeV}$
 - w/o Higgs search: $m_{top} = 177.0^{+10.8}_{-8.0} \text{ GeV}$

- Tevatron measurement:

$$m_{top} = 172.4 \pm 1.2 \text{ GeV}$$



- indirect fit results agree with experimental values
- results from Higgs searches significantly reduce the allowed parameter space
- good probe of SM, if M_H is measured at LHC and/or ILC

LHC, ILC (+GigaZ)

- exp. improvement on $M_W, m_t, \sin^2\theta_{\text{eff}}^l, R_l^0$

assumed $\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$, e.g. $\sigma(\Delta\alpha_{\text{had}}^{(5)}) \sim 7 \cdot 10^{-5}$

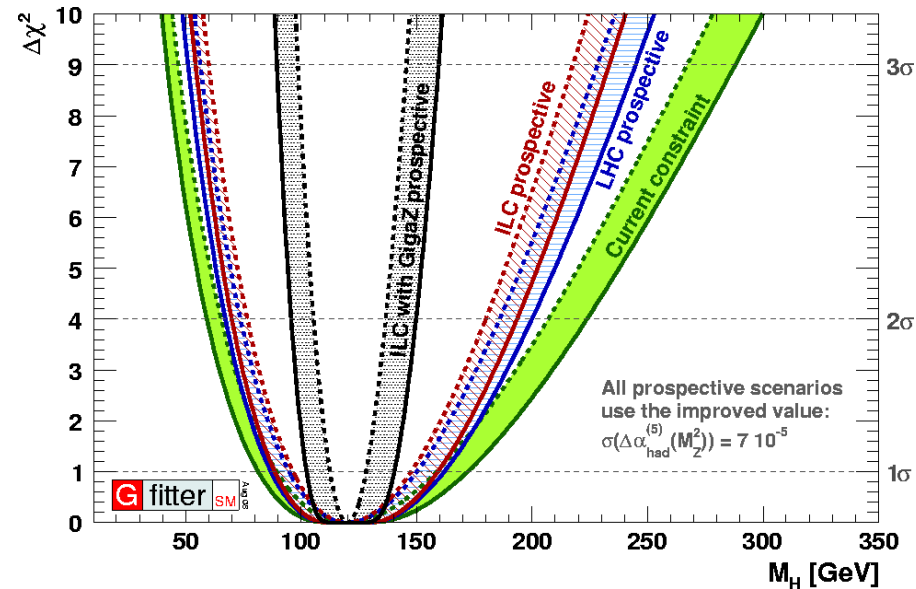
[F. Jegerlehner, hep-ph/0105283]

Fits:

- not used: α_S, M_H measurements
- assume $M_H = 120$ GeV
- improvement of M_H prediction
 - to be confronted with direct measurement \rightarrow goodness-of-fit
 - broad minima: Rfit treatment of theo. uncertainties
- GigaZ: significant improvement for $\alpha_S(M_Z^2)$

Quantity	Expected uncertainty			
	Present	LHC	ILC	GigaZ (ILC)
M_W [MeV]	25	15	15	6
m_t [GeV]	1.2	1.0	0.2	0.1
$\sin^2\theta_{\text{eff}}^l$ [10^{-5}]	17	17	17	1.3
R_l^0 [10^{-2}]	2.5	2.5	2.5	0.4
$\Delta\alpha_{\text{had}}^{(b)}(M_Z^2)$ [10^{-5}]	22 (7)	22 (7)	22 (7)	22 (7)
$M_H (= 120 \text{ GeV})$ [GeV]	$+56$ ($+52$) [$+39$] -40 (-39) [-31]	$+45$ ($+42$) [$+30$] -35 (-33) [-25]	$+42$ ($+39$) [$+28$] -33 (-31) [-23]	$+27$ ($+20$) [$+8$] -23 (-18) [-7]
$\alpha_S(M_Z^2)$ [10^{-4}]	28	28	27	6

[ATLAS, Physics TDR (1999)][CMS, Physics TDR (2006)][A. Djouadi et al., arXiv:0709.1893]
 [I. Borjanovic, EPJ C39S2, 63 (2005)][S. Haywood et al., hep-ph/0003275]
 [R. Hawkins, K. Mönig, EPJ direct C1, 8 (1999)]
 [A. H. Hoang et al., EPJ direct C2, 1 (2000)][M. Winter, LC-PHSM-2001-016]



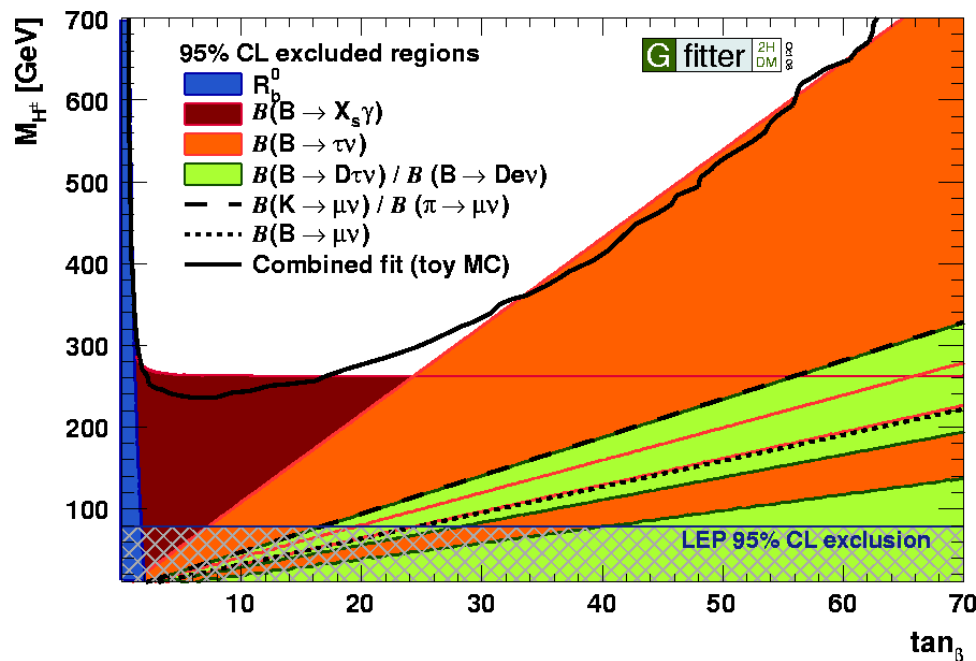
- 2HDM (Type-II)
 - additional Higgs doublet
 - one doublet couples to u-type, one doublet couples to d-type quarks
 - 6 free parameters $\rightarrow M_{H_{\pm}}, M_{A0}, M_{H0}, M_h, \tan\beta, |\alpha|$

- so far: only looked at processes sensitive to charged Higgs $\rightarrow M_{H_{\pm}}, \tan\beta$
- Overlay of individual 95% CL excluded regions
 - assuming $n_{\text{dof}}=1$ and 2-sided limits

- Combined fit:
 - resolved by MC toy study assuming 2-sided limits
 - $\chi^2_{\text{min}}=3.9$ at $M_H=858$ GeV and $\tan\beta=6.8$

- Excluded at 95% CL:

- small $\tan\beta$
- for all $\tan\beta$
 - $M_H < 240$ GeV
 - $M_H < 780$ GeV for $\tan\beta=70$



- Gfitter is a framework for involved fitting problems
- First theory package: Revisit of the electroweak fit of the SM
 - latest theoretical calculations and experimental results
 - advanced studies of the statistical properties of the fit
 - inclusion of direct Higgs searches
 - beyond Standard Model example: 2HDM (Type-II)
- Continuous Efforts
 - Keep existing parts up-to-date
- Next steps:
 - implementation of more theories, e.g. SUSY models, little Higgs
- More information:
 - <http://cern.ch/Gfitter>
 - paper submitted to Eur. Phys. J. C, (arXiv:0811.0009)

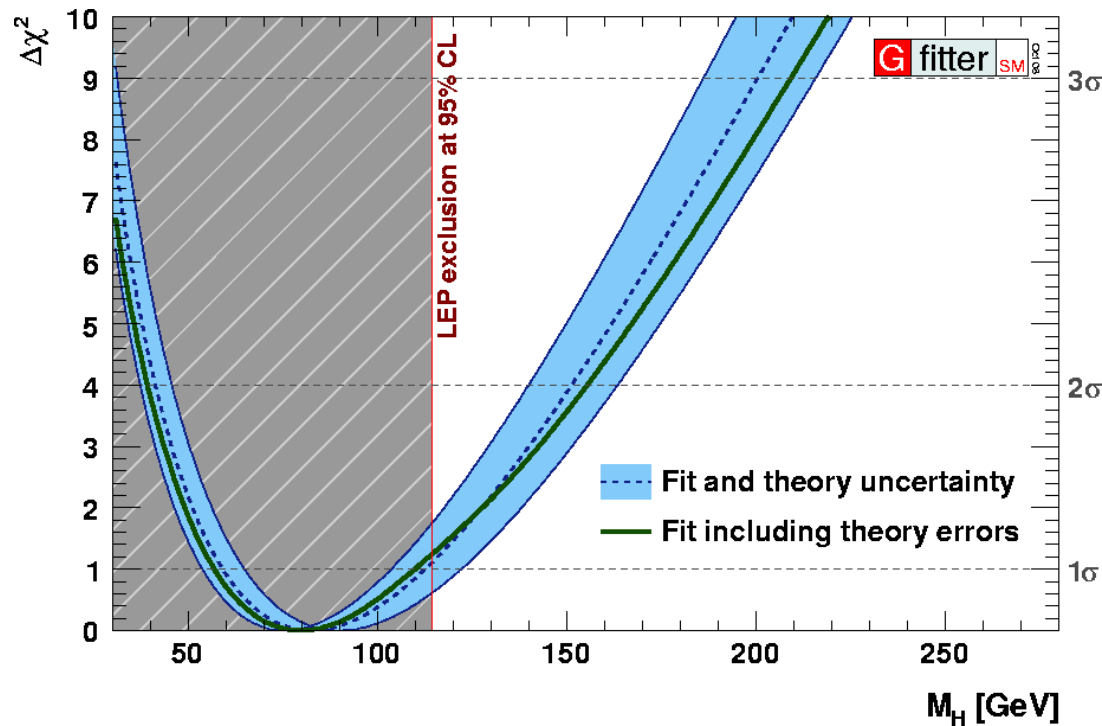
G fitter

Treatment of theo. Uncertainties

Uncertainties for Theory-Prediction (two main sources)

$$M_W \pm \Delta M_W (theo)$$

$$\sin^2 \Theta_{eff}^{lept} \pm \Delta \sin^2 \Theta_{eff}^{lept} (theo)$$



Old Treatment:

Band was done by **shifting** the predictions by these uncertainties **redoing** the scan and **choosing** the worst cases

New Treatment:

(à la Rfit [CKMFITTER])

if measurement

- within theory uncertainty: **no contribution** to χ^2 .
- outside theory uncertainty: χ^2 determined by **distance** between **measurement** and **prediction \pm uncertainty**