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Revisiting the global electroweak fit of the Standard Model and Beyond

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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 (this talk)
    - G2HDM: Library for the 2HDM extension of the SM (this talk)
    - 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, default: TMinuit
- caching of computation results between fit steps
  - only theory predictions are recalculated that depend on modified parameters
  - substantial speed improvement
- advanced statistical analyses:
  - e.g. parameter scans, contours, MC toy analyses, goodness-of-fit p-value, …

More details:

- Gfitter homepage: http://cern.ch/Gfitter

Electroweak fit: theoretical predictions

- 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 $\sin^2\theta^l_{eff}$: 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: N^{3}LO of the massless QCD Adler function

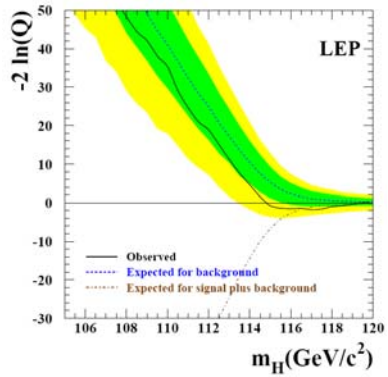
    [P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]
- Calculations and fit results thoroughly cross-checked against ZFitter (Fortran) package → excellent agreement
- Free fit parameters:
  - M_Z, M_H, m_t, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\alpha_S(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$
  - parameters for theoretical uncertainties on M_W (δM_W=4-6GeV), $\sin^2\theta^l_{eff}$ ($\delta\sin^2\theta^l_{eff} = 4.7\cdot10^{-5}$) (and the electroweak form factors ρ_Z^f, κ_Z^f)

Electroweak fit: experimental input

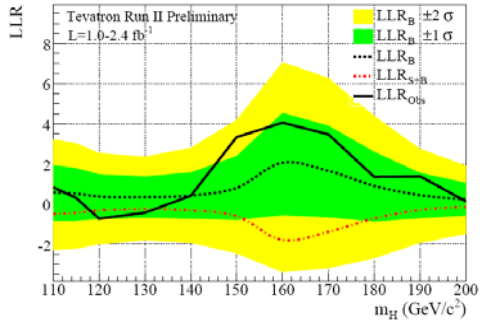
Parameter	Input value
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010
A_ℓ (⋆)	0.1499 ± 0.0018
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012
M_H [GeV] (○)	Likelihood ratios
M_W [GeV]	80.398 ± 0.025
Γ_W [GeV]	2.106 ± 0.050
$\overline{m}_c$ [GeV]	1.25 ± 0.09
$\overline{m}_b$ [GeV]	4.20 ± 0.07
m_t [GeV]	172.4 ± 1.2
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ (†△)	2768 ± 22
$\alpha_s(M_Z^2)$	–

- Usage of latest experimental results:
  - **Z-pole observables**: LEP/SLD results [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - **M_W and Γ_W**: weighted mean of 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 [CDF+D0, this conference]
  - **$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$:** [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 and Tevatron

[ADLO: Phys. Lett. B565, 61 (2003)]

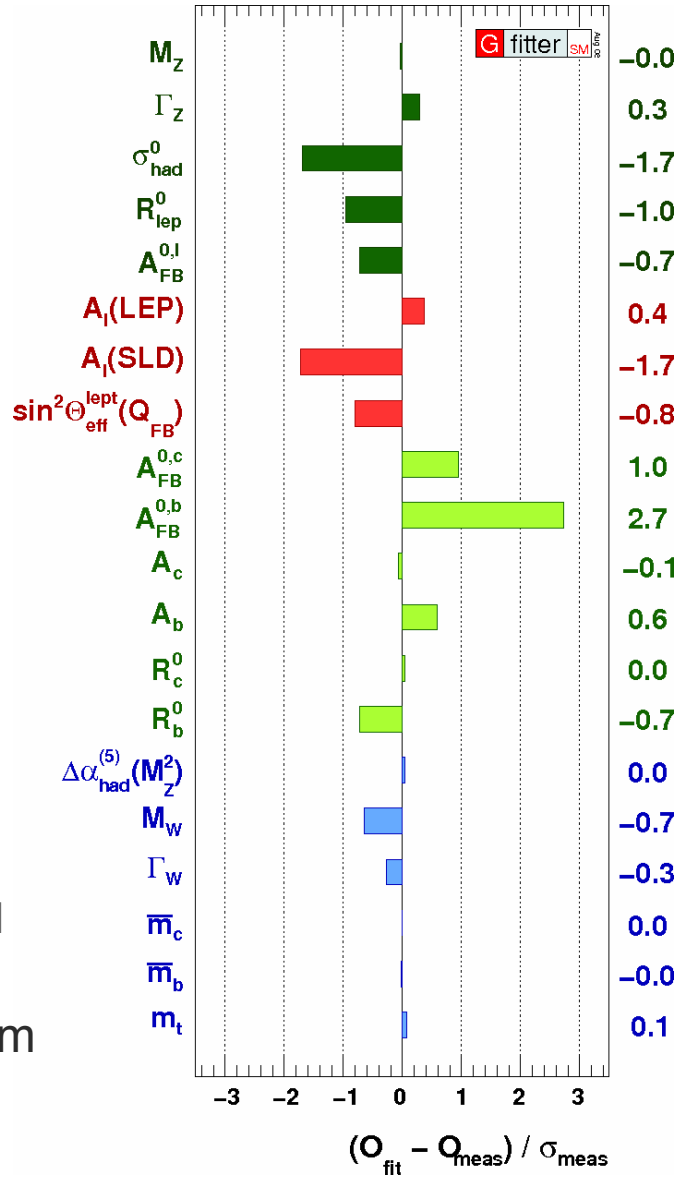


[CDF+D0: arXiv:0804.3423]



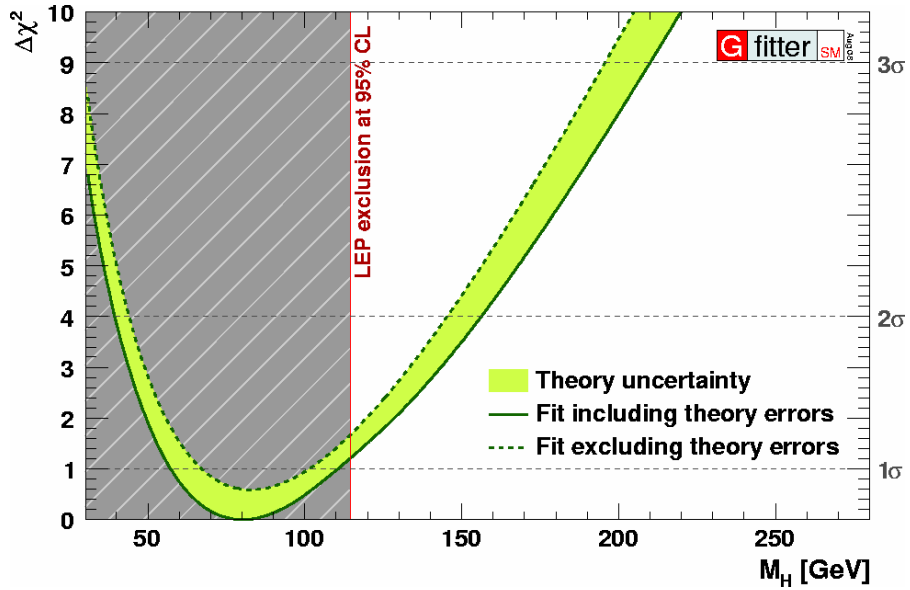
Electroweak fit: fit results

- Convergence and naïve p-values:
  - *standard fit*: $\chi^2_{min}=16.4 \rightarrow \text{Prob}(\chi^2_{min},13)=0.23$
  - *complete fit*: $\chi^2_{min}=17.9 \rightarrow \text{Prob}(\chi^2_{min},14)=0.21$
- Pull values of *standard fit*:
  - no value exceeds 3σ
  - known tension: leptonic and hadronic asymmetries
- α_S from *complete fit*: $\alpha_s(M_Z^2) = 0.1194\,^{+0.0028}_{-0.0027} \pm 0.0001$
  - 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 N^{3}LO result from τ decay [M. Davier et al., arXiv:0803.0979]

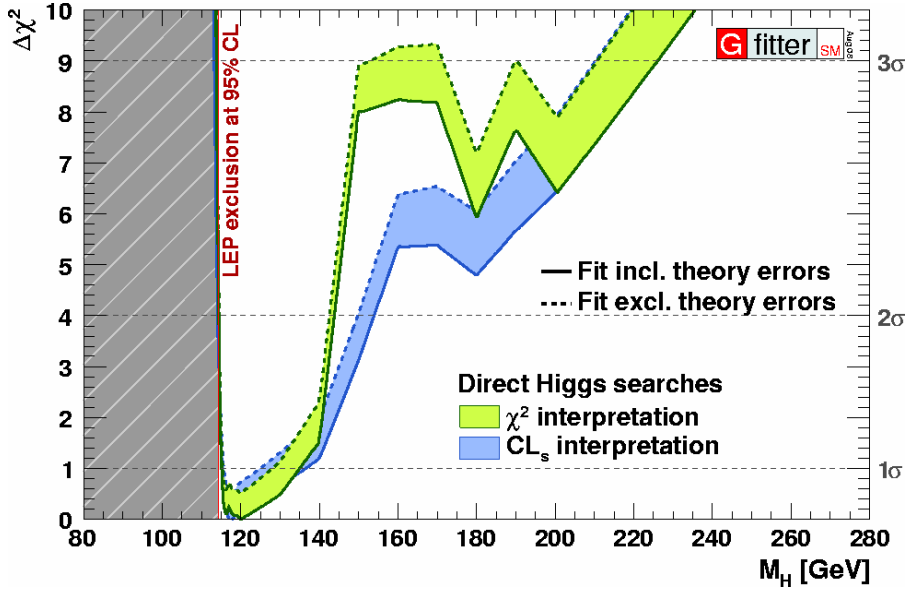


Electroweak fit: results on M_H

- M_H from *standard fit*:
  - central value ±1σ: $M_H = 80^{+30}_{-23}$ GeV
  - 2σ interval: [39, 156] GeV
  - 3σ interval: [26, 210] GeV
  - theory errors with Rfit scheme →smaller n_{dof} and smaller χ^2_{min}

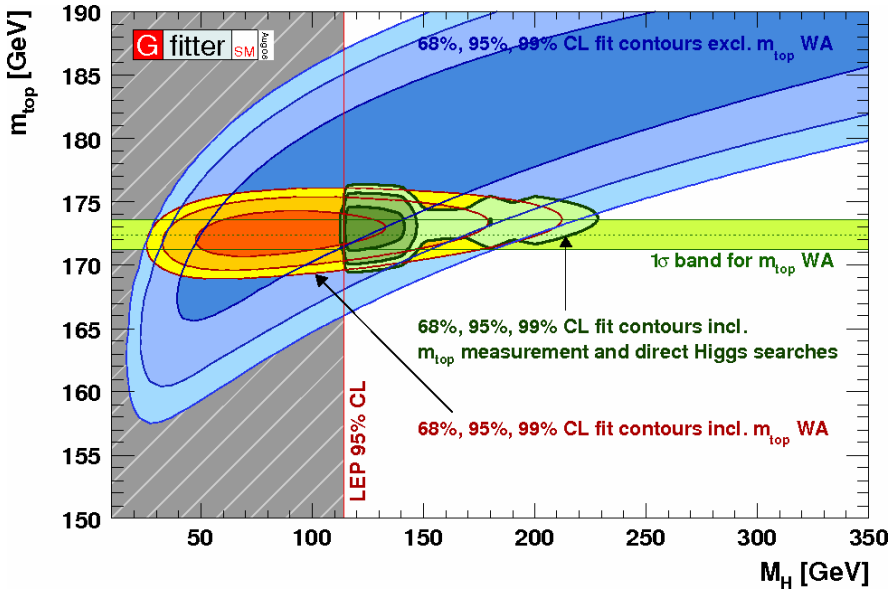


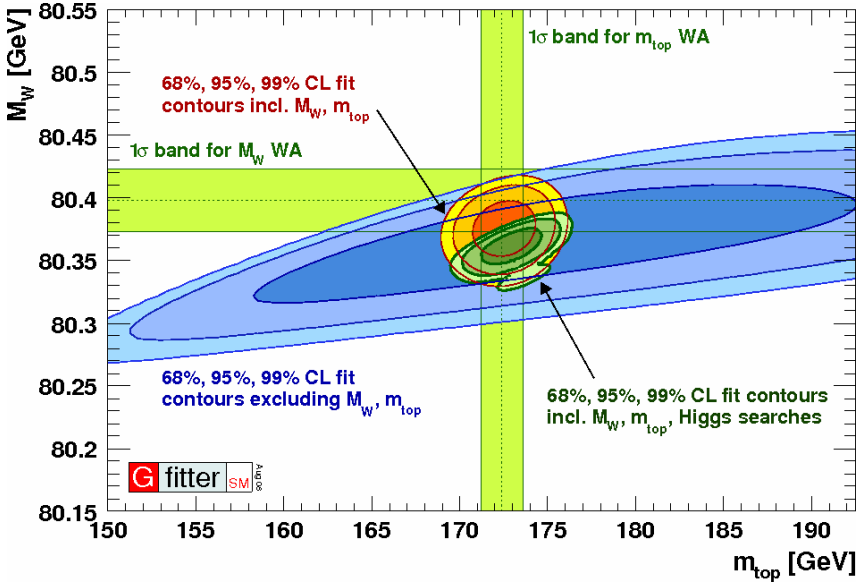
- M_H from *complete fit* (i.e. incl. direct Higgs searches):
  - χ^2 interpretation of search results: deviation of log-likelihood-ratio in data and (S+B) hypothesis.
    - central value ±1σ: $M_H = 120^{+15}_{-5}$ GeV
    - 2σ interval: [114.4, 144] GeV
  - conservative CL_S-like interpretation
    - central value ±1σ: $M_H = 117^{+21}_{-2}$ GeV
    - 2σ interval: [114.2, 154] GeV



Electroweak fit: 2-dim results

- Gfitter allows 1-dim, 2-dim scans and contour plots
- 3 different types of fits:
  - indirect (i.e. excluding the respective measurements)
  - including the measurements
  - including in addition the results from direct Higgs searches





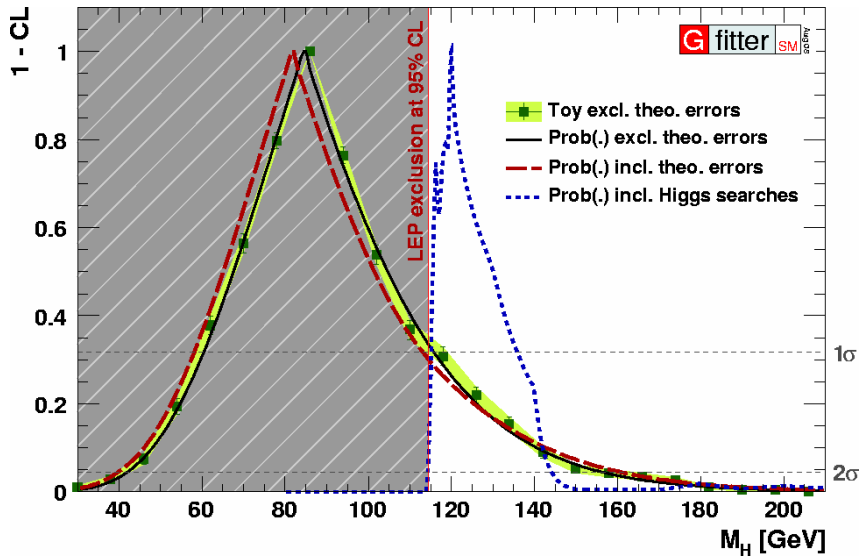
- Indirect fit results agree with experimental values
- Results from Higgs searches significantly reduce the allowed parameter space.

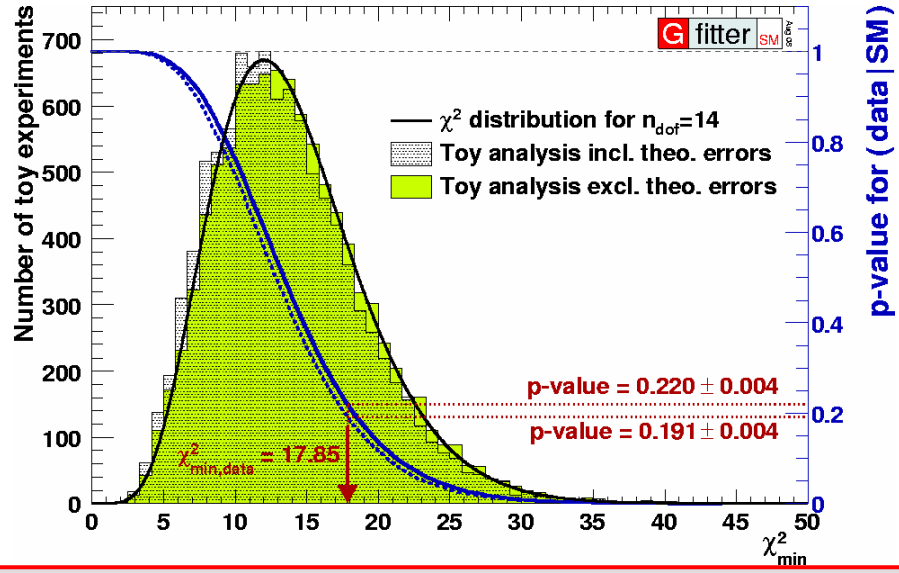
Electroweak fit: statistical analysis

- 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().
- Example: evaluation of p-value of SM fit
  - MC toy with 10 000 experiments.
  - good agreement with ideal χ^2 function
  - result:

$$\text{p-value}\,(\text{data}|\text{SM}) \;=\; 0.220 \pm 0.004\,{}_{-0.029}$$

using m_t=172.6±1.4 GeV [arXiv:0803.1683]





Electroweak fit: prospects

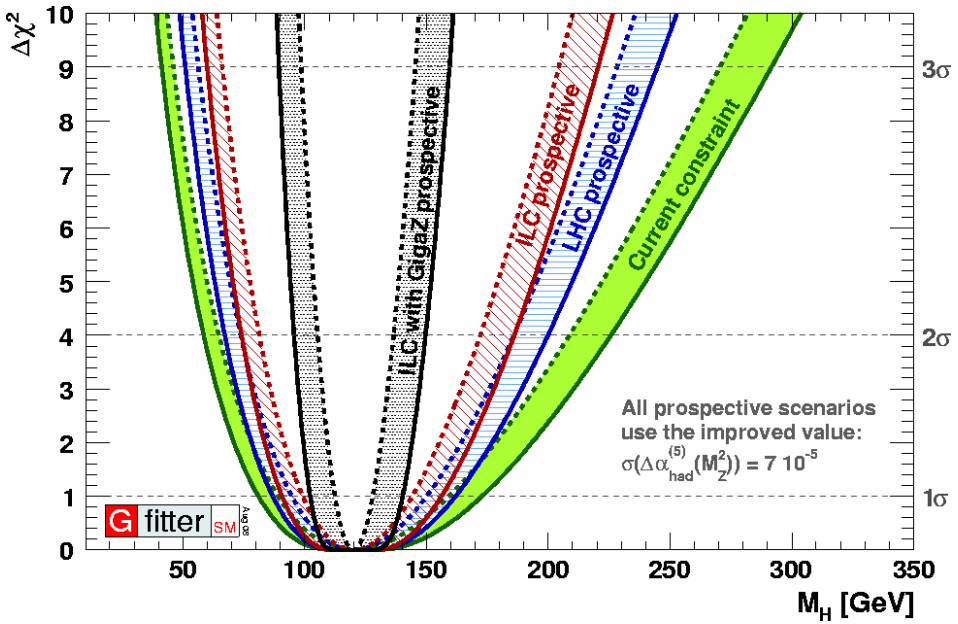
- LHC, ILC (+GigaZ)
  - exp. improvement on M_W, m_t, $\sin^2\theta^l_{eff}$, R_l^0
- improved $\Delta\alpha_{had}^{(5)}(M_Z^2)$ needed, e.g. $\sigma(\Delta\alpha_{had}^{(5)})\sim 7\cdot 10^{-5}$

[F. Jegerlehner, hep-ph/0105283]

Quantity	Present	Expected uncertainty LHC	ILC	GigaZ (ILC)
M_W [MeV]	25	15	15	6
m_t [GeV]	1.2	1.0	0.2	0.1
$\sin^2\theta^\ell_{\text{eff}}$ $[10^{-5}]$	17	17	17	1.3
R^0_ℓ $[10^{-2}]$	2.5	2.5	2.5	0.4
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$ $[10^{-5}]$	22 (7)	22 (7)	22 (7)	22 (7)
$M_H(=120\text{ GeV})$ [GeV]	$^{+56}_{-41}$ $(^{+53}_{-39})$ $[^{+39}_{-31}]$	$^{+46}_{-35}$ $(^{+42}_{-33})$ $[^{+30}_{-25}]$	$^{+40}_{-32}$ $(^{+36}_{-29})$ $[^{+24}_{-20}]$	$^{+26}_{-23}$ $(^{+20}_{-18})$ $[^{+8}_{-8}]$
$\alpha_s(M_Z^2)$ $[10^{-4}]$	28	28	27	7

[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. Hawkings, K. Mönig, EPJ direct C1, 8 (1999)]
[A. H. Hoang et al., EPJ direct C2, 1 (2000)][M. Winter, LC-PHSM-2001-016]

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



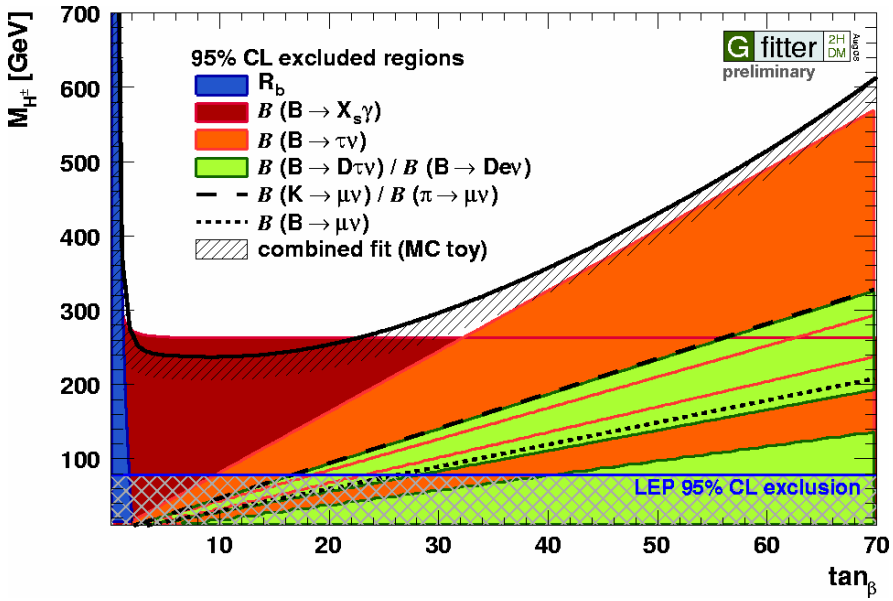
2HDM fit: experimental input and theory

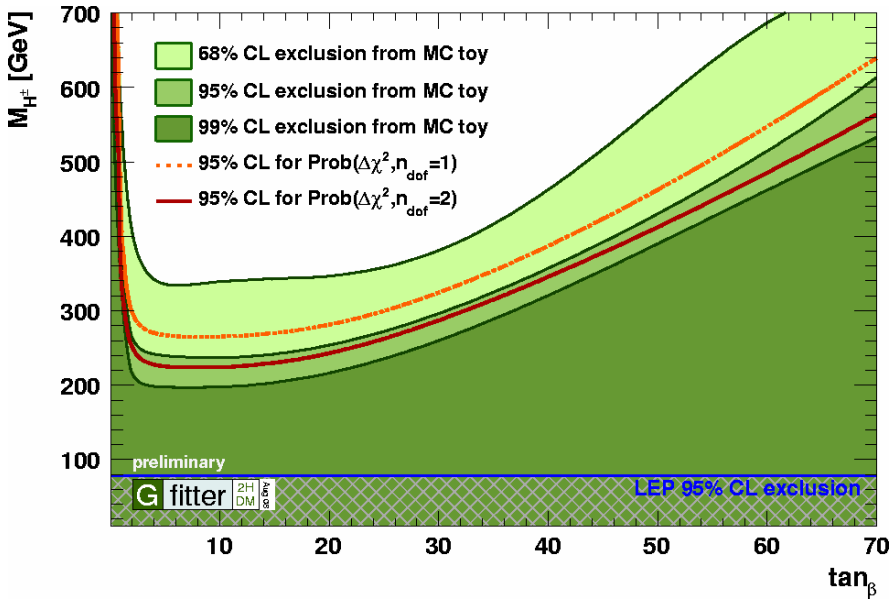
- Implementation of 2HDM (Type-II) as first extension of SM
- 2HDM (Type-II)
  - additional Higgs doublet
  - one doublet couples to u-type, one doublet couples to d-type quarks
  - 6 free parameters → $M_{H\pm}$, M_{A0}, M_{H0}, M_h, tanβ, |α|
- so far: only looked at processes sensitive to charged Higgs
  → $M_{H\pm}$, tanβ

observable	input value	exp. ref	calculation
R_b^0	0.21629 ± 0.00066	[ADLO, Phys. Rept.427, 257 (2006)	[H. E. Haber and H. E. Logan, Phys. Rev. D62, 015011 (2000)]
BR (B→$X_s\gamma$)	(3.52±0.23±0.09)·10^{-4}	[HFAG, latest update]	[M. Misiak et al., Phys. Rev. Lett. 98, 022002 (2007)]
BR (B→τν)	(1.41±0.43)·10^{-4}	[HFAG, latest update]	[W. S. Hou, Phys. Rev. D48, 2342 (1993)]
BR (B→μν)	>1.7·10^{-6} at 90% CL	[HFAG, arXiv:0704.3575]	[W. S. Hou, Phys Rev. D48, 2342 (1993)]
BR (K→μν)/ BR(π→μν)	1.004±0.007	[FlaviaNet,, arXiv:0801.1817]	[FlaviaNet, arXiv:0801.1817]
BR(B→Dτν)/ BR(B→Deν)	0.416±0.117±0.052	[Babar, Phys. Rev. Lett 100, 021801 (2008)]	[J. F. Kamenik and F. Mescia, arXiv:0802.3790]

2HDM fit: fit results

- Overlay of individual 95% CL excluded regions
  - assuming n_{dof}=1 and 2-sided limits
- Combined fit:
  - excluded area depends on assumptions (n_{dof}=1, n_{dof}=2)
  - resolved by MC toy study
  - 2-sided limits
  - χ^2_{min}=2.3 at M_H=850 and tanβ=10
- Excluded at 95% CL:
  - small tanβ
  - for all tanβ
    - M_H < 240 GeV
    - M_H< (8.6 tanβ) GeV





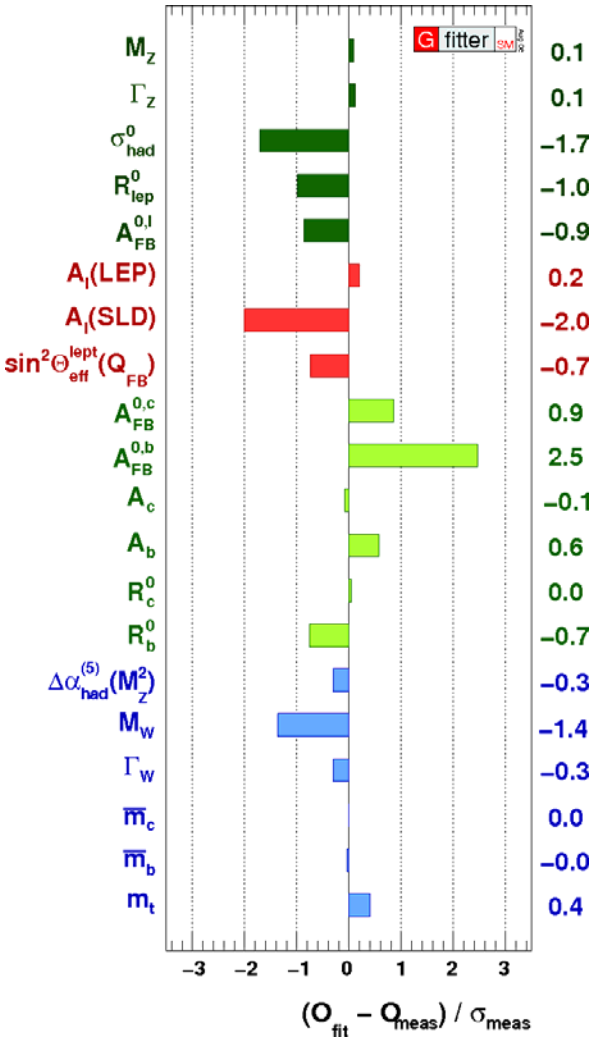
Summary

- Gfitter is a new SW 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
- Example for SM extension: 2HDM (Type-II)
- Future steps:
  - publication of results expected soon
  - continued support for SM and 2HDM fits: http://cern.ch/Gfitter
  - implementation of more theories, e.g. supersymmetric models

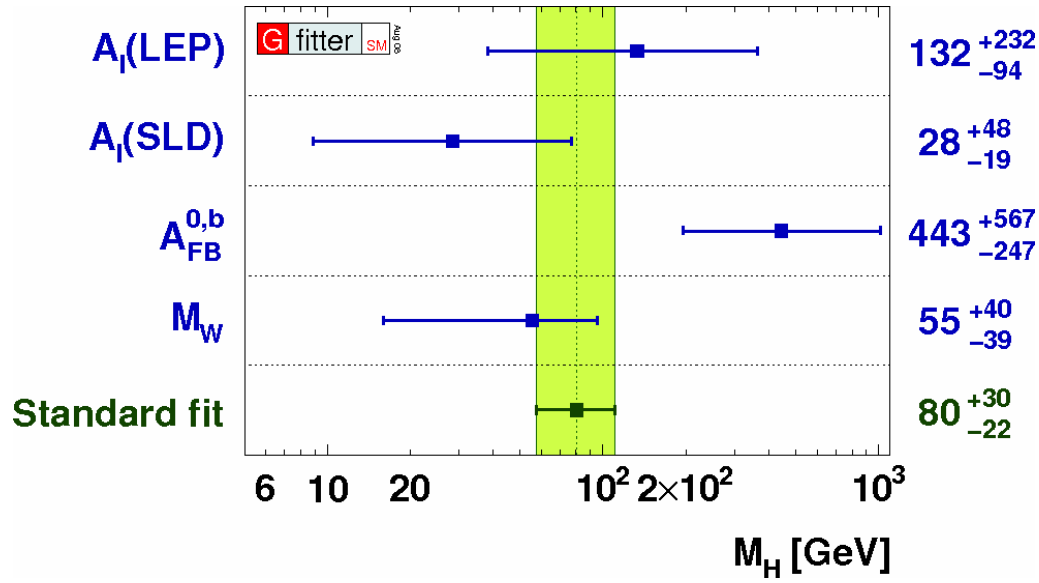
Back-up slides

Additional results of the electroweak fit

- Pull values of *complete fit*



- Results for M_H in the *standard fit* excluding all sensitive observables, except for the one given.



Additional results of the electroweak fit

- Comparison of standard treatment of theoretical uncertainties with Rfit treatment
- 2-dim scan: $\Delta\alpha_{had}^{(5)}(M_Z^2)$-$M_H$
- p-value of the SM fit for fixed values of M_H (using m_t=172.6±1.4 GeV) [arXiv:0803.1683]