
**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

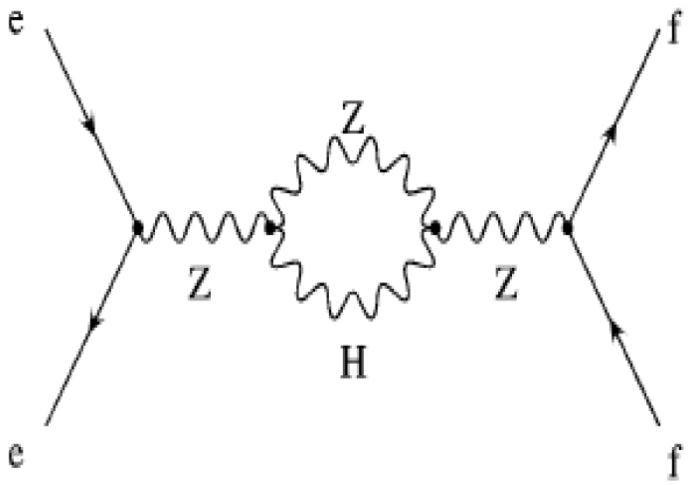
- Gfitter features:
  - consistent treatment of statistical, systematic and theoretical errors, correlations, and inter-parameter dependencies
    - theoretical uncertainties: Rfit prescription [A Höcker et al., EPJ C21, 225 (2002)]
      - theory uncertainties included in $\chi^2$ estimator with flat 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.

# 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 $\sin^2\theta^f_{eff}$: 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]



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  - radiator functions: N$^3$LO of the massless QCD Adler function

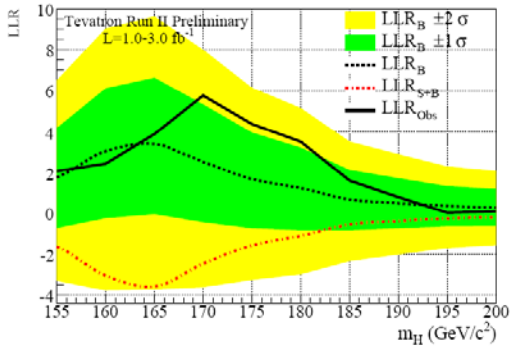
    [P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]
- calculations thoroughly cross-checked against ZFitter (Fortran) package → excellent agreement
- free fit parameters:
  - $M_Z$, $M_H$, $m_t$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\alpha_S(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$
  - parameters for theoretical uncertainties on $M_W$ ($\delta M_W$=4-6GeV), $\sin^2\theta^l_{eff}$ ($\delta\sin^2\theta^l_{eff}$ =4.7·10$^{-5}$) (and the electroweak form factors $\rho_Z^f$, $\kappa_Z^f$)

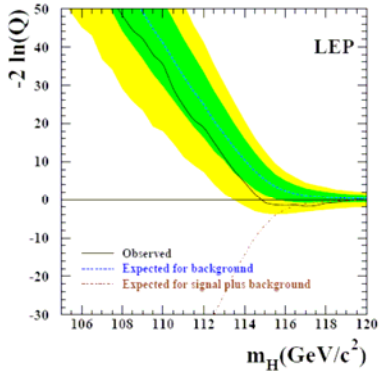
# Experimental Input

| Parameter | Input value | Free in fit |
|---|---|---|
| $M_Z$ [GeV] | $91.1875 \pm 0.0021$ | yes |
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | – |
| $\sigma^0_{\rm had}$ [nb] | $41.540 \pm 0.037$ | – |
| $R^0_\ell$ | $20.767 \pm 0.025$ | – |
| $A^{0,\ell}_{\rm FB}$ | $0.0171 \pm 0.0010$ | – |
| $A_\ell$ (*) | $0.1499 \pm 0.0018$ | – |
| $A_c$ | $0.670 \pm 0.027$ | – |
| $A_b$ | $0.923 \pm 0.020$ | – |
| $A^{0,c}_{\rm FB}$ | $0.0707 \pm 0.0035$ | – |
| $A^{0,b}_{\rm FB}$ | $0.0992 \pm 0.0016$ | – |
| $R^0_c$ | $0.1721 \pm 0.0030$ | – |
| $R^0_b$ | $0.21629 \pm 0.00066$ | – |
| $\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$ | $0.2324 \pm 0.0012$ | – |
| $M_H$ [GeV] (◇) | Likelihood ratios | yes |
| $M_W$ [GeV] | $80.398 \pm 0.025$ | – |
| $\Gamma_W$ [GeV] | $2.106 \pm 0.050$ | – |
| $\overline{m}_c$ [GeV] | $1.25 \pm 0.09$ | yes |
| $\overline{m}_b$ [GeV] | $4.20 \pm 0.07$ | yes |
| $m_t$ [GeV] | $172.4 \pm 1.2$ | yes |
| $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ (†△) | $2769 \pm 22$ | yes |
| $\alpha_s(M_Z^2)$ | – | yes |
| $\delta_{\rm th} M_W$ [MeV] | $[-4,4]_{\rm theo}$ | yes |
| $\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ (†) | $[-4.7,4.7]_{\rm theo}$ | yes |
| $\delta_{\rm th}\rho^f_Z$ (†) | $[-2,2]_{\rm theo}$ | yes |
| $\delta_{\rm th}\kappa^f_Z$ (†) | $[-2,2]_{\rm theo}$ | yes |

† 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 $\Gamma_W$**: 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 [arXivx:0808.1089 [hep-ex]]
  - **$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$**: [K. Hagiwara et al., Phys. Lett. B649, 173 (2007)] + Gfitter rescaling mechanism to account for $\alpha_S$-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]



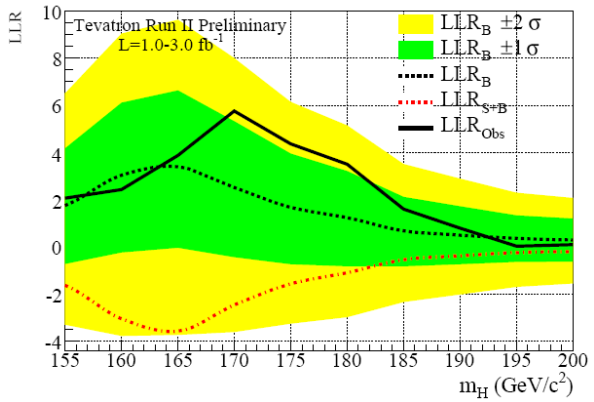



# Direct Higgs Searches

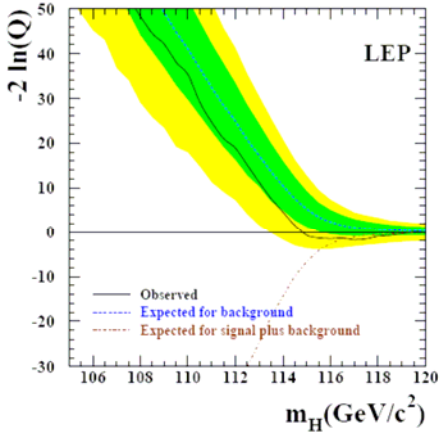
- Usage of $CL_{S+B}$:
  - describe probability of upwards fluctuations of the test statistics (LLR, -2lnQ)
  - transform one-sided $CL_{S+B}$ into a two-sided CL
  - contribution to $\chi^2$ estimator obtained via inverse error function

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

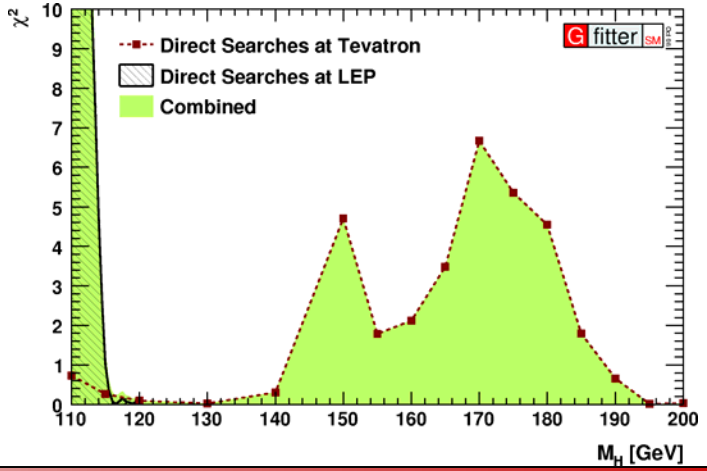
Tevatron



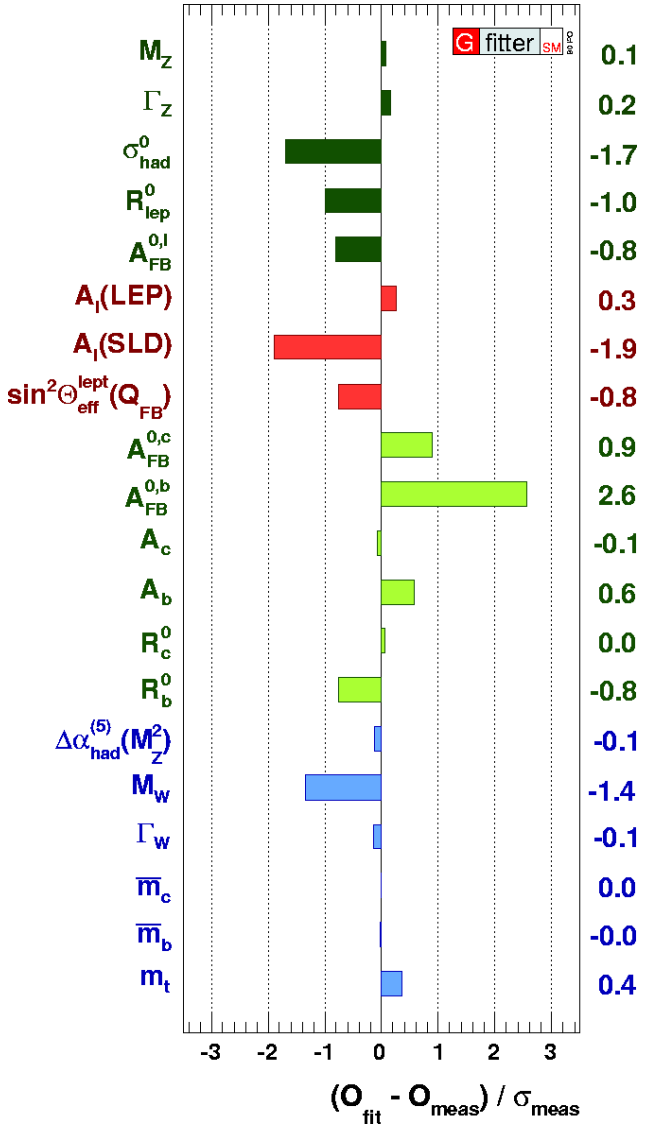

LEP




contribution to $\chi^2$ estimator



# Fit Results




- convergence and naïve p-values:
  - *standard fit*: $\chi^2_{min}=16.4 \rightarrow Prob(\chi^2_{min},13)=0.23$
  - *complete fit*: $\chi^2_{min}=18.0 \rightarrow Prob(\chi^2_{min},14)=0.21$
- $\alpha_S$ from *complete fit*: $\alpha_S(M_Z^2) = 0.1193^{+0.0028}_{-0.0027} \pm 0.0001$
  - 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 $\tau$ decay [M. Davier et al., arXiv:0803.0979]

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

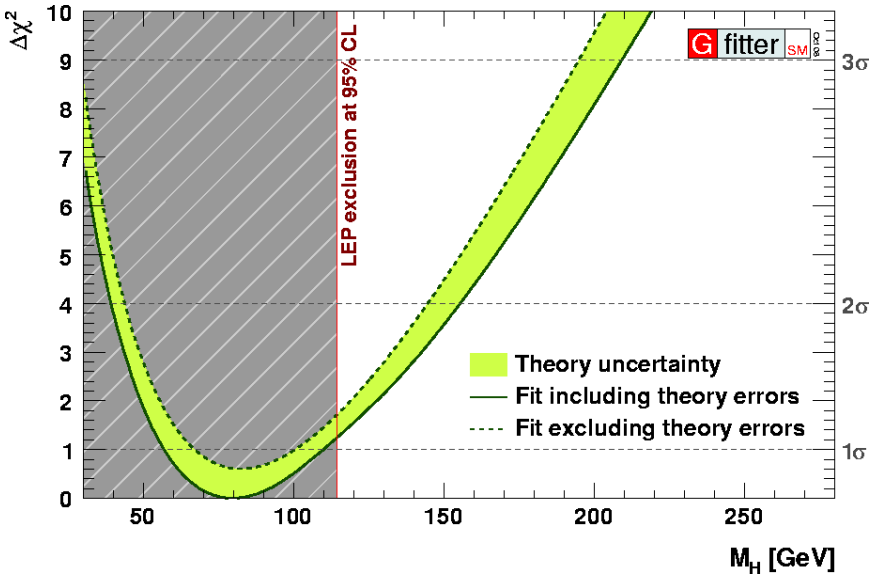
- pull values of *complete fit*
  - no value exceeds 3σ
  - FB asymmetry of bottom quarks -> largest contribution to $\chi^2$

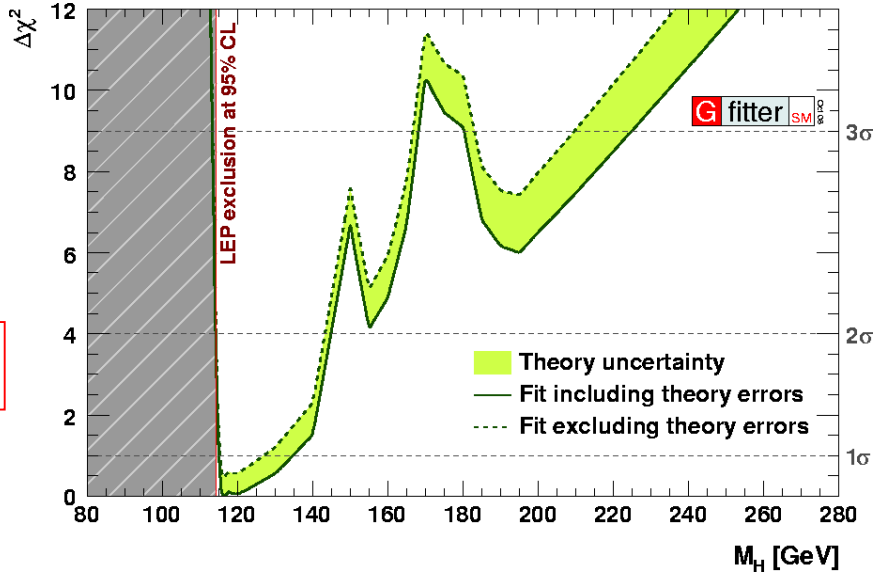
# Results for $M_H$

- $M_H$ from *standard fit*:
  - central value ±1σ: $M_H = 80^{+30}_{-23}\ GeV$
  - 2σ interval: [39, 155] GeV
  - 3σ interval: [26, 209] GeV

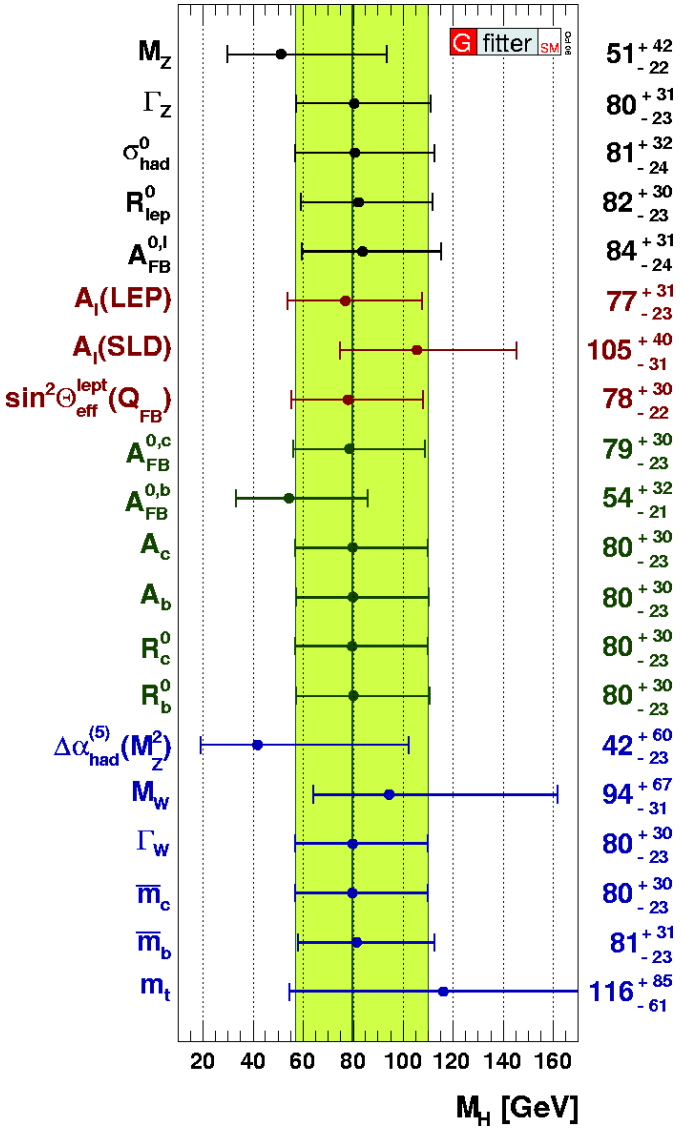
green band due to Rfit treatment of theory errors, fixed errors lead to larger $\chi^2$

- $M_H$ from *complete fit* (i.e. incl. direct Higgs searches):
  - central value ±1σ: $M_H = 116.4^{+18.3}_{-1.3}\ GeV$
  - 2σ interval: [114, 145] GeV



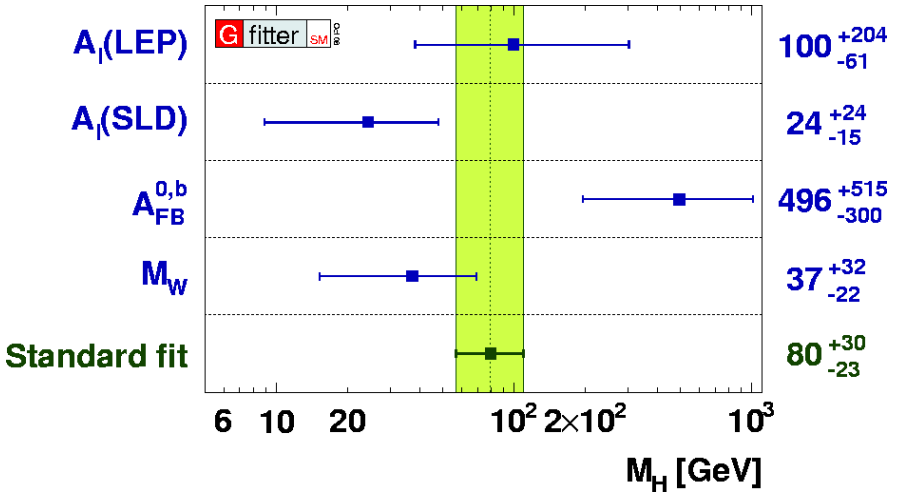



# More Detailed Analysis




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

$M_H$ determined only with one sensitive observable

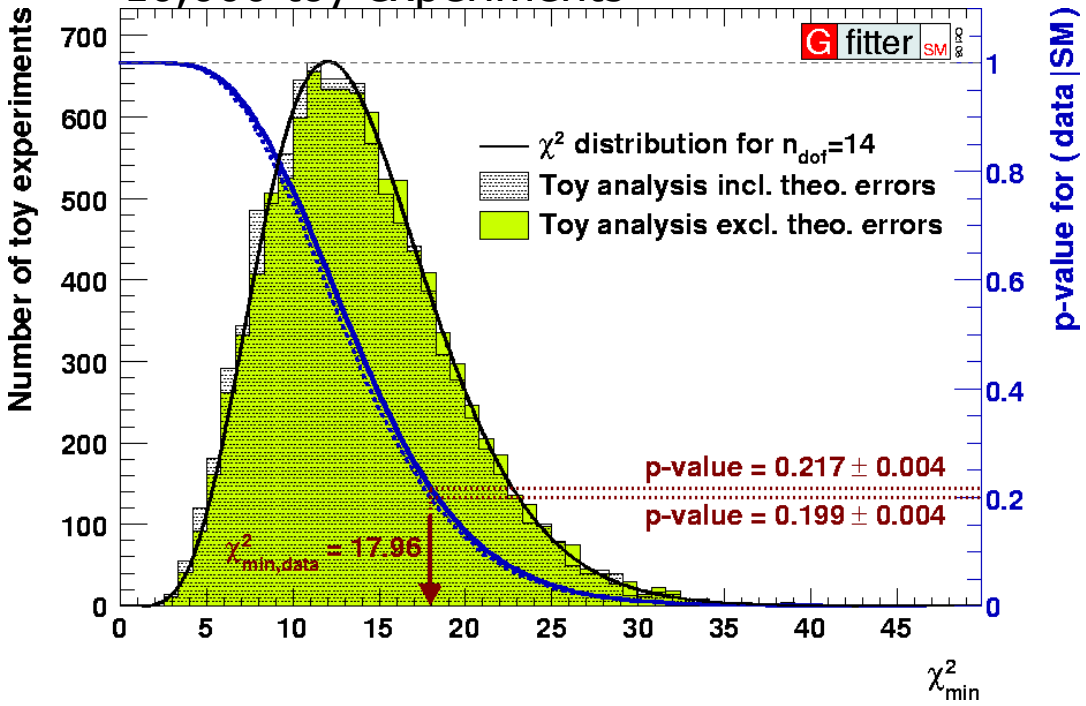


# Goodness of Global Fit

## 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 $\chi^2$

10,000 toy experiments




**Testing the SM**

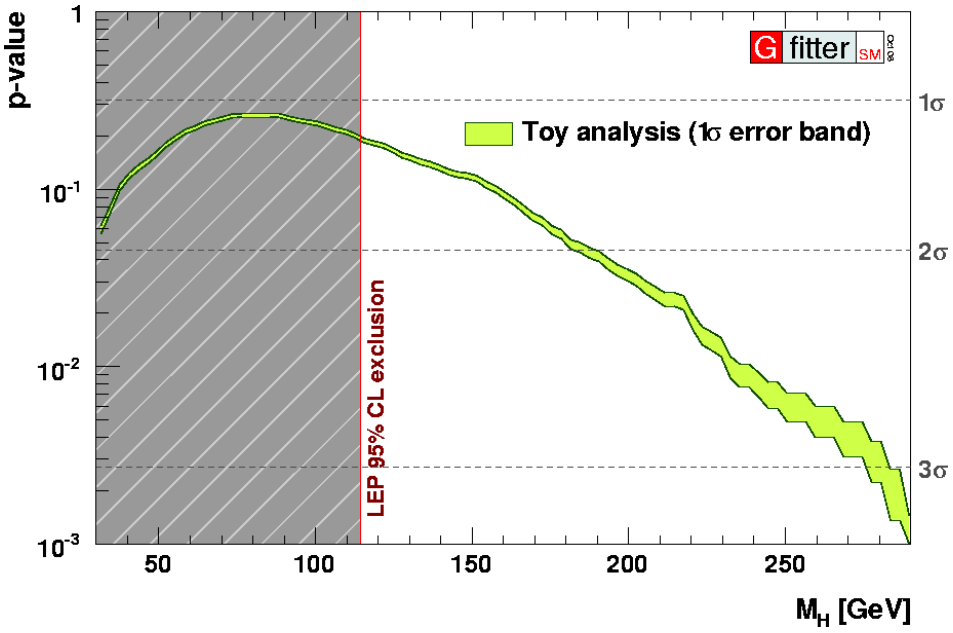
p-value: Probability

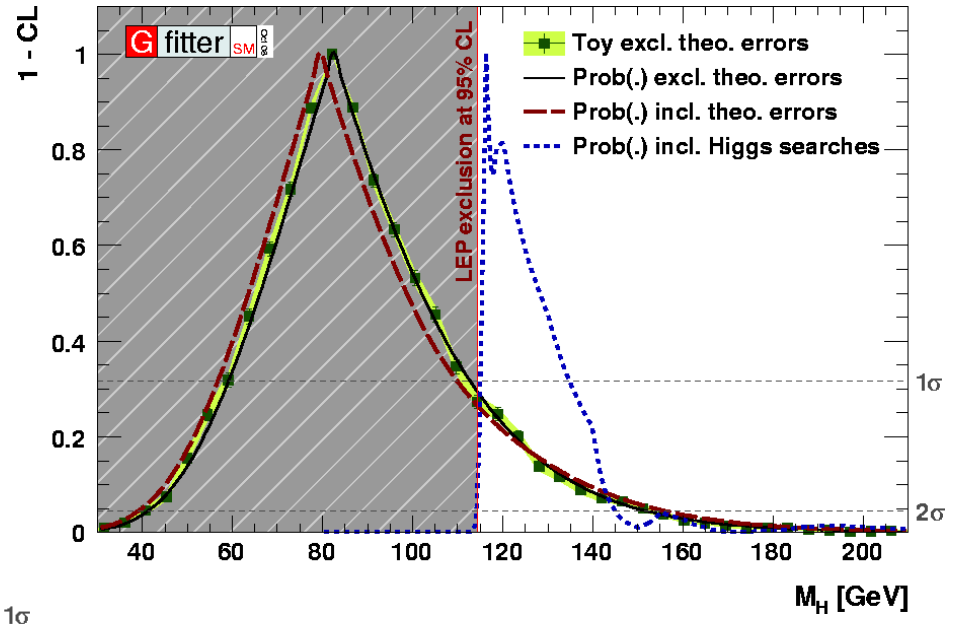
- for wrongly rejecting the SM
- for getting a $\chi^2$ larger than the $\chi^2$ of the fit

p-value = (21.7±0.4)%
No strong requirement for new physics

# Advanced 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().

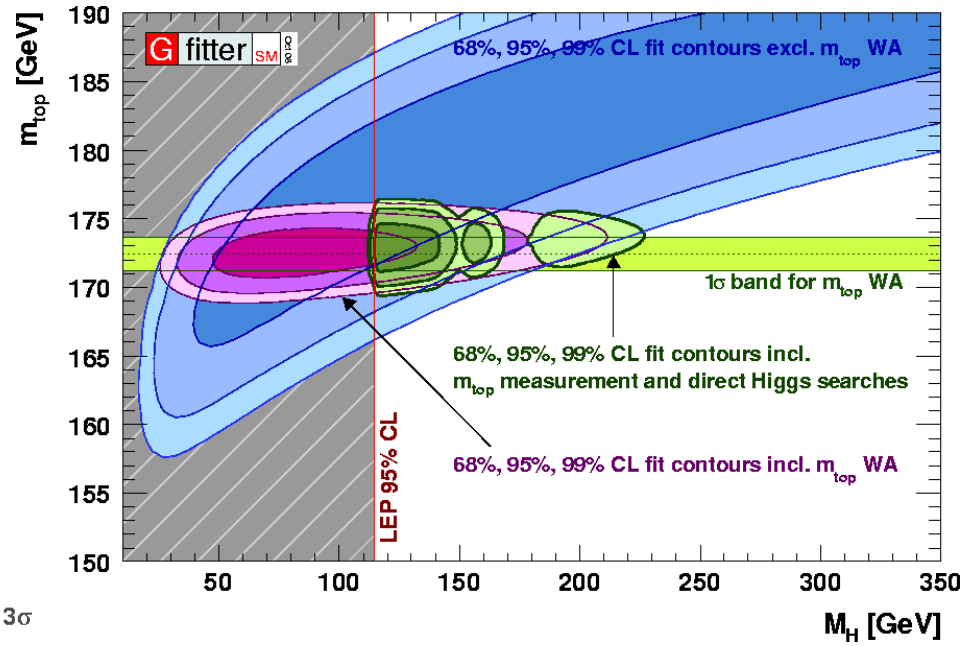


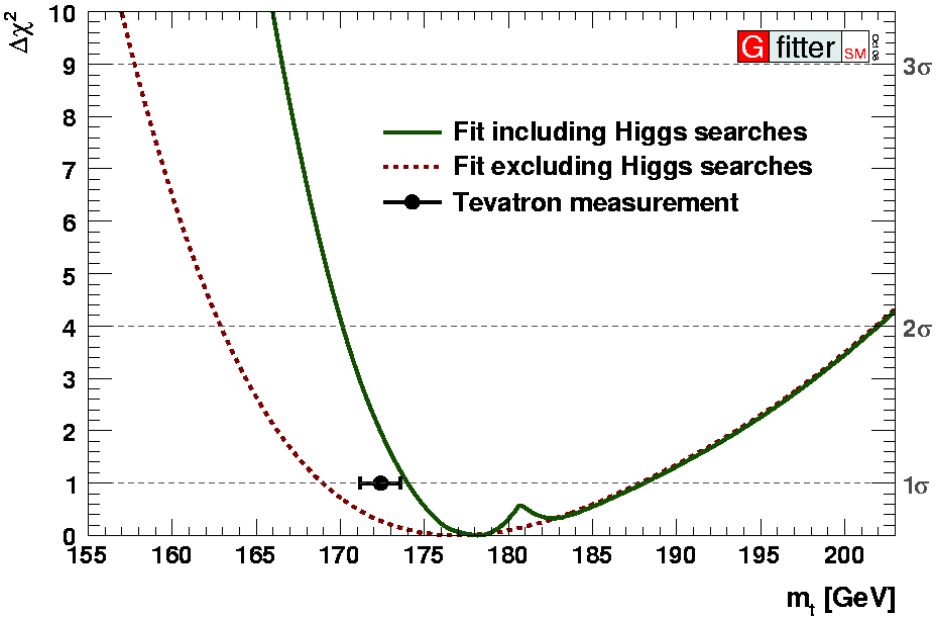




- p-values for fixed Higgs masses using toy experiment
- here: p-value is larger than for fit with free Higgs mass
  - Higgs mass fixed
  - $n_{dof}$ increased by one

# Top Quark Results

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

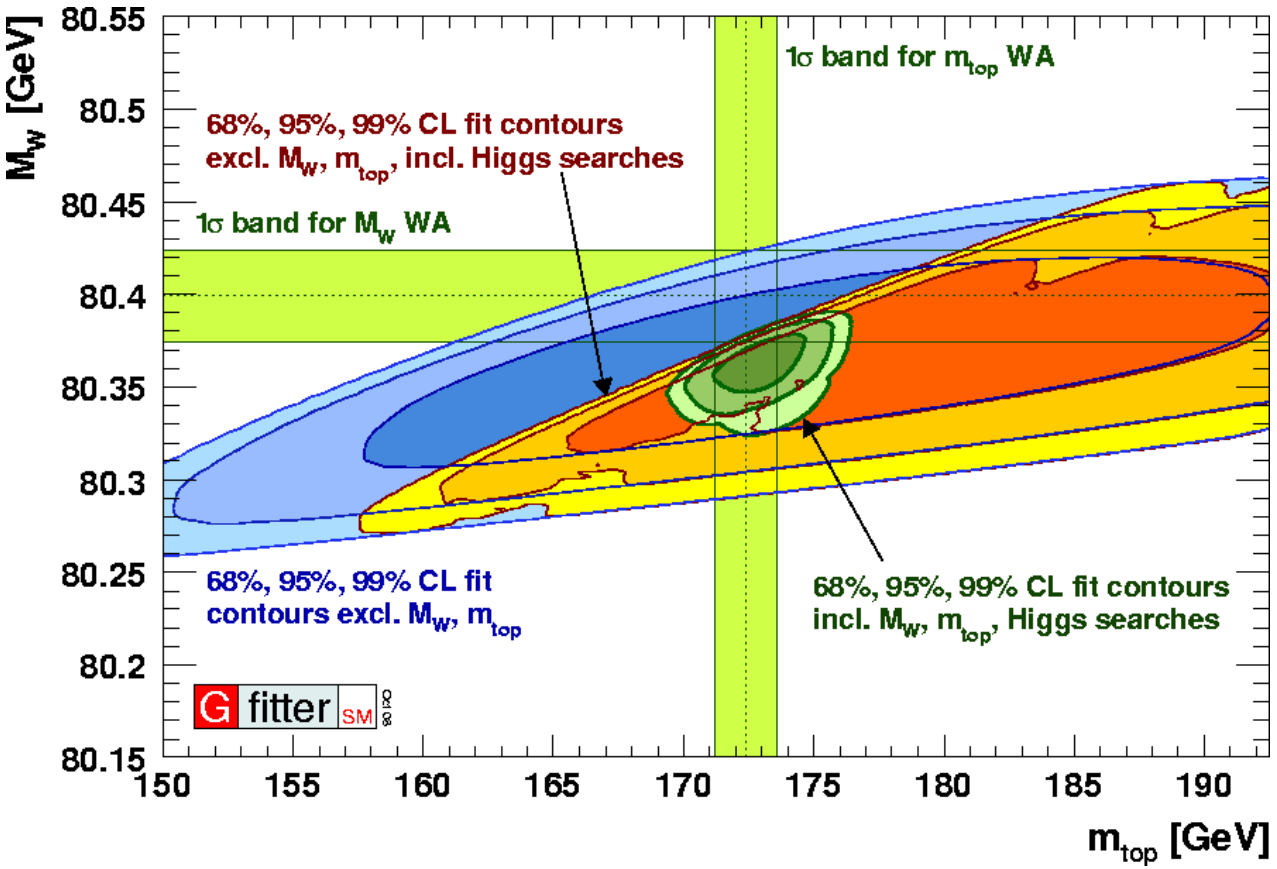



- Indirect determination of $m_{top}$
  - w Higgs search: $m_{top} = 178.2^{+9.8}_{-4.2}\ GeV$
  - w/o Higgs search: $m_{top} = 177.0^{+10.8}_{-8.0}\ GeV$
- Tevatron measurement:

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

# Top versus W Mass




- 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

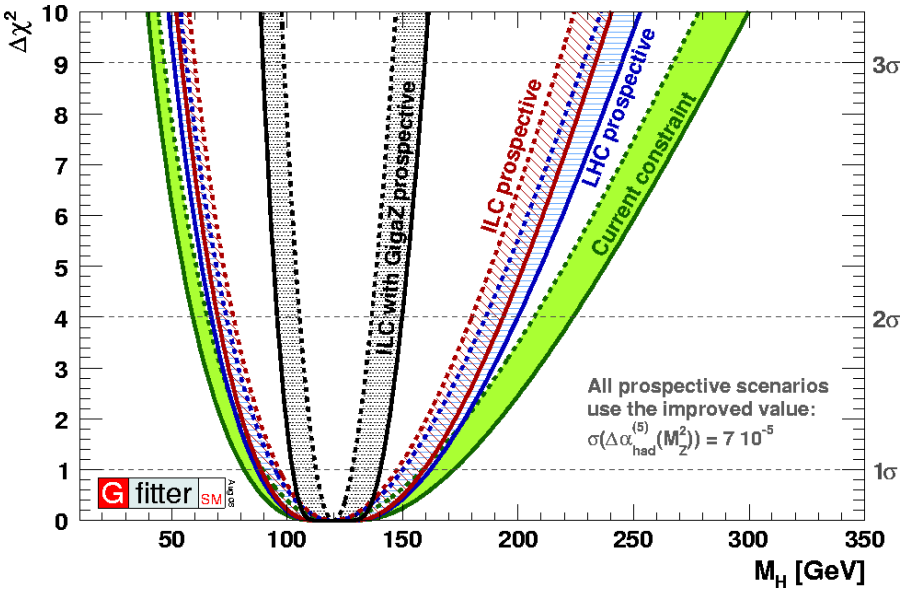
# Prospects for LHC and ILC

- LHC, ILC (+GigaZ)
  - exp. improvement on $M_W$, $m_t$, $\sin^2\theta^l_{eff}$, $R_l^0$
- assumed $\Delta\alpha_{had}^{(5)}(M_Z^2)$, 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 |
| $\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$ | 17 | 17 | 17 | 1.3 |
| $R_\ell^0$ $[10^{-2}]$ | 2.5 | 2.5 | 2.5 | 0.4 |
| $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $[10^{-5}]$ | 22 (7) | 22 (7) | 22 (7) | 22 (7) |
| $M_H(=120$ GeV) [ GeV] | $^{+56}_{-40}$ $(^{+52}_{-39})$ $[^{+39}_{-31}]$ | $^{+45}_{-35}$ $(^{+42}_{-33})$ $[^{+30}_{-25}]$ | $^{+42}_{-33}$ $(^{+39}_{-31})$ $[^{+28}_{-23}]$ | $^{+27}_{-23}$ $(^{+20}_{-18})$ $[^{+8}_{-7}]$ |
| $\alpha_s(M_Z^2)$ $[10^{-4}]$ | 28 | 28 | 27 | 6 |

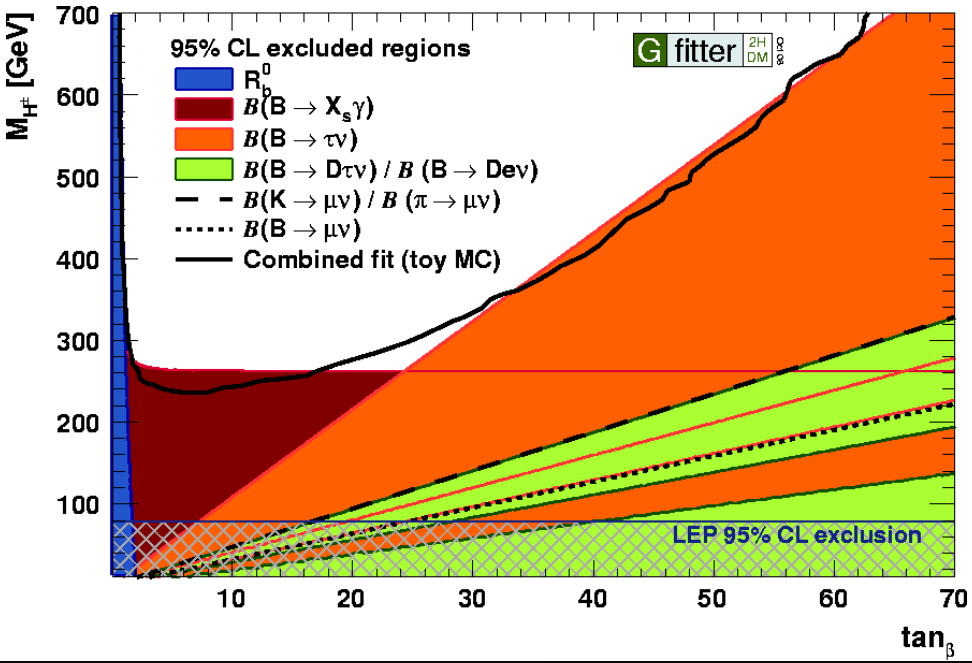
[ATLAS, Physics TDR (1999)][CMS, Physics TDR (2006)][A. Djouadi et al., arXiv:0709.1893]
[I. Borjanovic, EPJ C39S2, 63 (2005)][S. Haywood et al., hep-ph/0003275]
[R. Hawkings, K. Mönig, EPJ direct C1, 8 (1999)]
[A. H. Hoang et al., EPJ direct C2, 1 (2000)][M. Winter, LC-PHSM-2001-016]

- Fits:
  - not used: $\alpha_S$, $M_H$ 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 $\alpha_S(M_Z^2)$



# Two-Higgs-Doublet-Model

- 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, $|\alpha|$




- so far: only looked at processes sensitive to charged Higgs → $M_{H\pm}$, tanβ
- Overlay of individual 95% CL excluded regions
  - assuming $n_{dof}$=1 and 2-sided limits
- Combined fit:
  - resolved by MC toy study assuming 2-sided limits
  - $\chi^2_{min}$=3.9 at $M_H$=858 GeV and tanβ=6.8
- Excluded at 95% CL:
  - small tanβ
  - for all tanβ
    - $M_H$ < 240 GeV
    - $M_H$ < 780 GeV for tanβ=70

# Summary

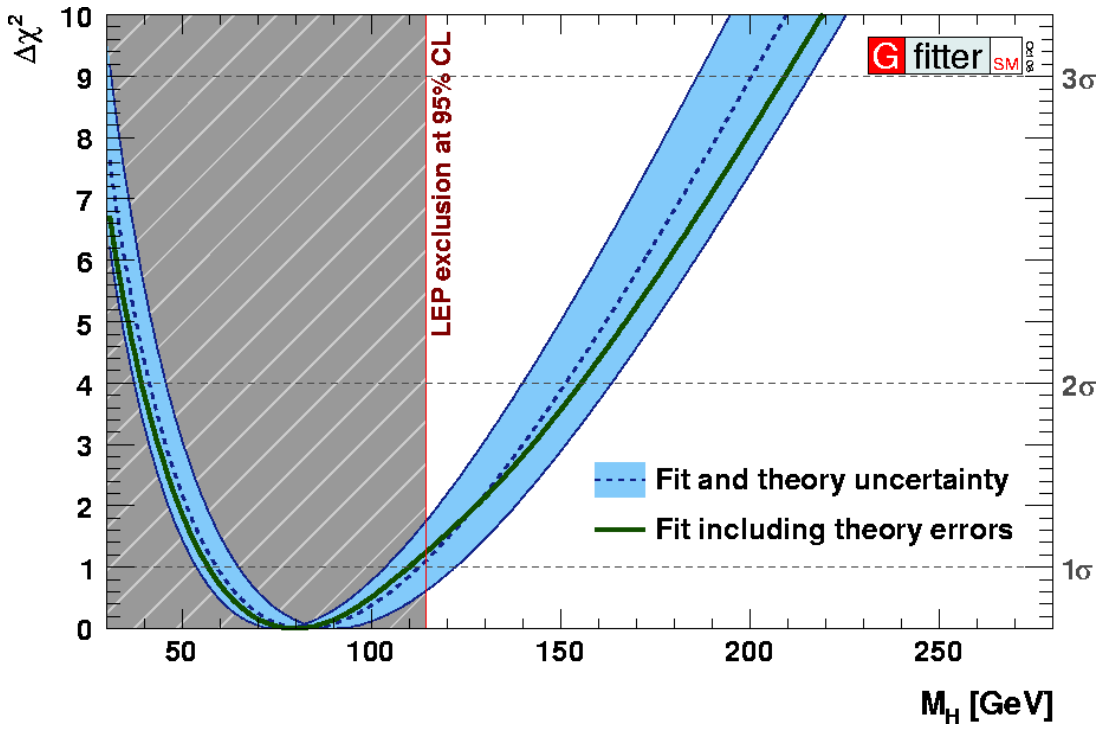
- Gfitter is a framework for involved fitting problems
- First theory package: Revisit of the electroweak fit of the SM
  - latest theoretical calculations and experimental results
  - advanced studies of the statistical properties of the fit
  - inclusion of direct Higgs searches
  - beyond Standard 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)

# Backup

# Treatment of theo. Uncertainties

Uncertainties for Theory-Prediction (two main sources)

$$M_W \pm \Delta M_W(theo) \qquad \sin^2\Theta^{lept}_{eff} \pm \Delta\sin^2\Theta^{lept}_{eff}(theo)$$




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 $\chi^2$.
- outside theory uncertainty: $\chi^2$ determined by **distance** between **measurement** and **prediction ± uncertainty**