Max Baak (CERN)
on behalf of the Gfitter group (*)

European Physical Society – HEP
16th-22nd July 2009, Krakow

Gfitter

http://cern.ch/Gfitter

Gfitter paper published in Eur. Phys. J. C 60, 543 (2009)

Constraints on New Physics theories with Gfitter

- Introduction: Gfitter, the SM fit
- Oblique parameters
- Littlest Higgs model
- Two Higgs doublet model (Type-II)

(*) M.B. (CERN), H. Flächer (CERN), M. Goebel (Univ. Hamburg, DESY), J. Haller (Univ. Hamburg), A. Höcker (CERN), D. Ludwig (Univ. Hamburg, DESY), K. Mönig (DESY), M. Schott (CERN), J. Stelzer (DESY)

The Gfitter Project

G fitter

A Generic Fitter Project
for HEP Model Testing

- Flexible framework for involved fitting problems in the LHC era (and beyond)
  - Based on ROOT framework (math libraries, drawing)
- Modular design: Physics plug-in packages
  - Library for the Standard Model fit to the electroweak precision data
  - Library for SM extensions via the oblique parameters
  - Library for the 2HDM extension of the SM
- Consistent treatment of: correlations and inter-parameter dependencies, statistical, systematic, theoretical uncertainties
  - Theoretical uncertainties: Rfit prescription [CKM fitter, EPJ C21, 225 (2002)]
    - Conservative approach. Included in χ^2 estimator with flat likelihood in allowed ranges
- Advanced statistical analysis methods:
  - E.g. goodness-of-fit, p-value, parameter scans, MC toy analyses, etc.
  - Frequentist approach

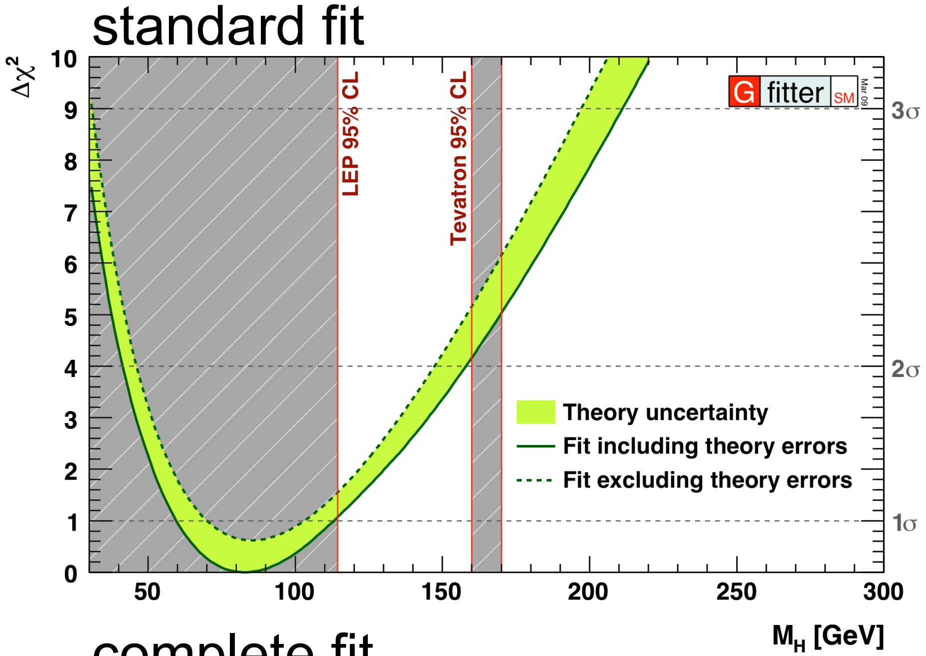
Gfitter SM

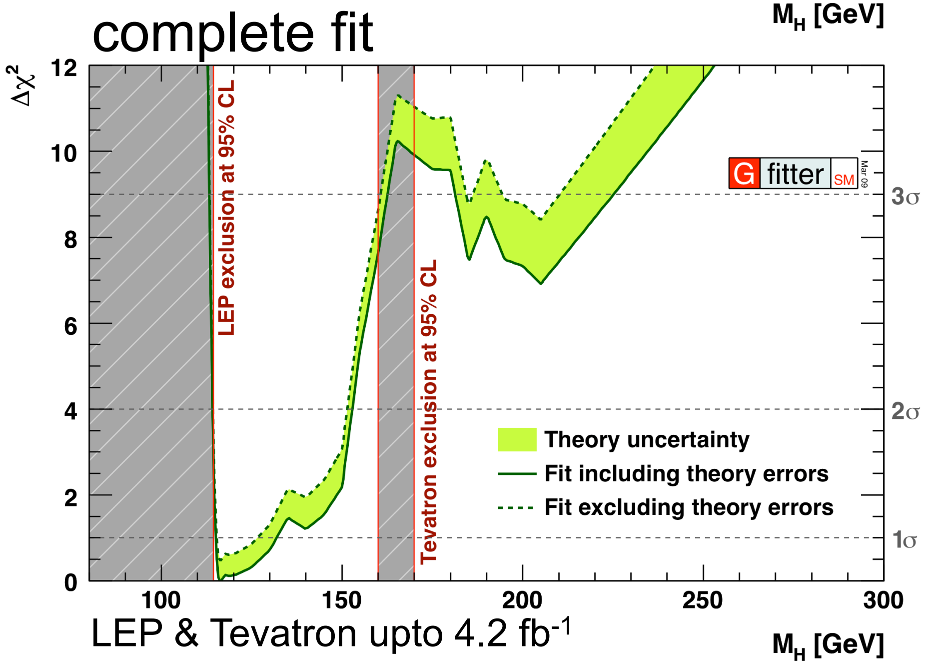
A Gfitter Package for the Global Electroweak Fit

- Complete re-implementation of electroweak theory
  - SM predictions of electroweak precision observables
  - Excellent agreement with ZFitter
- State-of-the art calculations in OMS scheme
  - Radiator functions: N^3LO of the massless QCD Adler function
    [P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]
  - 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., Nucl.Phys.B813:174-187 (2009) and refs.]
- Two electroweak fits performed
  - 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:0903.4001]

SM Fit Results – Higgs Mass Constraints

- See talk A. Hoecker for details on SM fit!
- M_H from standard fit:
  - Central value ±1σ: $M_H = 83^{+30}_{-23}$ GeV
  - 2σ interval: [41,158] GeV
  - 3σ interval: [28,211] GeV
- green error band from theoretical errors
  - Included in χ^2 with "flat likelihood term"
- M_H from complete fit:
  - Central value ±1σ: $M_H = 116.4^{+15.6}_{-1.3}$ GeV
  - 2σ interval: [114,153] GeV

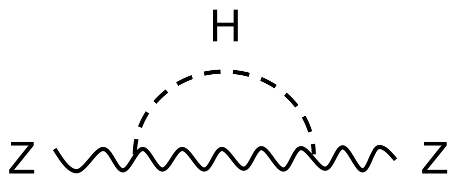




- Goodness of fit:
  - Standard fit: $\chi^2/n_{dof} = 16.4/13$
  - Complete fit: $\chi^2/n_{dof} = 17.8/14$
- Probability of falsely rejecting SM ('p-value') evaluated using toy-MC
  - $(20.4 \pm 0.4_{-0.2})\%$
- No requirement for new physics

Test of SM extensions via Oblique Corrections

- At low energies, BSM physics appears dominantly through vacuum polarization corrections



  - Aka, oblique corrections

- Oblique corrections reabsorbed into electroweak parameters
  - Appearing in: M_W^2, $\sin^2\theta_{eff}$, G_F, α, etc

- Electroweak fit sensitive to BSM physics through oblique corrections
  - In direct competition with sensitivity to Higgs loop corrections

- Oblique corrections from New Physics described through STU parametrization
[Peskin and Takeuchi, Phys. Rev. D46, 1 (1991)]

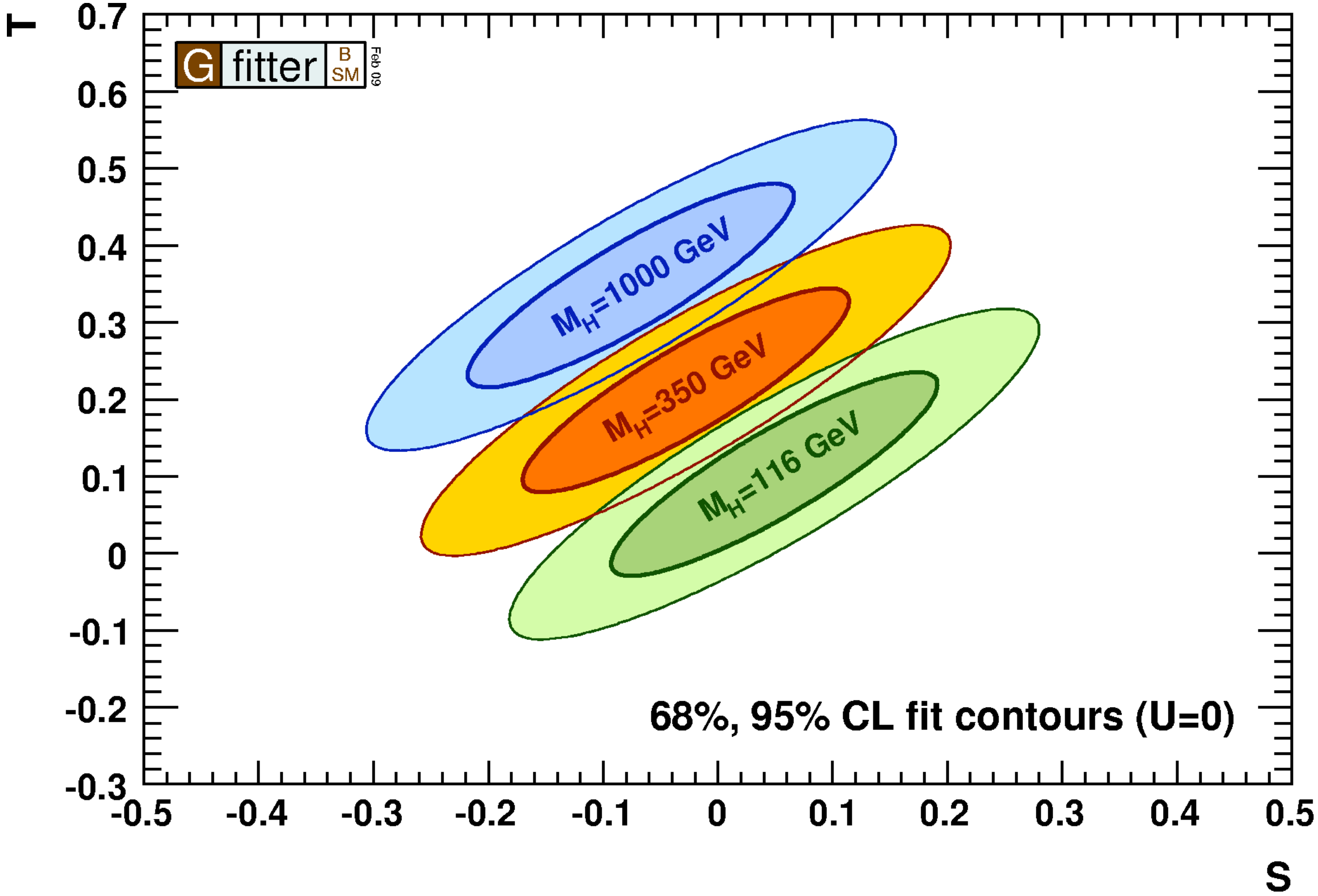
$$O_{meas} = O_{SM,REF}(m_H, m_t) + c_S S + c_T T + c_U U$$

- S : New Physics contributions to neutral currents
- T : Difference between neutral and charged current processes (sensitive to isospin violation)
- U : (+S) New Physics contributions to charged currents. U only sensitive to W mass and width. [Usually very small in NP models (often: U=0)]

- Also implemented: correction to Z→bb coupling, extended parameters (VWX)
[Burgess et al., Phys. Lett. B326, 276 (1994)]
[Burgess et al., Phys. Rev. D49, 6115 (1994)]

Fit to Oblique Parameters

- S,T,U derived from fit to electroweak observables (see global SM fit)
  - Other floating fit parameters: M_Z, $\alpha_s(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$
- 68%, 95% CL ellipses for various M_H values, and m_t = 173.1 GeV (fixed)



M_H=116 (350) GeV

S=0.02(-0.06) ± 0.11
T=0.05(0.15) ± 0.12
U=0.07(0.08) ± 0.12

Higgs corrections to STU:

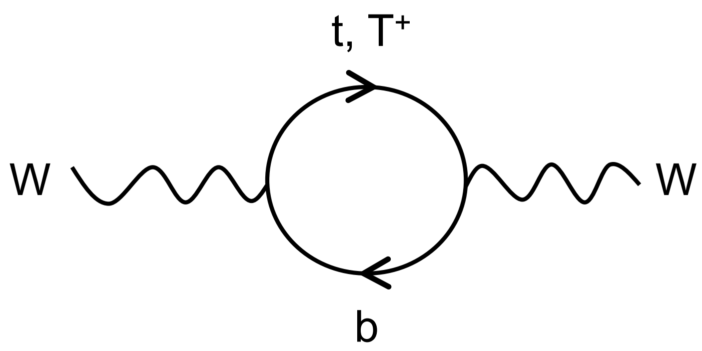
$$S = -\frac{1}{12\pi}\log\frac{m_H^2}{m_{H,\mathrm{ref}}^2}$$

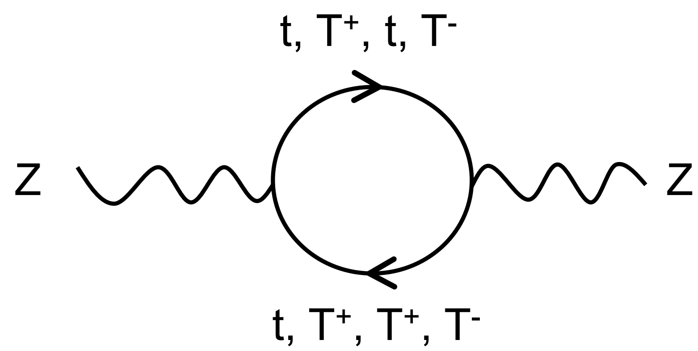
$$T = \frac{3}{16\pi c_W^2}\log\frac{m_H^2}{m_{H,\mathrm{ref}}^2}$$

$$U = 0$$

Littlest Higgs Model, with T-Parity

- LHM solves hierarchy problem, non-linear sigma model
- ‘Littlest’ HM: broken Global SU(5)/SO(5) symmetry
  - Higgs = lightest pseudo-Nambu-Goldstone boson
  - New SM-like fermions and gauge bosons at TeV scale
  - SM contributions to Higgs mass cancelled by new particles
- T-parity = symmetry like R-parity (not time-invariance)
  - Symmetry forbids direct couplings of new gauge bosons to SM particles
  - Provides natural dark matter candidate
- Two new heavy top-quark states: T-even m_{T+} and T-odd m_{T-}
- Dominant oblique corrections:



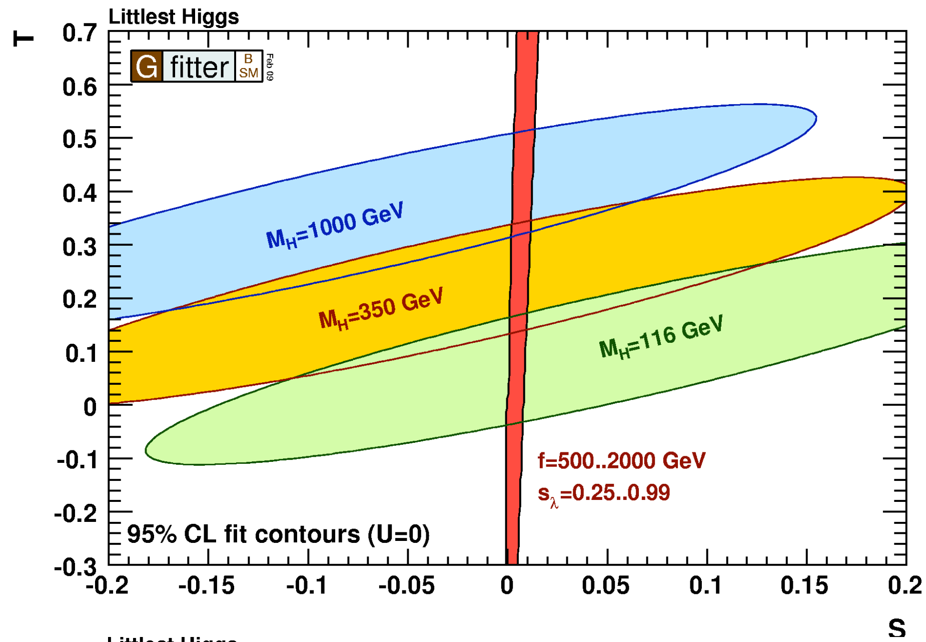


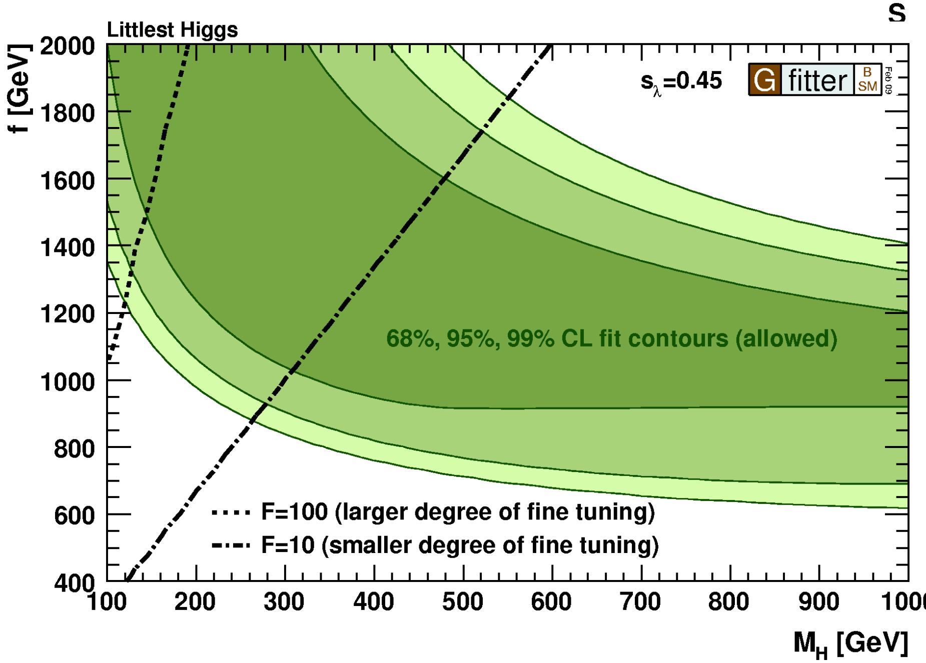
Littlest Higgs with T-Parity

- STU predictions (oblique corrections) inserted for Littlest Higgs model
  [Hubisz et al., JHEP 0601:135 (2006)]

- Parameters of LH model
  - f : symmetry breaking scale (scale of new particles)
  - $s_\lambda \cong m_{T-} / m_{T+}$: ratio of T-odd/-even masses in top sector
  - Order one-coefficient δ_c (value depends on detail of UV physics)
    - Treated as theory uncertainty in fit (Rfit) : δ_c= [-5,5]
- F: degree of fine-tuning

- LH model prefers large Higgs mass, with only small degree of fine-tuning





A Gfitter Package for 2HDM SM Extensions

- Two Higgs Doublet Model (Type-II)
  - SM extended by additional Higgs doublet (2HDM)
  - One Higgs doublet couples to up-type fermions, other doublet couples to down-type fermions
  - Five Higgs bosons: 3 neutral (A^0, h^0, H^0), two charged ($H^{\pm}$)
  - 6 Free parameters $\rightarrow$ $M_{H\pm}$, M_{A0}, M_{H0}, M_h, $\tan\beta$, $|\alpha|$
  - [Type-II 2HDM resembles Higgs sector in MSSM]

Two Higgs Doublet Model

- We have looked at processes sensitive to charged Higgs interactions

$$\mathcal{L}_{H^\pm ff} = \frac{g}{2\sqrt{2}m_W}\left\{H^+\bar{U}\left[M_U V_{CKM}(1-\gamma_5)\cot\beta + V_{CKM}M_D(1+\gamma_5)\tan\beta\right]D + \text{h.c.}\right\}$$

- Interaction has similar structure as W-boson
  - Left-handed coupling: $1/\tan\beta$, right-handed coupling: $\tan\beta$
- Sensitive parameters → $M_{H\pm}$, $\tan\beta$
- LEP limit: $M_{H\pm}$>78.6 GeV (95%CL), for any value of $\tan\beta$

- Measurements of interest from B-physics

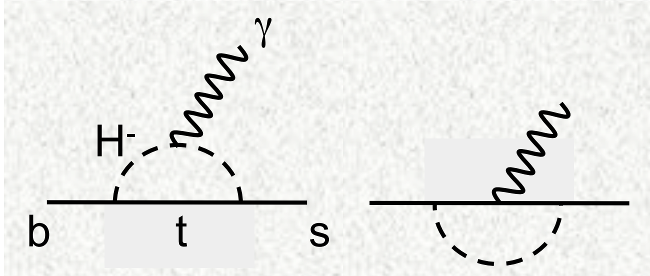
Observable	Input value	Exp. Ref.	Calculation
R_b^0	0.21629 ± 0.00066	[ADLO, Phys. Rept. 427, 257 (2006)]	[H. E. Haber and H. E. Logan, Phys. Rev. D62, 015011 (2000)]
BR ($B \to X_s\gamma$)	$(3.52\pm0.23\pm0.09)\cdot10^{-4}$	[HFAG, latest update]	[M. Misiak et al., Phys. Rev. Lett. 98, 022002 (2007)]
BR ($B \to \tau\nu$)	$(1.73\pm0.33)\cdot10^{-4}$	[P.Chang, Talk at ICHEP 2008]	[W. S. Hou, Phys. Rev. D48, 2342 (1993)]
BR ($B \to \mu\nu$)	$(-5.7\pm6.8\pm7.1)\cdot10^{-4}$	[E. Baracchini, Talk at ICHEP 2008]	[W. S. Hou, Phys Rev. D48, 2342 (1993)]
BR ($K \to \mu\nu$)/ BR($\pi \to \mu\nu$)	1.004±0.007	[FlaviaNet,, arXiv: 0801.1817]	[FlaviaNet, arXiv: 0801.1817]
BR($B \to D\tau\nu$)/ BR($B \to De\nu$)	0.416±0.117±0.052	[Babar, Phys. Rev. Lett 100, 021801 (2008)]	[J. F. Kamenik and F. Mescia, arXiv:0802.3790]

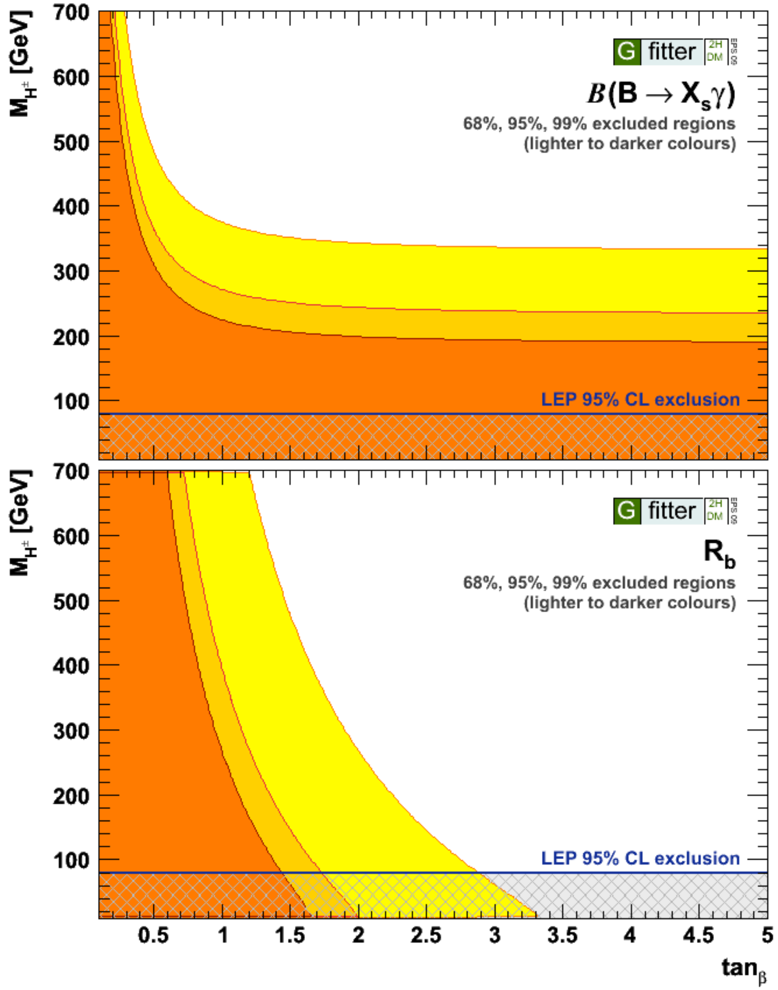
$b \to s\gamma$ and R^0_b

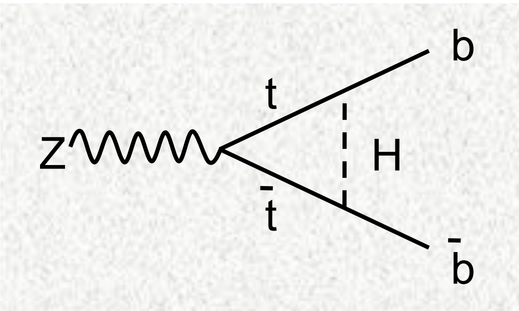
- Penguin dipole-moment of $b \to s\gamma$ allows combination of left- and right-handed Higgs couplings.
- Wilson coefficient:

$$C_7^H \approx -\frac{m_t^2}{2M_H^2}\left(\frac{7}{36}\frac{1}{\tan^2\beta} + \frac{2}{3}\ln\frac{m_H^2}{m_t^2} - \frac{1}{2}\right)$$

- $B \to X_s\gamma$: $M_H > 200$ GeV for $\tan\beta > 1$





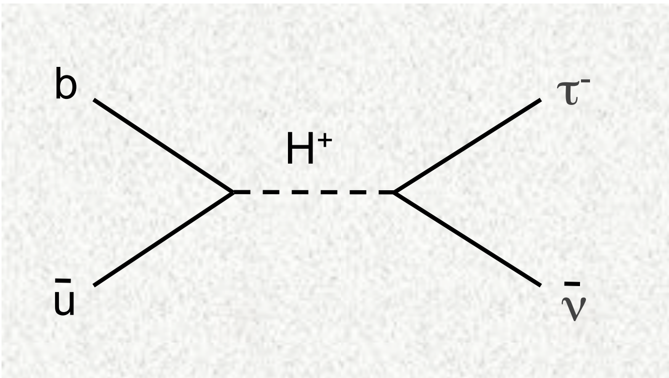


- Z vertex contribution suppressed by $1/\tan^2\beta$
- R^0_b sensitive to small $\tan\beta$ only

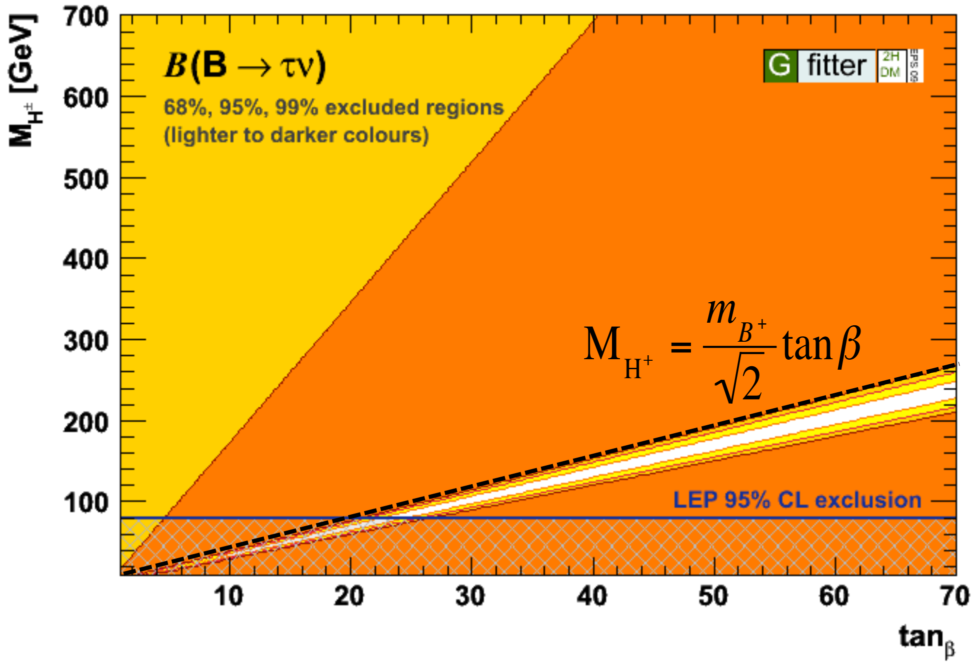
Strongest constraint: $B \rightarrow \tau\nu$

($BR\times10^{-4}$)	Oct '08	EPS '09	Reference
$BR(B\to\tau\nu)_{meas}$	1.51 ± 0.33	1.73 ± 0.35	FPCP 2009
$BR(B\to\tau\nu)_{SM}$	$1.20^{+0.36}_{-0.30}$	$0.87^{+0.21}_{-0.18}$	(Vub direct-measurements.)
V_{ub} ($\times10^{-3}$)	3.81 ± 0.47	3.70 ± 0.33	Gambino,Giordano, Ossola,Uraltsev
f_B (MeV)	216 ± 22	190 ± 13	HPQCD '09 using NRQCD, Davies at FPCP'09
$BR(B\to\tau\nu)_{CKM}$	$0.83^{+0.27}_{-0.10}$	$0.80^{+0.15}_{-0.09}$	CKM Fitter '09, indirect Vub

- Latest measurements used
- We use prediction based on direct measurements of V_{ub}.
- [2.1σ deviation between measurement and SM prediction for $BR(B\rightarrow\tau\nu)$]

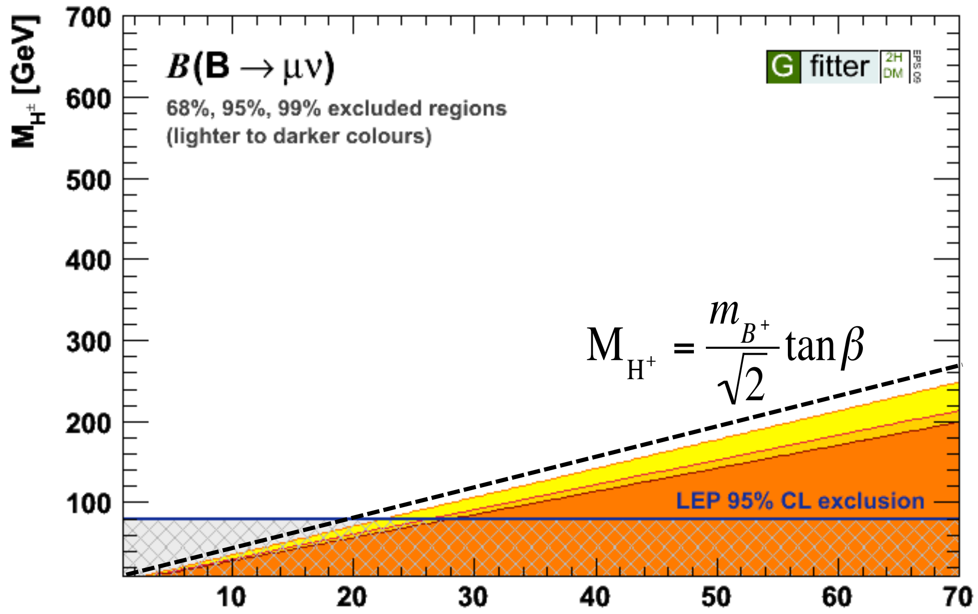


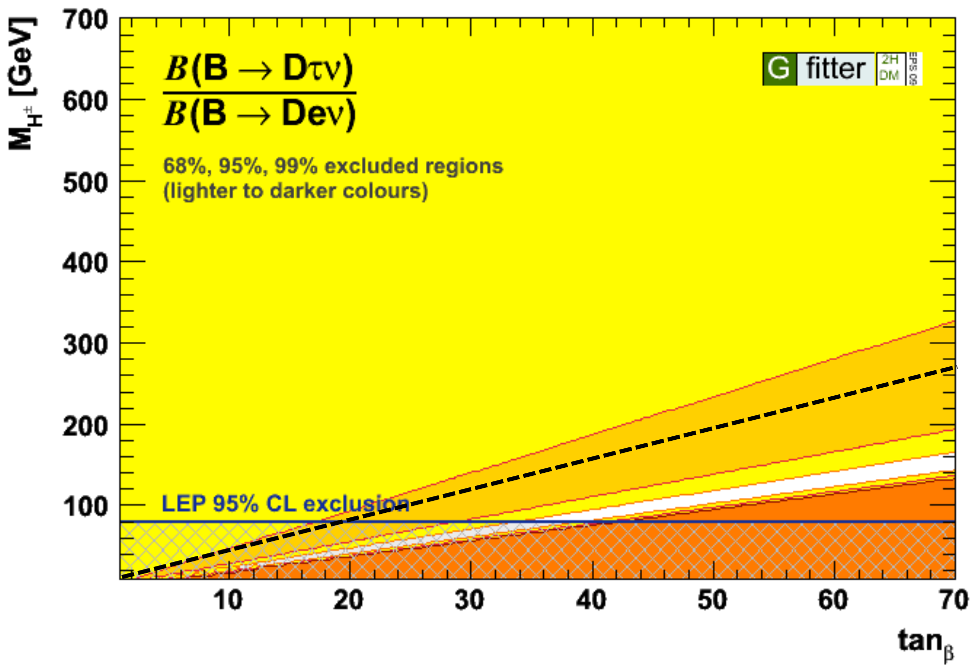
$$\frac{BR(B\to\tau\nu)_{2HDM}}{BR(B\to\tau\nu)_{SM}} = \left[1 - m_B^2 \frac{\tan^2\beta}{M_{H^\pm}^2}\right]^2$$

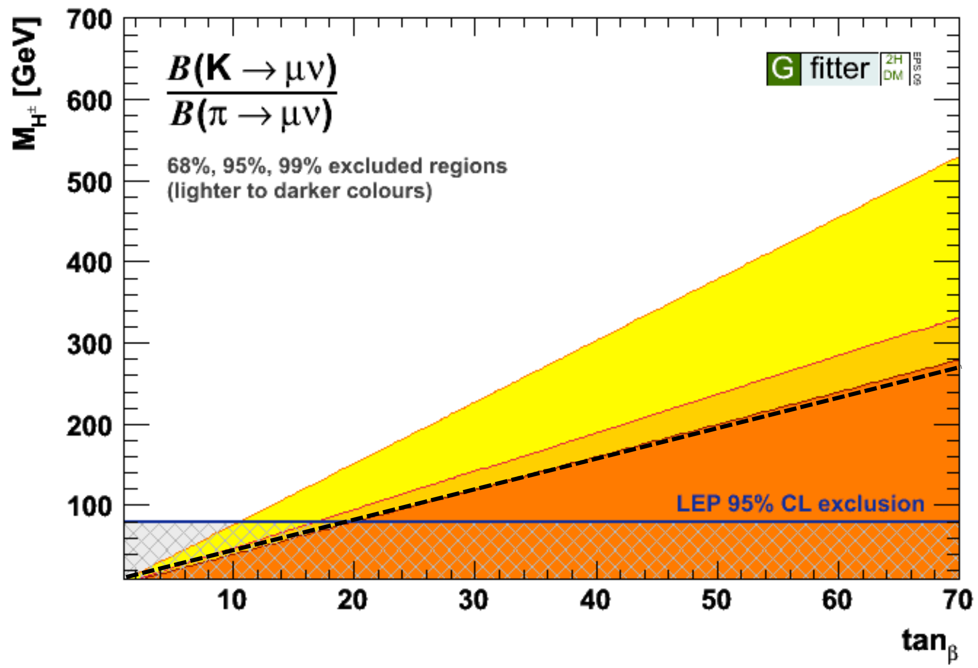


Other measurements w/ tree-level contributions

- Weak upper-limit on BR(B→μν)
- Favored solution of BR(B→τν) excluded by combination of:
  - BR(K→μν) / BR(π→μν)
  - BR(B→Dτν) / BR(B→Deν)
  - $B \to X_s\gamma$

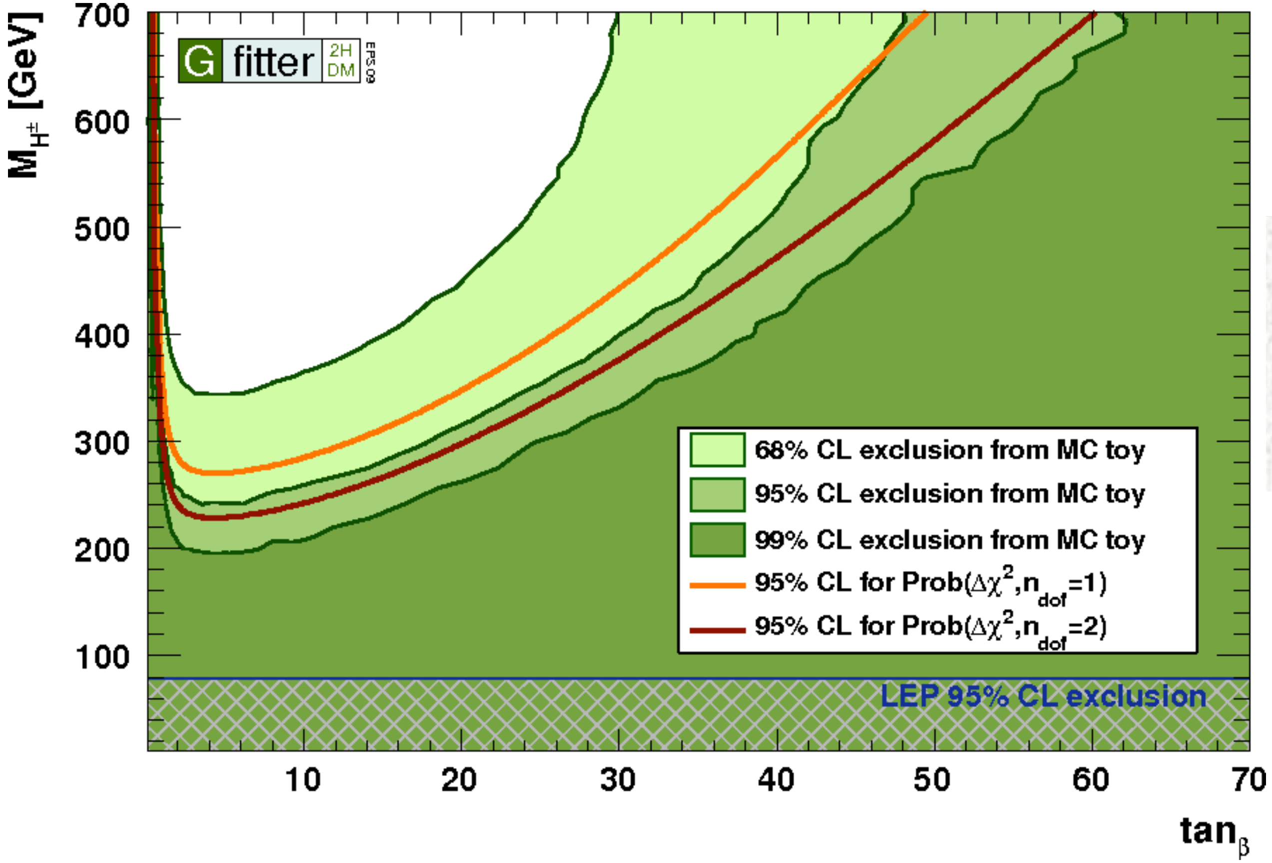






2HDM: Combined Fit

- Combined exclusion area depends on assumption on number of dof.
  - n_{dof}=1 : where single constraint dominates.
  - n_{dof}=2 : several observables contribute.
- MC toy study to resolve exclusion area
- [Combined limit not necessarily stronger than single constraint due to increasing n_{dof}]



- Excluded at 95% CL
  - Small $\tan\beta$
  - M_H < 240 GeV for all $\tan\beta$
  - M_H < 780 GeV for $\tan\beta$=70

Conclusion & Prospects

- Gfitter = powerful framework for involved HEP model fit problems
  - w/ advanced studies of statistical fit properties
- Results of SM electroweak fit
  - → See talk by Andreas Hoecker
  - No requirement for physics beyond SM (large p-value)
- Tests of New Physics models through oblique corrections
  - Constraints on Littlest Higgs model
- Constraints on Two-Higgs-Doublet Model (Type II)
  - Excluded @ 95% CL: $M_H < 240$ GeV for all $\tan\beta$

- Expect to see more NP models tested by Gfitter in near future!

- More information / all results at:
  - http://cern.ch/Gfitter
  - Continuous support & updates
  - Paper published in Eur. Phys. J. C 60, 543 (2009)

Gfitter

A Generic Fitter Project for HEP Model Testing

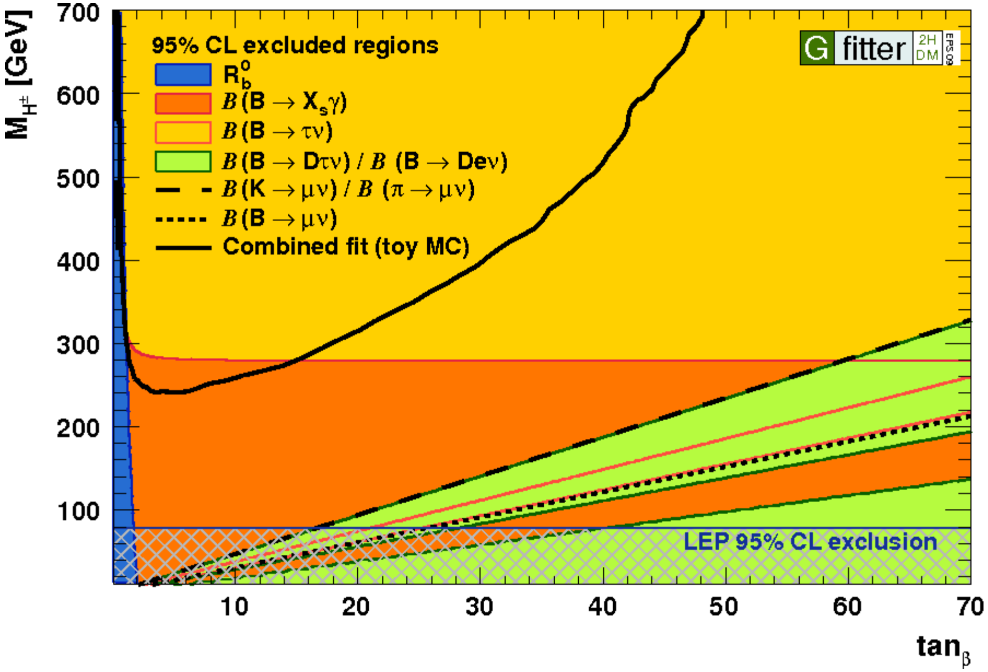
Backup

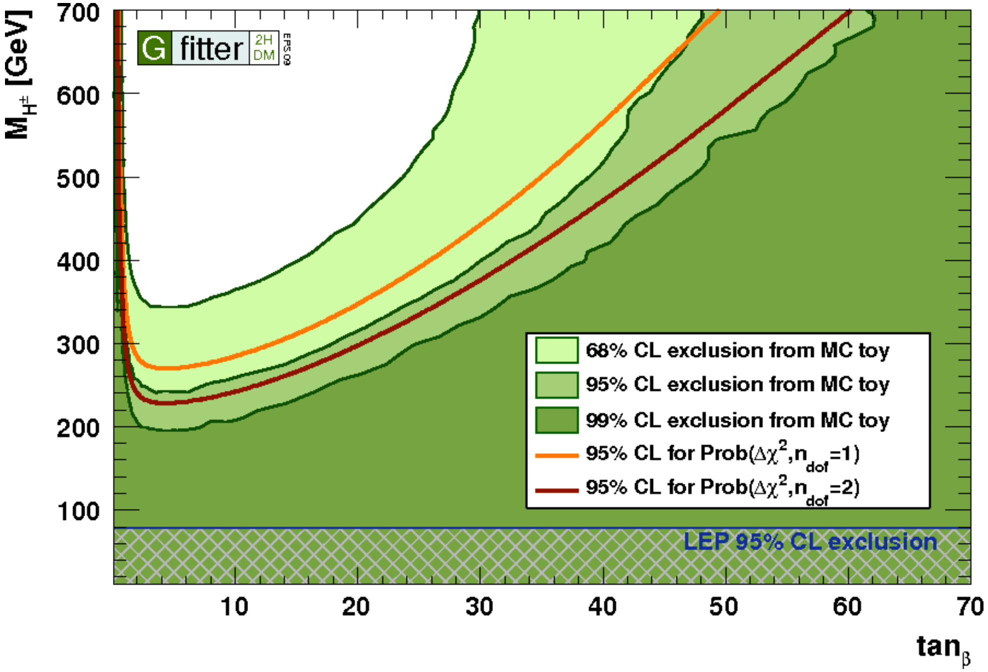
2HDM: Combined Fit

- Below: overlay of individual 95% CL excluded regions
  - Assuming n_{dof}=1 and 2-sided limits
- Combined exclusion area depends on assumption on number of dof.
  - n_{dof}=1 : where single constraint dominates.
  - n_{dof}=2 : several observables contribute.

- MC toy study to resolve exclusion area
- [Combined limit not necessarily stronger than single constraint due to increasing n_{dof}]

- Excluded at 95% CL
  - Small tanβ
  - M_H < 240 GeV for all tanβ
  - M_H < 780 GeV for tanβ=70





The Electroweak Fit – Experimental Input

- Z-pole precision cross-section and asymmetry measuments from LEP / SLC(*):
  - M_Z, Γ_Z [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - Hadronic x-section at Z pole σ^0_{had}
  - Leptonic ratio R^0_l
  - Hadronic ratios R^0_c, R^0_b (*)
  - FB asymmetries $A_{FB}^{0,l,c,b}$ (f.s. angular distributions) (*)
  - LR asymmetries (*)
    - SLC A_l, A_c, A_b (IS polarization), LEP A_l (τ polarization)
  - FB charge asymmetry Q_{FB}
- M_H in complete fit: likelihood ratios from LEP/Tevatron
- M_W and Γ_W from LEP/Tevatron [ADLO,CFD+D0: arXiv:0811.4682]
- $\overline{m}_c$, $\overline{m}_b$ world averages [PDG, J. Phys. G33,1 (2006)]
- m_t latest Tevatron average [arXivx:0808.1089 [hep-ex]]
- $\Delta\alpha_{had}^{(5)}(M_Z^2)$ including α_S dependency [Hagiwara et al., PLB649,173,'07]
- Theoretical uncertainties
  - M_W (δM_W=4-6MeV), $\sin^2\theta^l_{eff}$ ($\delta\sin^2\theta^l_{eff}$ =$4.7\cdot 10^{-5}$)
- Floating fit parameters
  - M_Z, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\alpha_S(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$, m_t, M_H

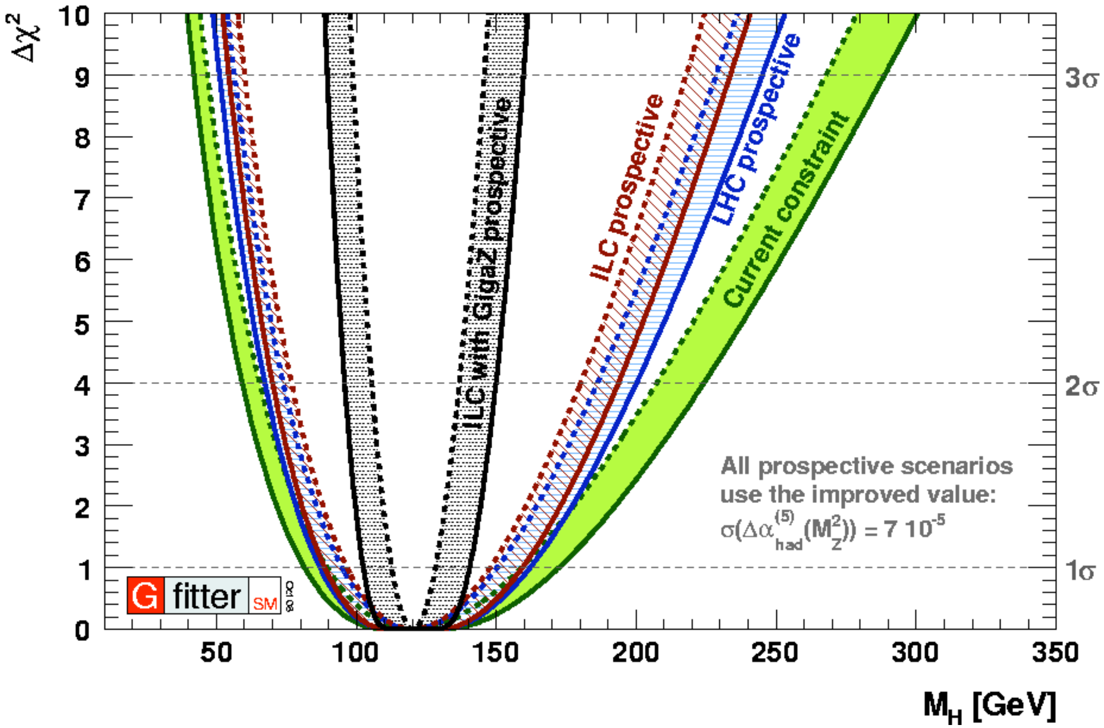
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010
A_ℓ $^{(\star)}$	0.1499 ± 0.0018
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 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] $^{(\circ)}$	Likelihood ratios
M_W [GeV]	80.399 ± 0.023
Γ_W [GeV]	2.098 ± 0.048
$\overline{m}_c$ [GeV]	1.25 ± 0.09
$\overline{m}_b$ [GeV]	4.20 ± 0.07
m_t [GeV]	173.1 ± 1.3
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2768 ± 22
$\alpha_s(M_Z^2)$	–
$\delta_{\rm th}M_W$ [MeV]	$[-4, 4]_{\rm theo}$
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$
$\delta_{\rm th}\rho^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$
$\delta_{\rm th}\kappa^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$

† in units of 10^{-5}

Prospects for LHC and ILC

- LHC, ILC (+GigaZ)*
  - Exp. improvement on M_W, m_t, $\sin^2\theta^l_{eff}$, R_l^0
  - In addition improved $\Delta\alpha_{had}^{(5)}(M_Z^2)$
    [F. Jegerlehner, hep-ph/0105283]

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
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	17	17	17	1.3
R^0_ℓ $[10^{-2}]$	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

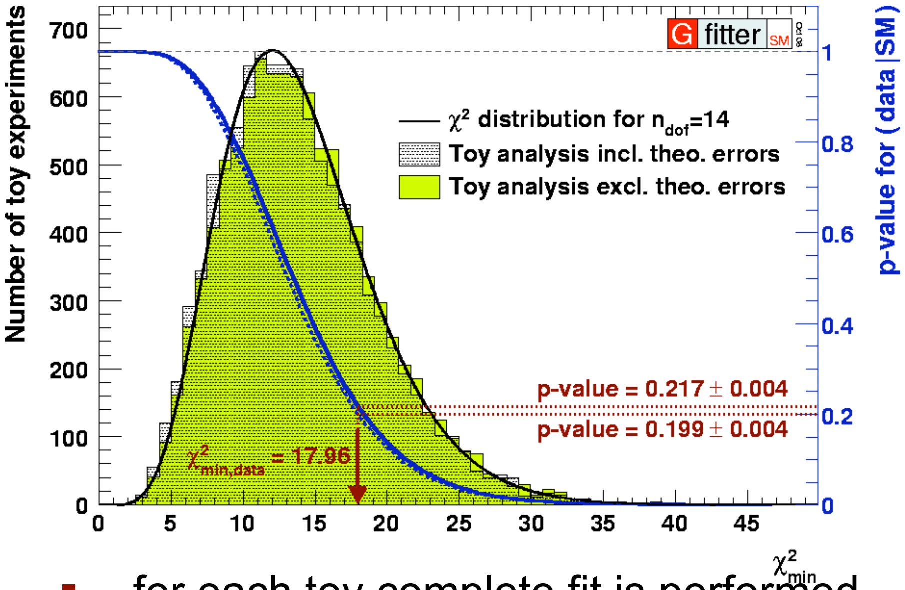


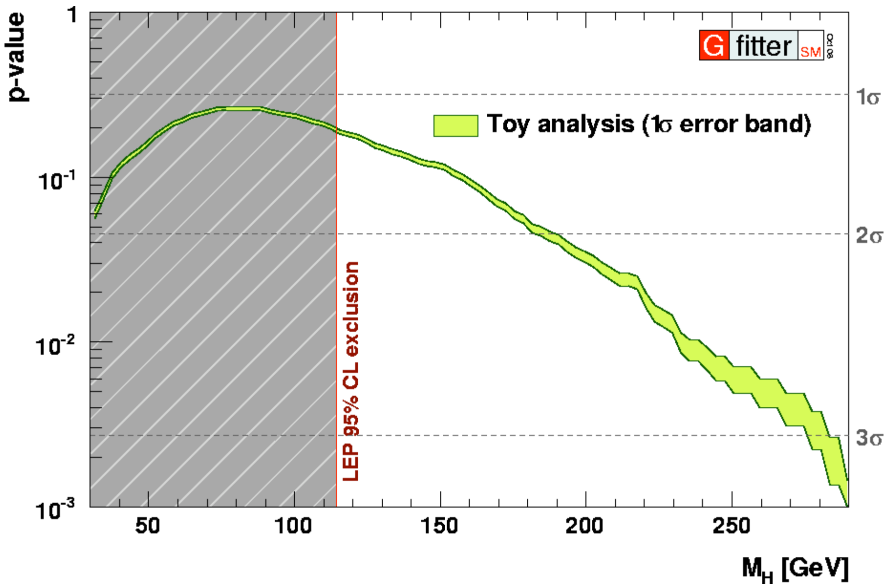
- Assume M_H=120 GeV by adjusting central values of observables
- Improvement of M_H prediction
  - to be confronted with direct measurement → goodness-of-fit
  - Broad minima: Rfit treatment of theo. uncertainties
- GigaZ: significant improvement for M_H and $\alpha_S(M_Z^2)$

*[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]

Goodness of Global Fit

- determine p-value by using MC toy experiments
  - p-value: probability for wrongly rejecting the SM
  - p-value: probability for getting a $\chi^2_{min,toy}$ larger than the $\chi^2_{min,data}$ from data





- for each toy complete fit is performed
- p-value = $(21.7 \pm 0.4_{-0.2})$%
  - no significant requirement for new physics

- derivation of p-value for standard fit as function of M_H
- small p-values for large Higgs masses (M_H~250 GeV)

- usually unable to indicate signals for physics beyond SM
  - sensitive observables mixed with insensitive ones