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

Rencontres de Moriond ElectroWeak
La Thuile, 13th-20th March 2011

Gfitter

http://cern.ch/Gfitter

Global ElectroWeak fit of Standard Model and Beyond with Gfitter

(*) M. Baak, M. Goebel, J. Haller, A. Höcker, D. Ludwig, K. Mönig, M. Schott, J. Stelzer

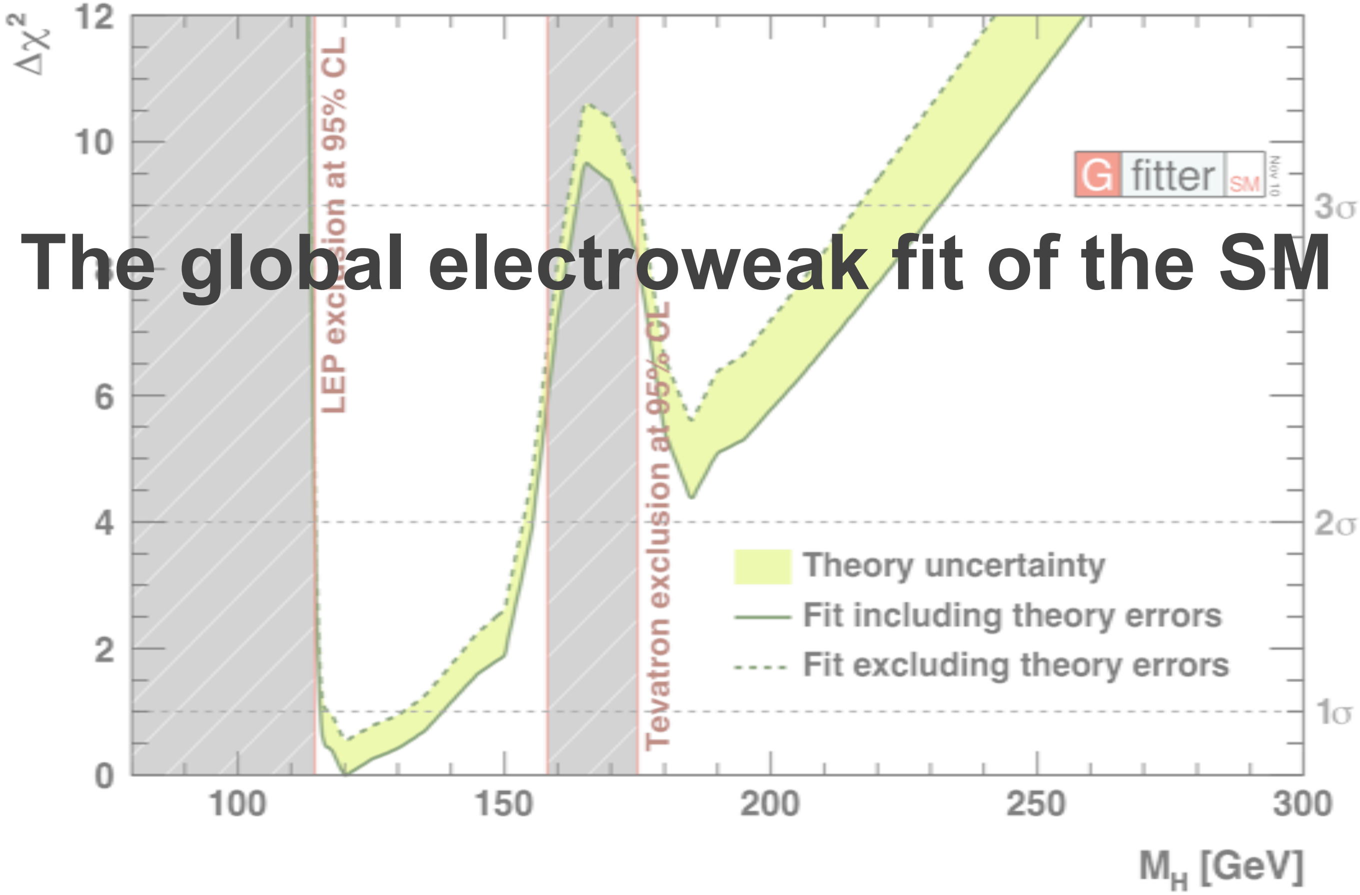
The Gfitter Project – Introduction

Gfitter

A Generic Fitter Project for HEP Model Testing

- Gfitter = state-of-the-art HEP model testing tool for LHC era
- Gfitter software and features:
  - Modular, object-oriented C++, relying on ROOT, XML, python, RooWorkspaces.
  - Core package with data-handling, fitting, and statistics tools
    - Various fitting tools: Minuit (1/2), Genetic Algorithms, Simulated Annealing, etc.
    - Consistent treatment of statistical, systematic, theoretical uncertainties (Rfit prescription), correlations, and inter-parameter dependencies.
      - » Theoretical uncertainties included in χ^2 with flat likelihood in allowed ranges
    - Full statistics analysis: goodness-of-fit, p-values, parameter scans, MC analyses.
  - Independent physics “plug-in” libraries: SM, 2HDM, oblique parameters, SUSY, ...
- Main publication: EPJ C60, 543-583, 2009 [arXiv:0811.0009]
  - Updates and new results available at: www.cern.ch/Gfitter

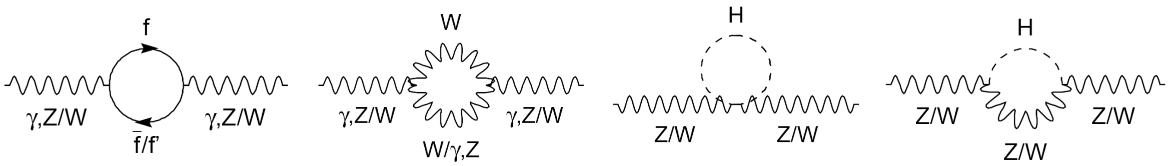
- Today: latest global electroweak fit, BSM constraints from oblique corrections

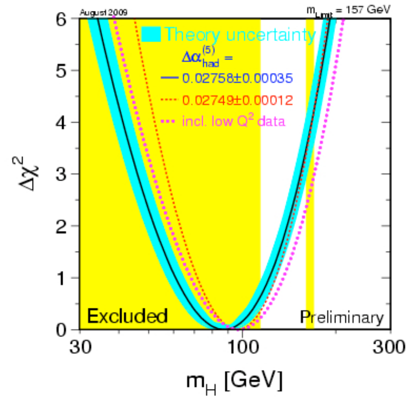


The global electroweak fit of the SM

The global electroweak fit with Gfitter

- A Gfitter package for the global EW fit of the SM
  - New implementation of SM predictions of EW precision observables
  - Based on huge amount of pioneering work by many people (ZFITTER)
  - Radiative corrections are important
    - Logarithmic dependence on M_H through virtual corrections





- State-of-the art calculations; in particular:
  - Radiator functions: N^{3}LO of the massless QCD Adler function, used for Z and W hadronic decay widths
    [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.]
    - Theoretical uncertainties: M_W (δM_W=4-6MeV), $\sin^2\theta^l_{eff}$ ($\delta\sin^2\theta^l_{eff}$ =$4.7\cdot10^{-5}$)
  - 2-loop EW form-factors: taken and adapted from ZFITTER
    [A.B. Abruzov et al., Comput. Phys. Commun. 174 (2006) 728-758]

- Wherever possible, calculations thoroughly cross-checked against ZFITTER → excellent agreement

Electroweak fit – Experimental input

- **Free fit parameters:**
  - M_Z, M_H, m_t, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\alpha_S(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$
    - Scale parameters for theoretical uncertainties on M_W, $\sin^2\theta^l_{eff}$ (and the EW form factors ρ_Z^f, κ_Z^f)

- **Latest experimental input:**
  - Z-pole observables: LEP / SLC results
    [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - M_W and Γ_W latest from LEP/Tevatron (03/2010)
    [ADLO,CFD+D0: arXiv:0908.1374v1]
  - m_{top} : latest Tevatron average (07/2010)
    [CDF&D0: new combination ICHEP'10]
  - m_c, m_b world averages
    [PDG, J. Phys. G33,1 (2006)]
  - $\Delta\alpha_{had}^{(5)}(M_Z^2)$ including α_S dependency (10/2010)
    [Davier et al., arXiv:1010.4180]
  - Direct Higgs searches from LEP/Tevatron/LHC (03/2011)
    [ADLO: Phys. Lett. B565, 61 (2003)], [CDF+D0: Moriond 2011][ATLAS+CMS: Moriond 2011]

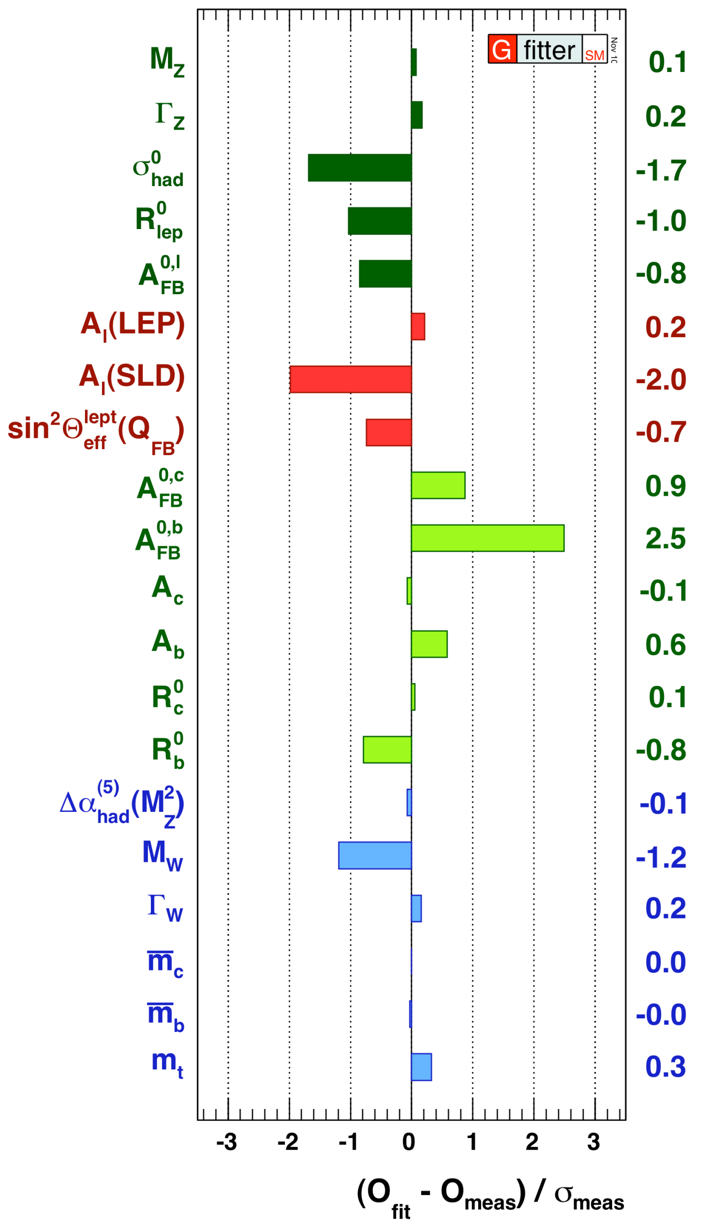
New!

- Not considered: $\sin^2\theta_{eff}$ results from NuTeV (uncertainties from NLO and nucl. effects of bound nucleon PDF) and APV and polarized Möller scattering (exp. accuracy too low)

M_Z [GeV]	91.1875 ± 0.0021	LEP & SLC
Γ_Z [GeV]	2.4952 ± 0.0023	LEP & SLC
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP & SLC
R^0_ℓ	20.767 ± 0.025	LEP & SLC
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP & SLC
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP & SLC
A_c	0.670 ± 0.027	LEP & SLC
A_b	0.923 ± 0.020	LEP & SLC
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP & SLC
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP & SLC
R^0_c	0.1721 ± 0.0030	LEP & SLC
R^0_b	0.21629 ± 0.00066	LEP & SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP & SLC
M_H [GeV] $^{(\circ)}$	Likelihood ratios	LEP & Tevatron & LHC
M_W [GeV]	80.399 ± 0.023	LEP & Tevatron
Γ_W [GeV]	2.085 ± 0.042	LEP & Tevatron
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.3 ± 1.1	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2749 ± 10	
$\alpha_s(M_Z^2)$	$-$	

Electroweak Fit – SM Fit Results

Standard fit w/o direct Higgs searches



- **Pull values of complete fit**
  - No individual value exceeds 3σ
  - FB asymmetry of bottom quarks
    → largest contribution to χ^2
  - Small contributions from M_Z, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$
    - Input accuracies exceed fit requirements

- **Goodness of fit – naïve p-value:**
  - Excluding direct Higgs searches: χ^2_{min}=16.6
    → Prob(χ^2_{min}, 13) = 22 %
  - Consistent when including direct Higgs searches:
    → p-value = 25 ± 1_{-2} % (as obtained from toys)
  - No indication for new physics

- ***N^3LO α_S* from fit:**
  - $\alpha_s(M_Z^2)$ = 0.1193 ± 0.0028 ± 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 result N^3LO from τ decays

[Davier et al., EPJ C56, 305 (2008), arXiv:0803.0979]

Electroweak Fit – w/o direct Higgs searches

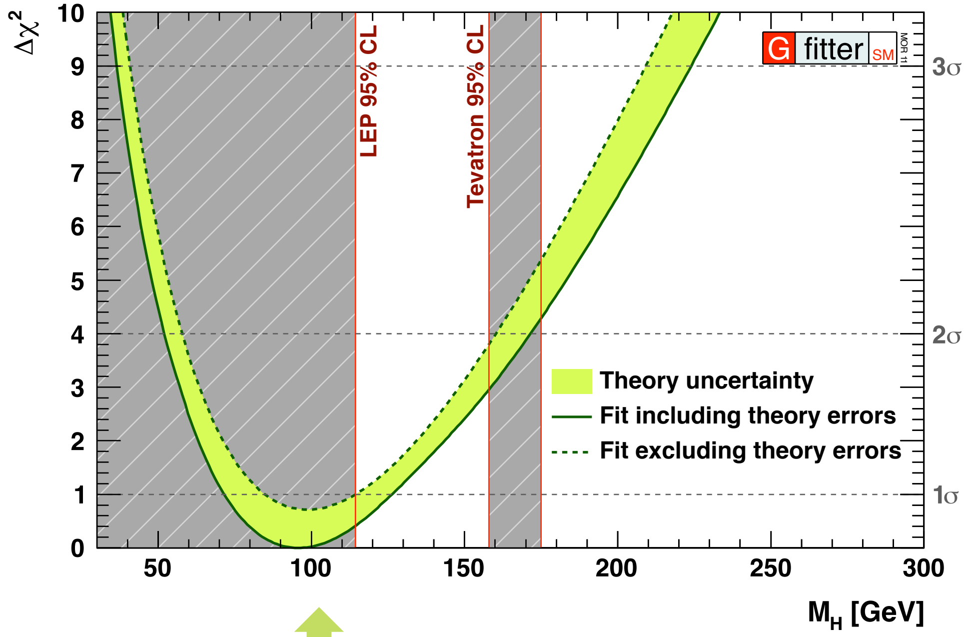
- M_H from fit w/o Higgs searches:
  - Central value ±1σ:

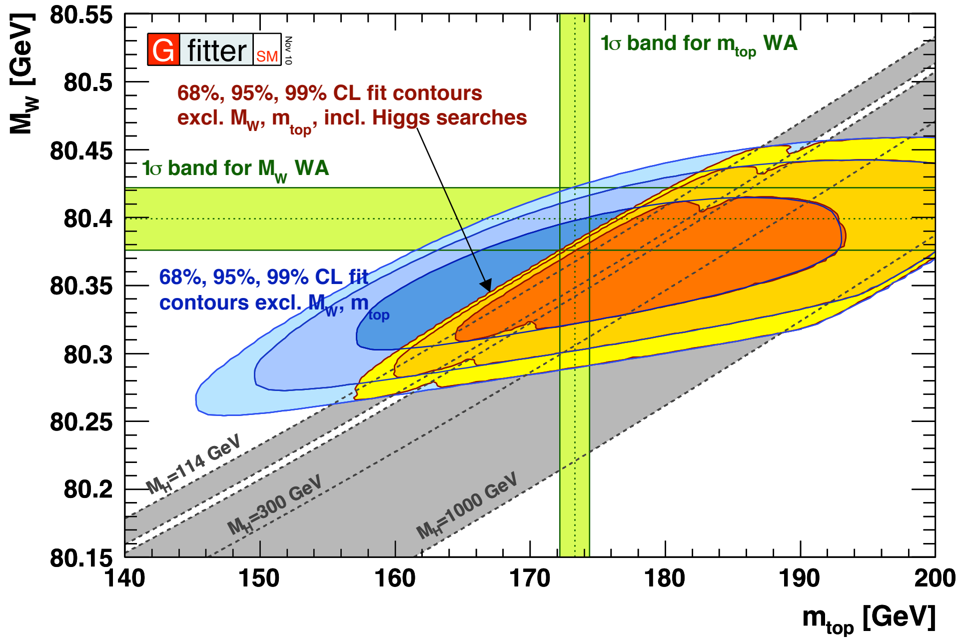
$$M_H = 95.7^{+30.3}_{-24.2}\ \text{GeV}$$

  - 2σ interval:

$$[52{,}171]\ \text{GeV}$$

- m_{top} vs M_W
  - Indirect results agree nicely with direct measurements.
  - Results from Higgs searches significantly reduces allowed indirect parameter space.
  - Illustrative probe of SM, if Higgs measured at LHC.

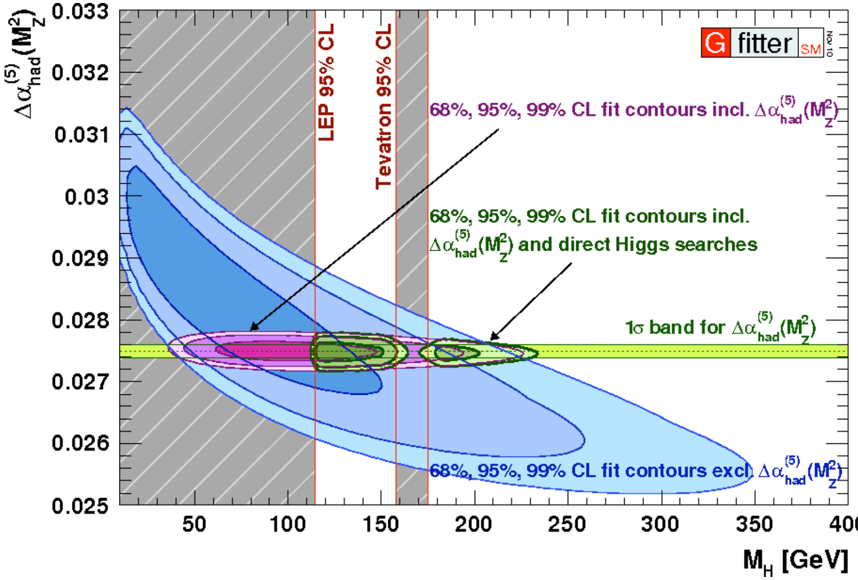


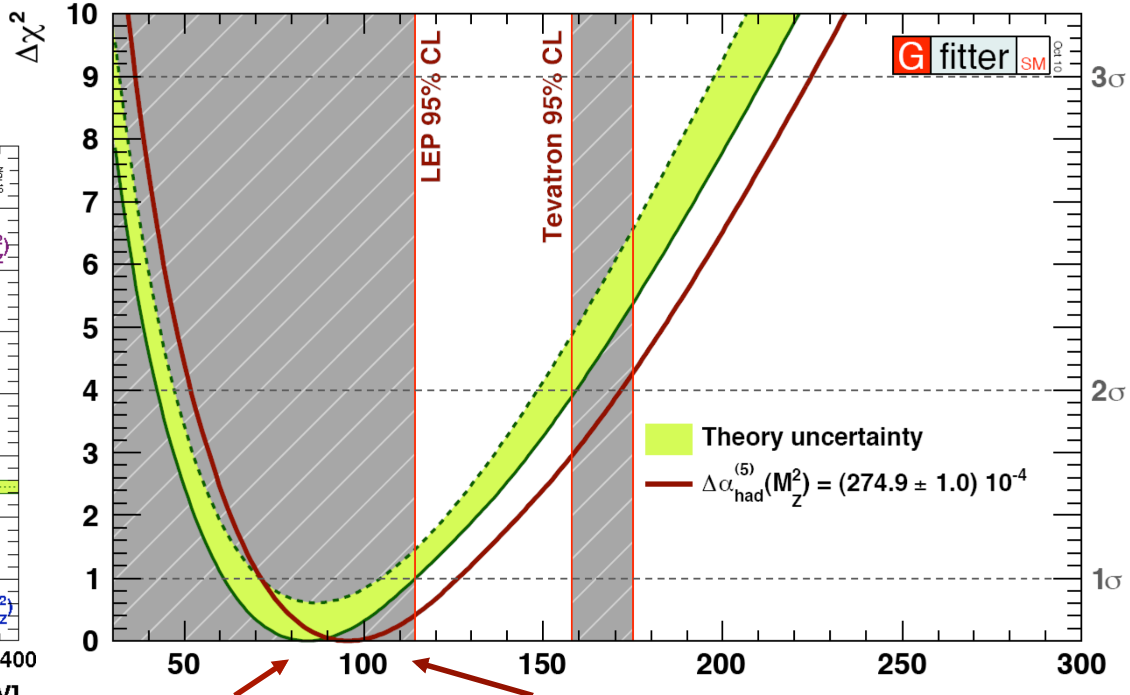


- Green error band from including / excluding theoretical errors in fit
  - Theoretical errors included in χ^2 with "flat likelihood term"

Electroweak fit – Impact of new $\Delta\alpha_{had}^{(5)}(M_Z^2)$

- We use latest value: $\Delta\alpha_{had}^{(5)}(M_Z) = (274.9 \pm 1.0)\cdot 10^{-4}$ [Davier et al., arXiv:1010.4180]
  - Includes (among others) new $\pi^+\pi^-$ and multi-hadron x-sections from BABAR
  - Value decreased compared with previous value: $\Delta\alpha_{had}^{(5)}(M_Z) = (276.8 \pm 2.2)\cdot 10^{-4}$ [Hagiwara et al., PLB B649, 173 (2007)]
- Increase of M_H by 12 GeV thanks to negative correlation (-39%)



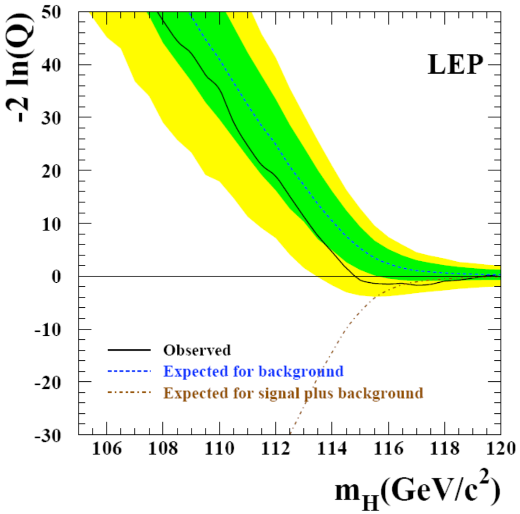


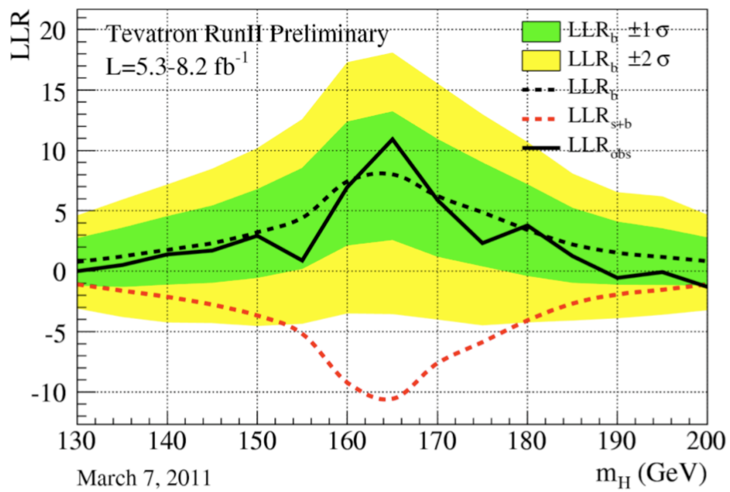
$M_H = 84^{+30}_{-23}$ GeV $\qquad M_H = 96^{+31}_{-24}$ GeV

- In comparison:
  - Preliminary value $(275.9\pm1.5)\cdot10^{-4}$ (Teubner at Tau2010): $M_H = 90^{+30}_{-24}$ GeV
  - LEP EW wg: $(275.8\pm3.5)\cdot10^{-4}$ (Burghardt & Pietrzyk, 2005): $M_H = 89^{+36}_{-26}$ GeV

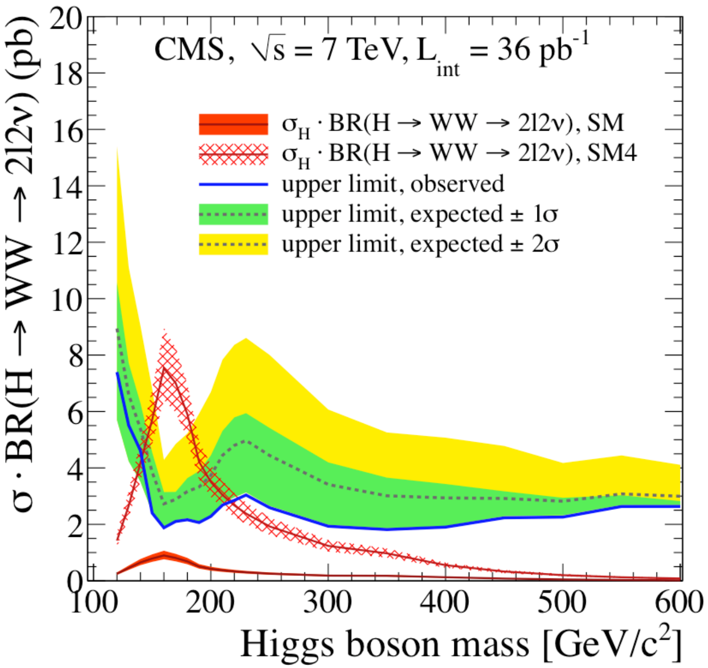
Electroweak fit – Experimental input

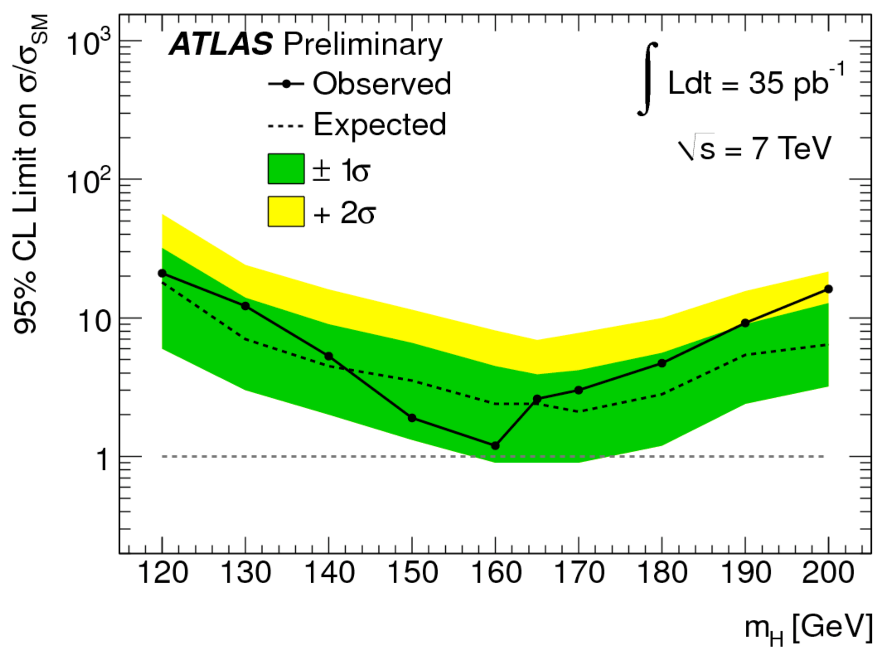
- **Direct Higgs searches**
  - LEP: Higgs-Strahlung
    [ADLO: Phys. Lett. B565, 61 (2003)]
    - ee → ZH (H→bb, ττ)
  - Tevatron: various channels
    gg fusion with H → WW,
    assoc. prod., VBF
    [FERMILAB-CONF-11-044-E]





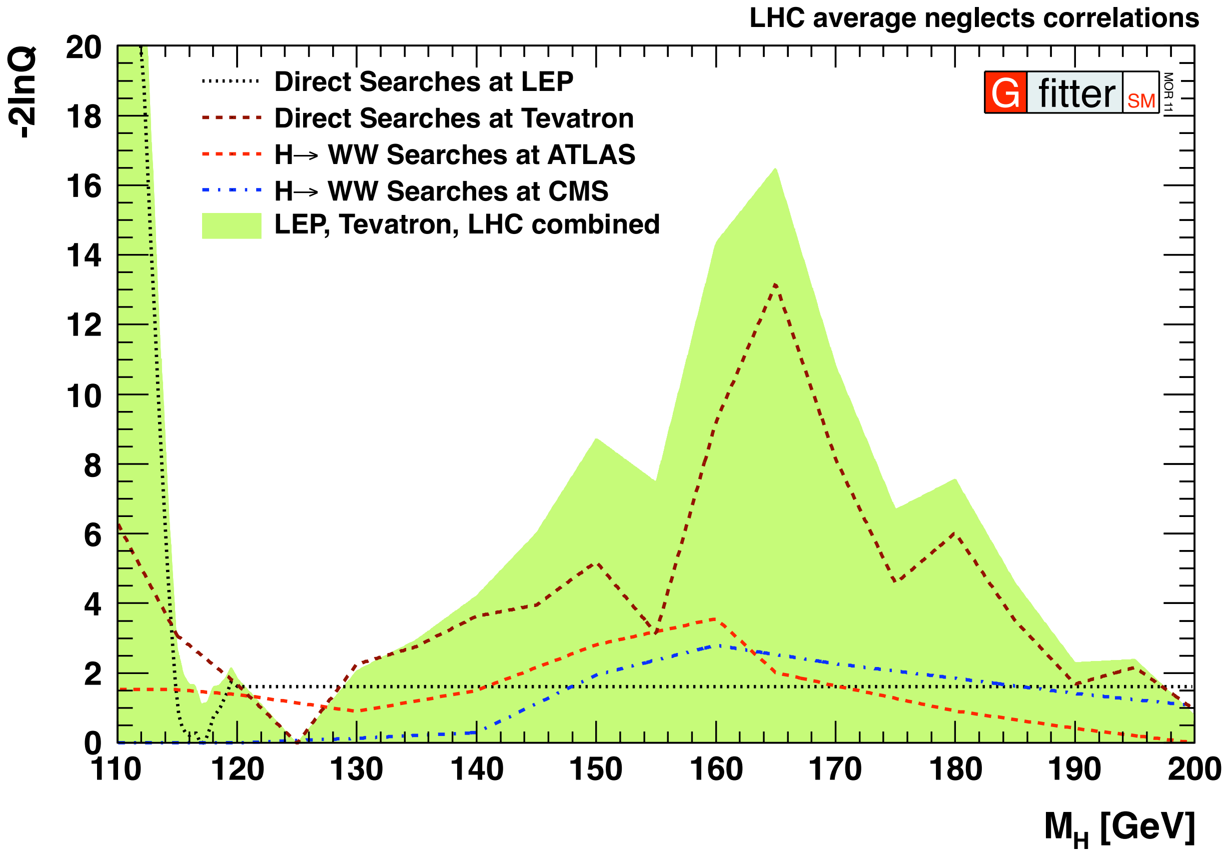
  - CMS & ATLAS: latest H→WW results, 35 and 36 /pb
    [CMS: arXiv:1102:5429] [ATLAS: ATLAS-CONF-2011-005]





Statistical interpretation direct Higgs searches

- Statistical interpretation
  - Experiments measure test statistic: $LLR = -2\ln Q$, where $Q = L_{S+B}/L_B$
  - Transformed by experiments into 1-sided upper limit ($CL_S = CL_{S+B}/CL_B$) using pseudo experiments
  - We transform 1-sided CL_{S+B} into 2-sided CL^{2s}_{S+B}
    - SM is null hypothesis. We measure both down- and up-ward deviations from SM !
  - χ^2 contribution calculated via inverse error function: $d\chi^2 = \mathrm{Erf}^{-1}(1-CL^{2s}_{S+B})$
- Alternative treatment, followed here:
  - χ^2 contribution is: $-2\ln Q$
  - Lacks statistical information from experiments.
  - No 2-sided interpretation
  - ATLAS CL_{S+B} not public ☹
- Note about combination of ATLAS and CMS H→WW results
  - Ignores correlations between x-section theory and luminosity uncertainties !
  - Tevatron/LHC combination procedure needed; ATLAS/CMS expected this summer.



Electroweak Fit – with direct Higgs searches

- LEP + Tevatron (Fall 2010) :
  - CL_{s+b}^{2s} central value ±1σ: $M_H = 120.2^{+17.9}_{-5.2}$ GeV
  - 2σ interval:

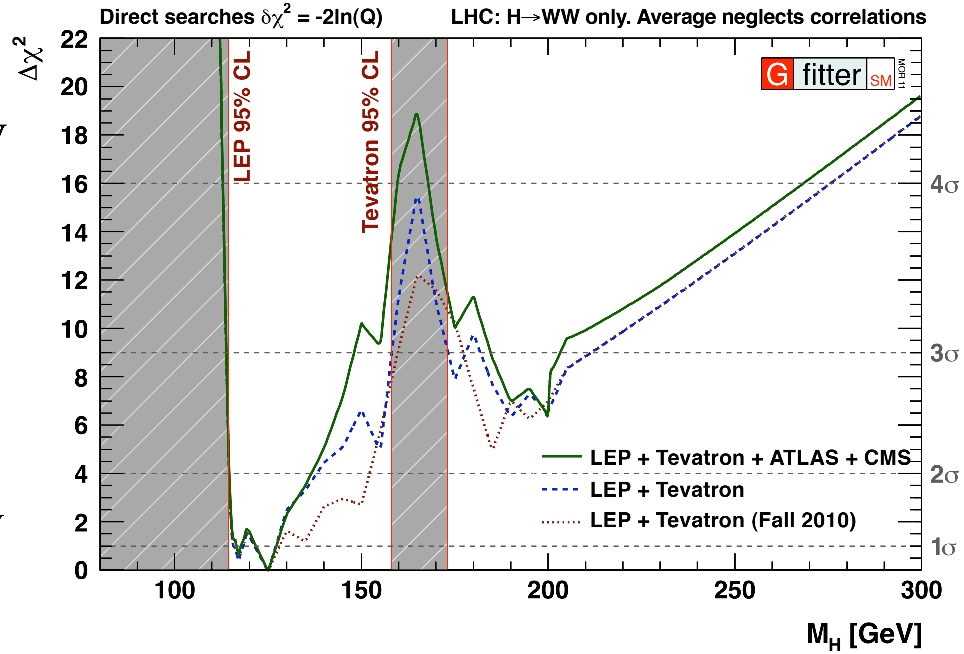
$$-2\ln Q: \quad [115,152]\ \text{GeV}$$
$$CL_{s+b}^{2-sided}: \quad [114,155]\ \text{GeV}$$

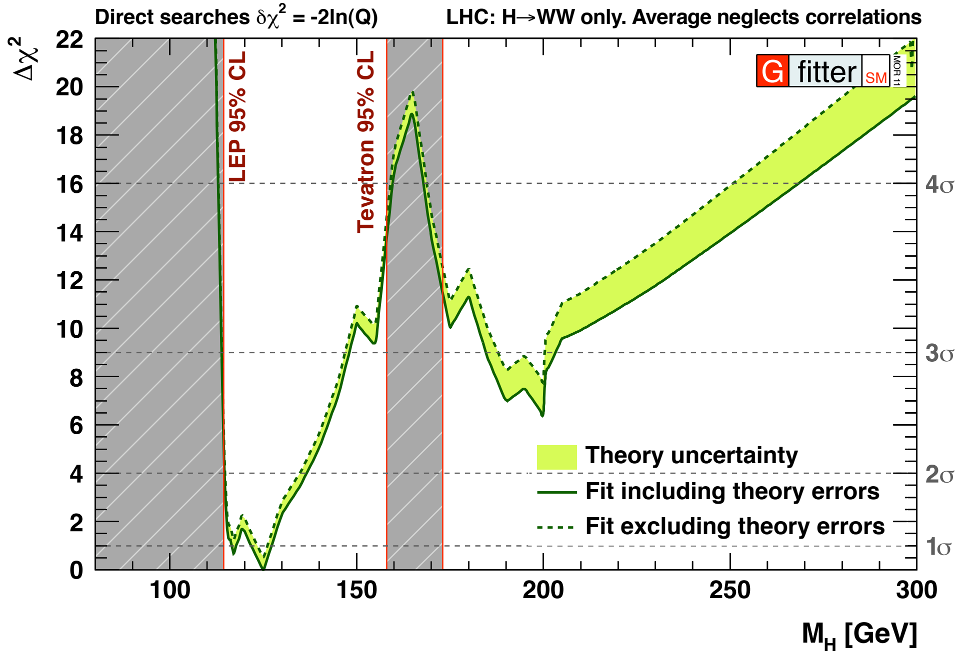
- LEP + Tevatron (Moriond 2011) :
  - CL_{s+b}^{2s} central value ±1σ: $M_H = 120.2^{+12.3}_{-4.7}$ GeV
  - 2σ interval:

$$-2\ln Q: \quad [115,138]\ \text{GeV}$$
$$CL_{s+b}^{2-sided}: \quad [114,149] \cup [152,155]\ \text{GeV}$$

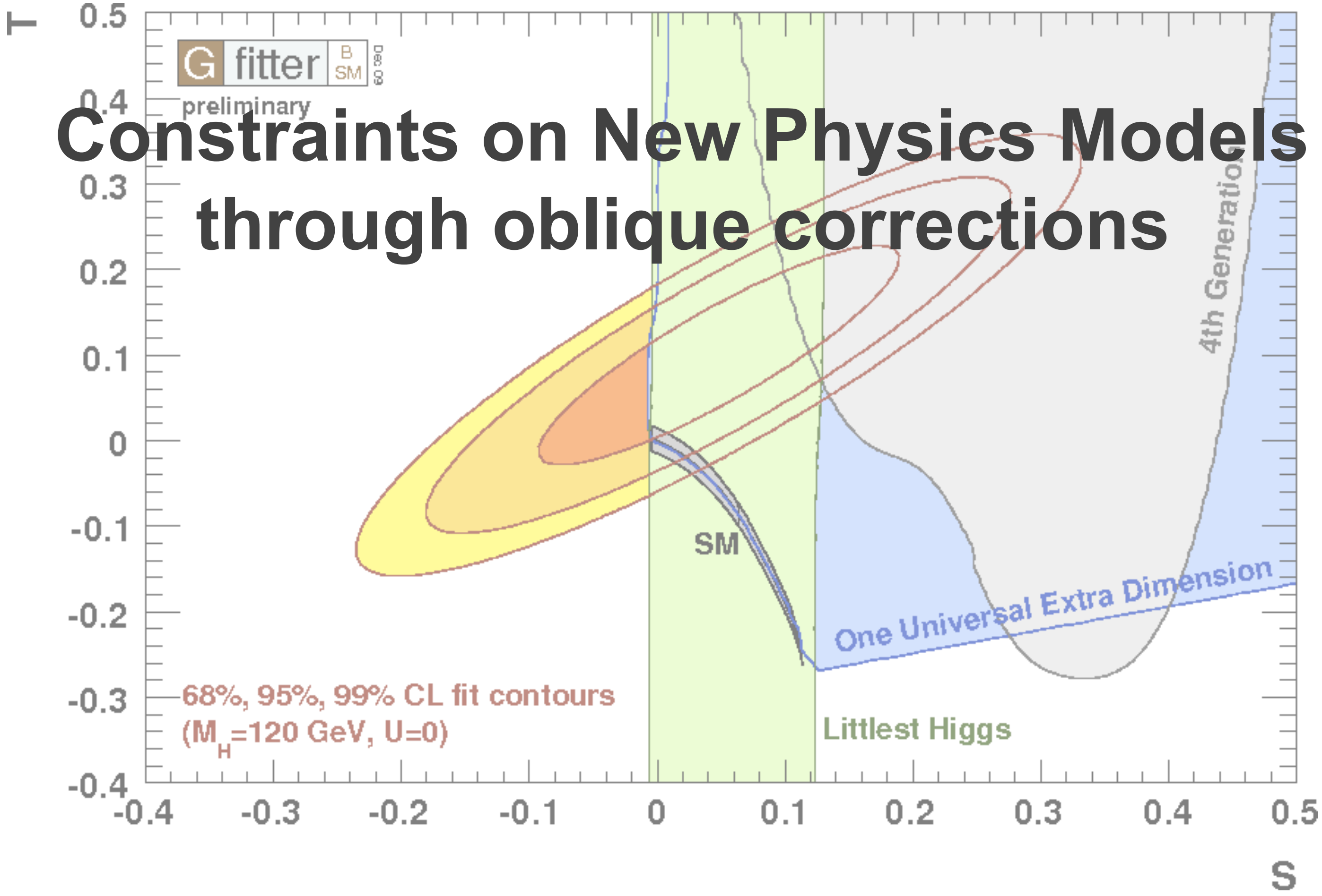
- Fit with LEP + Tevatron + LHC (H➔WW) searches (Moriond 2011) :
  - Central value unchanged
  - 2σ interval:

$$-2\ln Q: \quad [115,137]\ \text{GeV}$$
$$CL_{s+b}^{2-sided}: \quad [114,14?]\ \text{GeV}$$



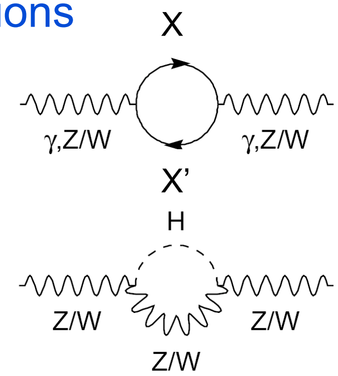


Constraints on New Physics Models through oblique corrections



A Gfitter package for Oblique Corrections

- At low energies, BSM physics appears dominantly through vacuum polarization corrections
  - Aka, "oblique corrections"
- Oblique corrections reabsorbed into electroweak parameters
  - $\Delta\rho$, $\Delta\kappa$, Δr 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 weak 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 obtained from fit to EW observables

- Results for STU:

$S = 0.02 \pm 0.11$

$T = 0.05 \pm 0.12$

$U = 0.07 \pm 0.12$

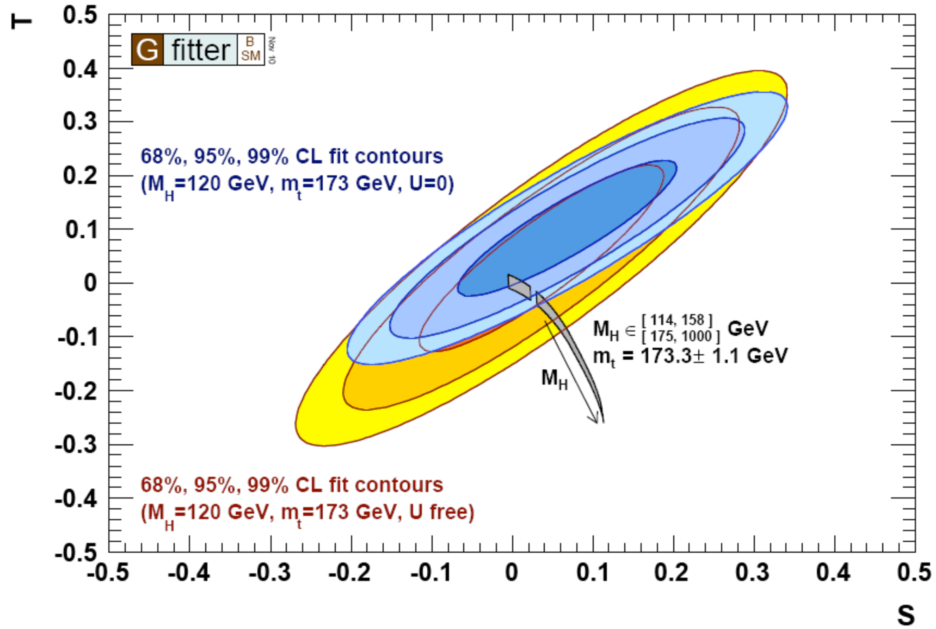
	S	*T*	*U*
S	1	0.879	-0.469
T		1	-0.716
U			1

- Dark grey area: SM prediction
  - SM_{ref} chosen at: M_H = 120 GeV and m_t = 173.1 GeV
  - This defines (S,T,U) = (0,0,0)

- S, T: logarithmically dependent on M_H

- Comparison of EW data w/ SM prediction:
  - Preference for small M_H
  - No indication for new physics

Blue: U=0 , yellow: U=free



Fit to Oblique Parameters

- S,T,U obtained from fit to EW observables

- Results for STU:

  S = 0.02 ± 0.11

  T = 0.05 ± 0.12

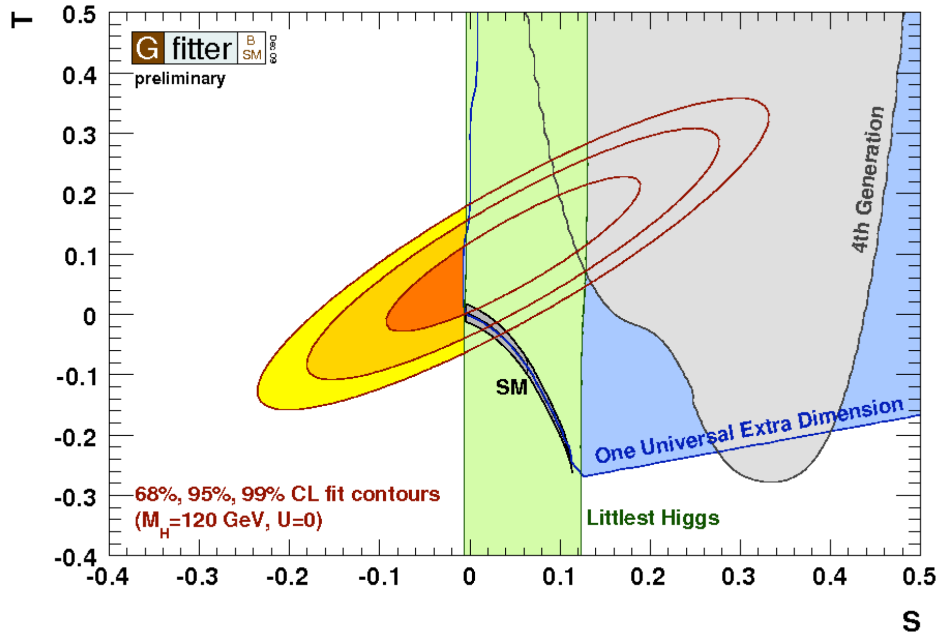
  U = 0.07 ± 0.12

	S	*T*	*U*
S	1	0.879	-0.469
T		1	-0.716
U			1

- Dark grey area: SM prediction
  - SM_{ref} chosen at: M_H = 120 GeV and m_t = 173.1 GeV
  - This defines (S,T,U) = (0,0,0)

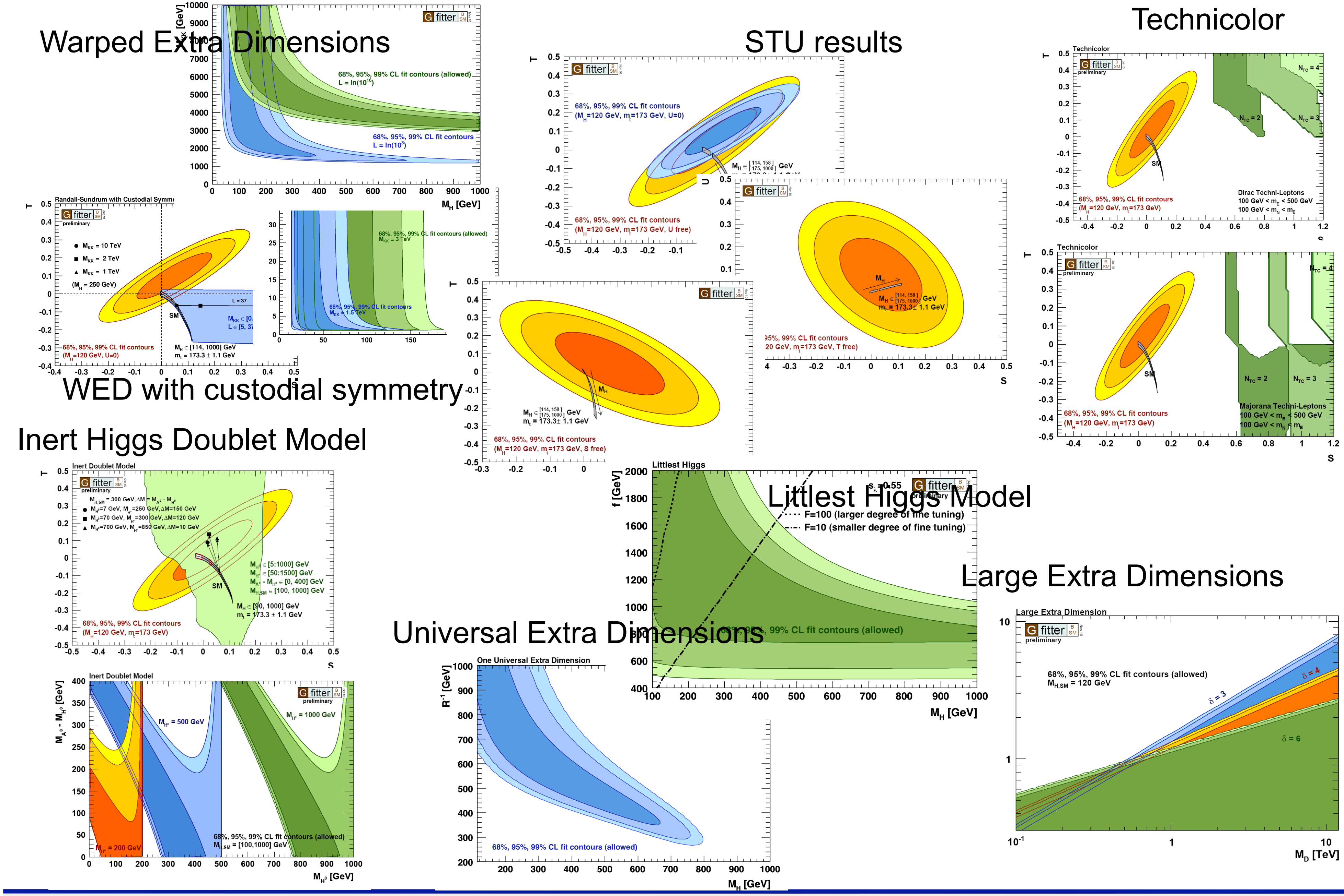
- S, T: logarithmically dependent on M_H

- Comparison of EW data w/ SM prediction:
  - Preference for small M_H
  - No indication for new physics



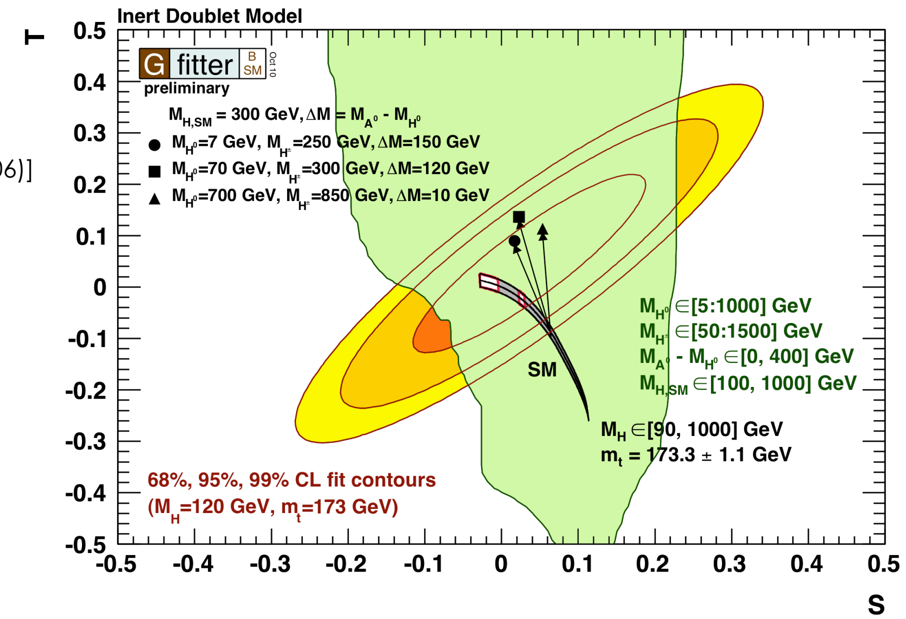
- Many new physics models also compatible with the EW data:
  - Variation of model parameters often allows for large area in ST-plane.
  - Tested: UED, 4[th] fermion generation, Littlest Higgs, SUSY, etc.

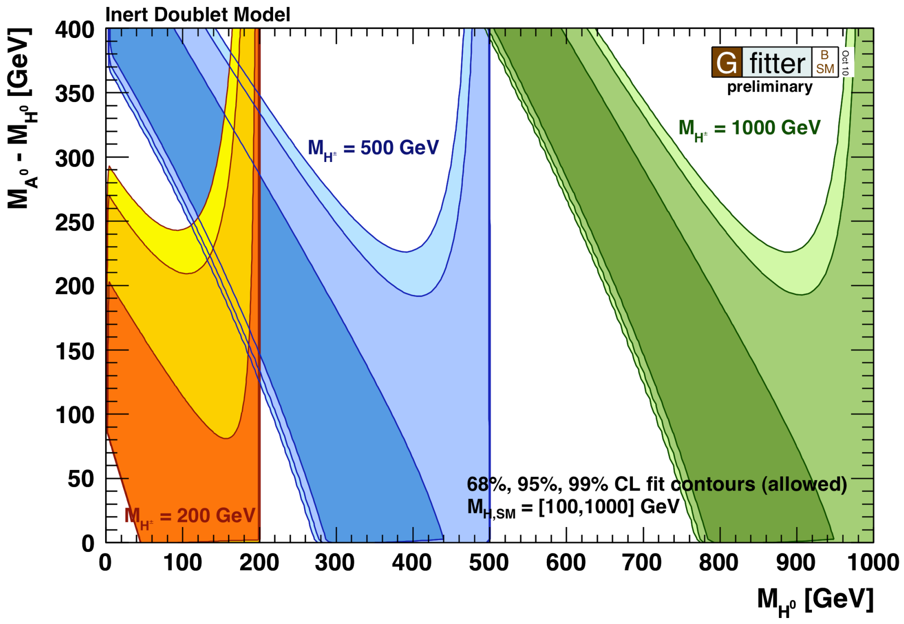
Many BSM theories can be tested …



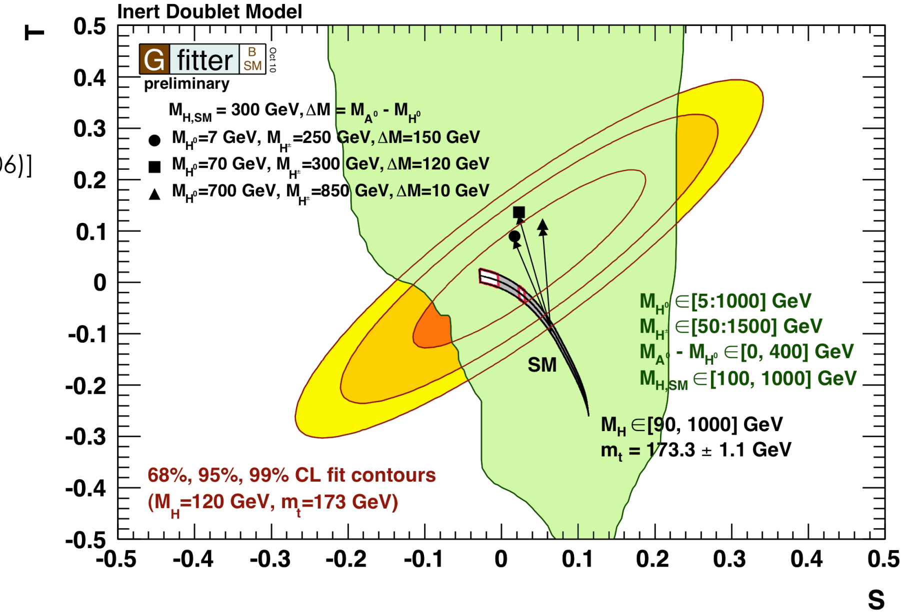
Inert Higgs Doublet Model

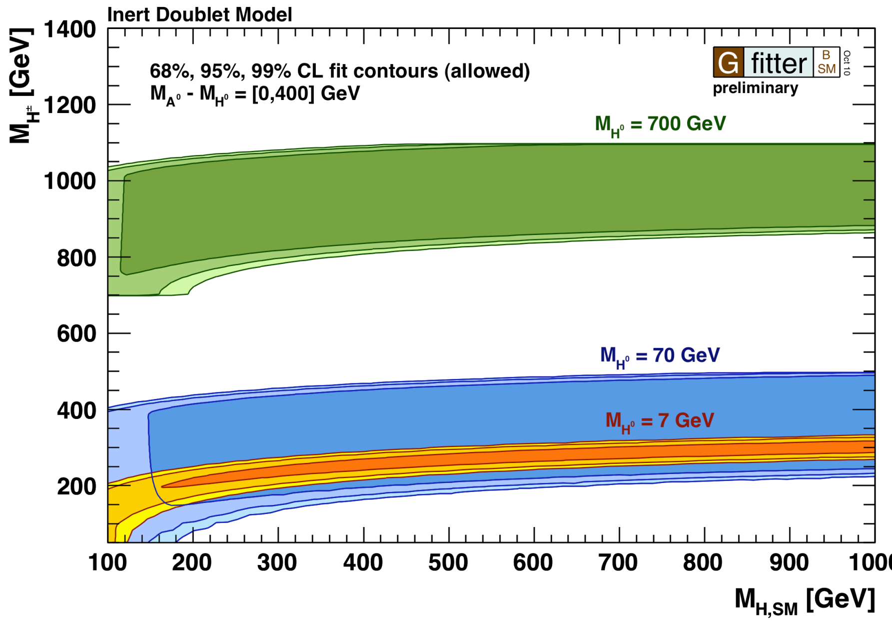
- IDM: introduction of extra Higgs doublet to help solve hierarchy problem [Barbieri et al., hep-ph/0603188v2 (2006)]
  - Doublet does not couple to fermions ("inert"). Does not acquire a VEV.
- Three new Higgses
  - Two neutral (M_H, M_A), one charged (M_{H+}).
- Lightest inert particle ("LIP") is stable (M_L), assumed neutral.
  - Natural dark matter candidate
- Contributions to:
  - T: isospin violation between neutral and charged Higgses.
  - S: H^+H^- and HA loop corrections to self energy of Z-photon propagator
- Results: large SM Higgs mass allowed.





- IDM: introduction of extra Higgs doublet to help solve hierarchy problem [Barbieri et al., hep-ph/0603188v2 (2006)]
  - Does not couple to fermions ("inert"). Does not acquire a VEV.
- Three new Higgses
  - Two neutral (M_H, M_A), one charged (M_{H+}).
- Lightest inert particle ("LIP") is stable (M_L), assumed neutral.
  - Natural dark matter candidate
- Contributions to:
  - T: isospin violation between neutral and charged Higgses.
  - S: H^+H^- and HA loop corrections to self energy of Z-photon propagator
- Results: large SM Higgs mass allowed.

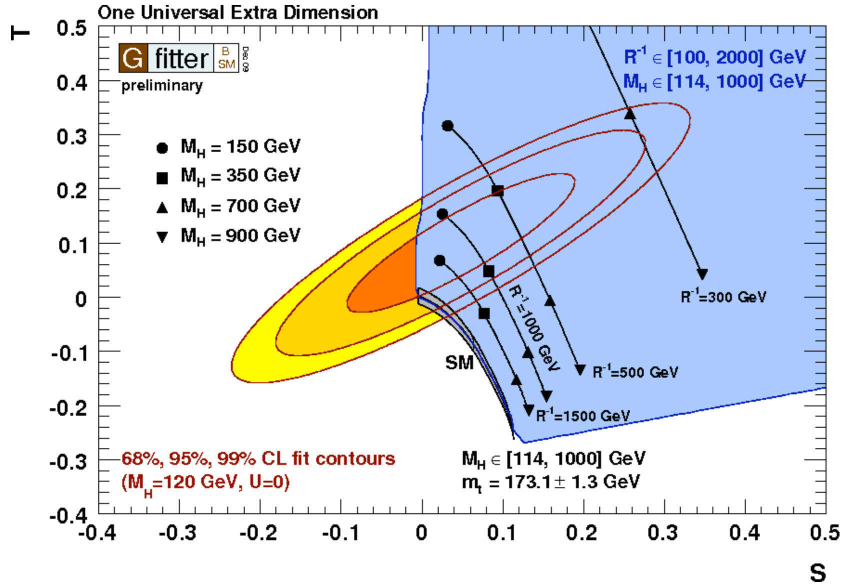




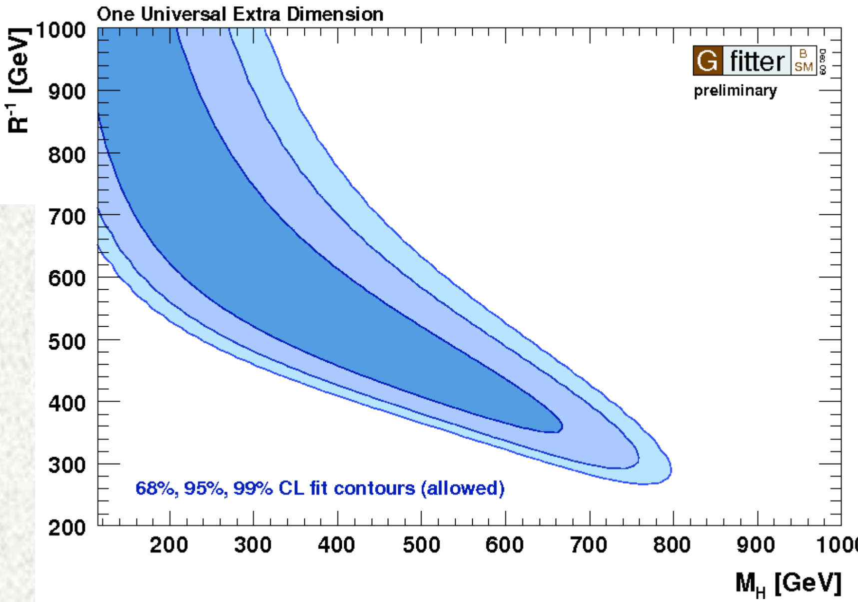
Universal Extra Dimensions

[Appelquist et al., Phys. Rev. D67 055002 (2003)] [Gogoladze et al., Phys. Rev. D74 093012 (2006)]

- UED:
  - All SM particles can propagate into ED
  - Compactification → KK excitations
  - Conservation of KK parity
    - Phenomenology similar to SUSY
    - Lightest stable KK state: DM candidate
  - Model parameters:
    - d_{ED}: number of ED (fixed to d_{ED}=1)
    - R^{-1}: compactification scale (m_{KK}~n/R)



- Contribution to vac. polarisation (*STU*):
  - From KK-top/bottom and KK-Higgs loops
  - Dependent on R^{-1}, M_H (and m_t)

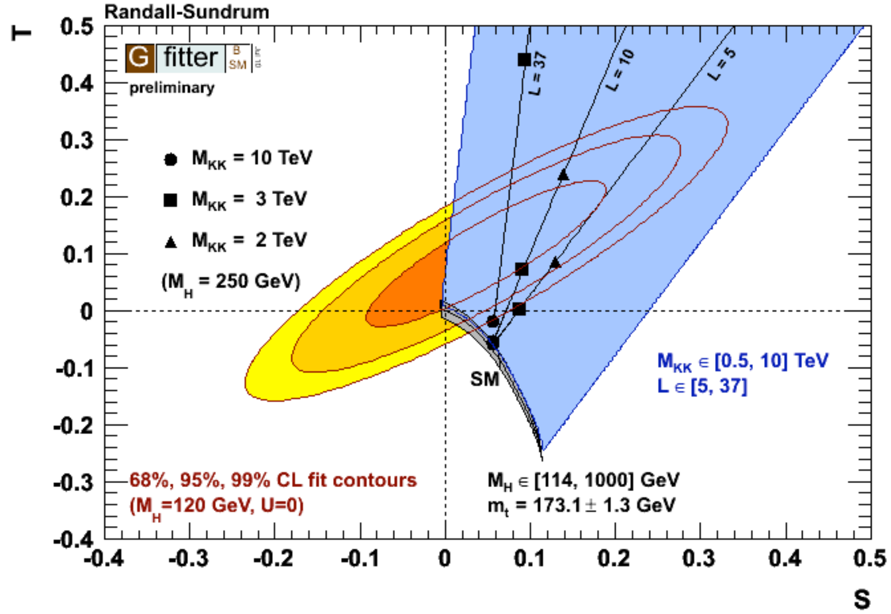


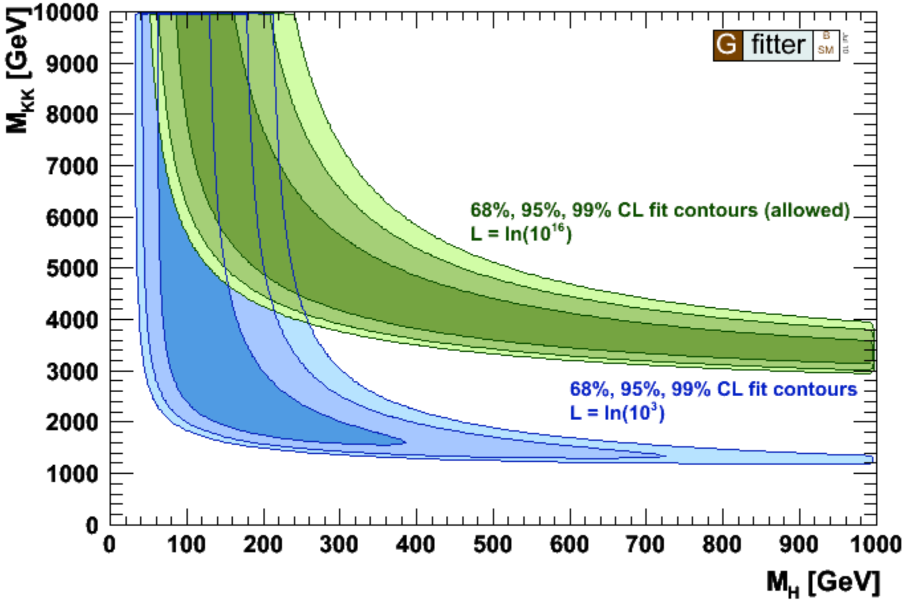
- Results:
  - Large R^{-1}: UED approaches SM (exp.)
    - Only small M_H allowed
  - Small R^{-1}: large UED contribution can be compensated by large M_H
  - Excluded: R^{-1}< 300 GeV and M_H > 800 GeV

Warped Extra Dimensions (Randall-Sundrum)

[L. Randall, R. Sundrum, Phys. Rev. Lett. 83, 3370 (1999)] [M. Carena et al., Phys. Rev. D68, 035010 (2003)]

- Introduction of one extra dimension (ED) to help solve the hierarchy problem
- RS model characterized by one warped ED, confined by two three-branes
  - Higgs localized on “IR” brane
  - Gauge and matter fields allowed to propagate in bulk region
- SM particles accompanied by towers of heavy KK modes.
- Model parameters:
  - *L*: inverse warp factor, function of compactification radius, explains hierarchy between EW an Pl scale
  - M_{KK}: KK mass scale
- Results:
  - Large values of T possible
  - Large *L* forces large M_{KK} (several TeVs)
  - Some compensation if M_H is large

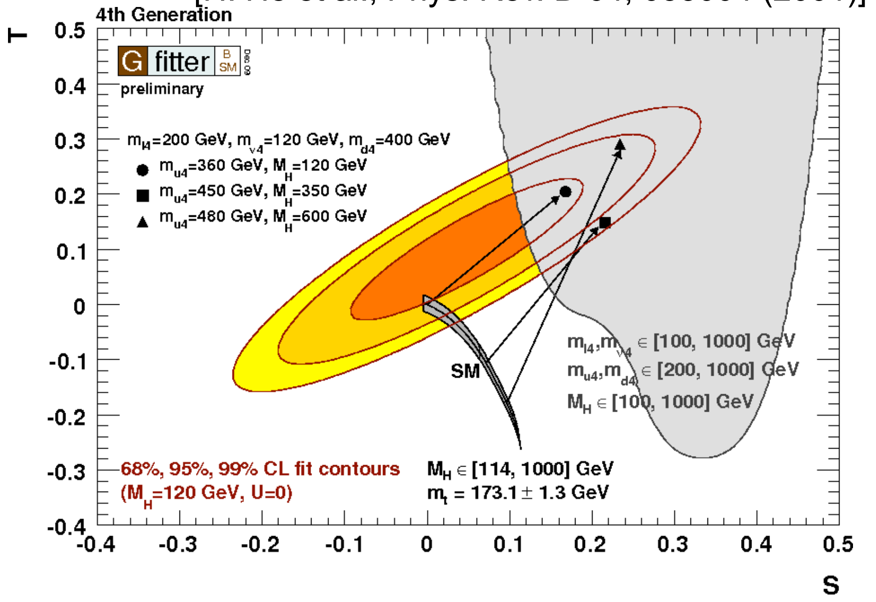


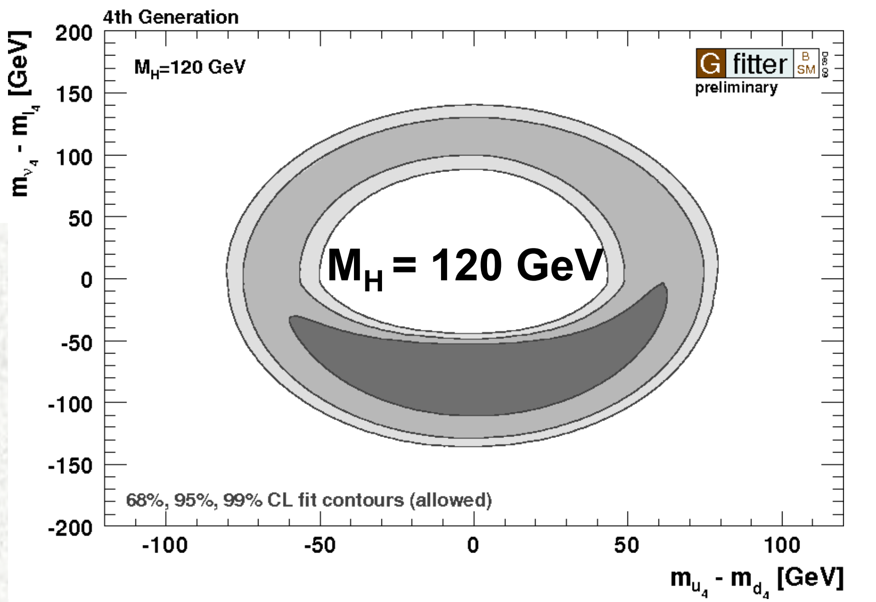


4^{th} fermion generation

- **Models with a fourth generation**
  - No explanation for *n=3* generations
  - Intr. new states for leptons and quarks
    - $\Psi_L = (\Psi_1, \Psi_2)_L,\ \Psi_{1,R},\ \Psi_{2,R}$
  - Free parameters: $m_{u_4}, m_{d_4}, m_{e_4}, m_{\nu_4}$
    - masses of new quarks and leptons
    - assume: no mixing of extra fermions
- **Contrib. to *STU* from new fermions**
  - Discrete shift in S from extra generation
  - Sensitive to mass difference between up- and down-type fields. (not to absolute mass scale)
- **CDF+D0 & CMS: SM4G Higgs partially excluded:**
  - CDF+D0: 131 > MH > 204 GeV @ 95% CL
  - CMD: 144 > MH > 207 GeV @ 95% CL
- **Results:**
  - With appropriate mass differences: 4^{th} fermion model consistent with EW data
    - In particular, again a large M_H is allowed
  - 5+ generations disfavored
  - Data prefer a heavier charged lepton / up-type quark (which both reduce size of S)

[H. He et al., Phys. Rev. D 64, 053004 (2001)]

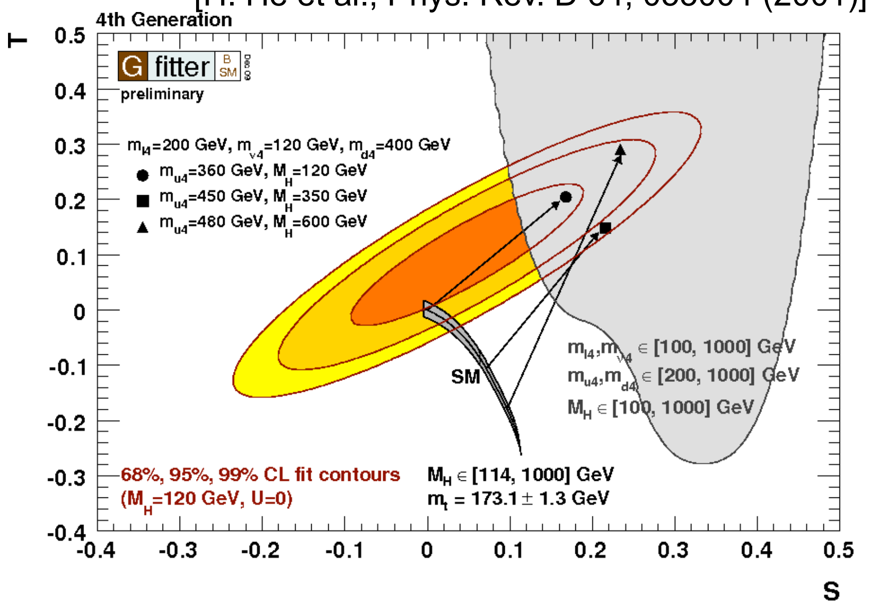


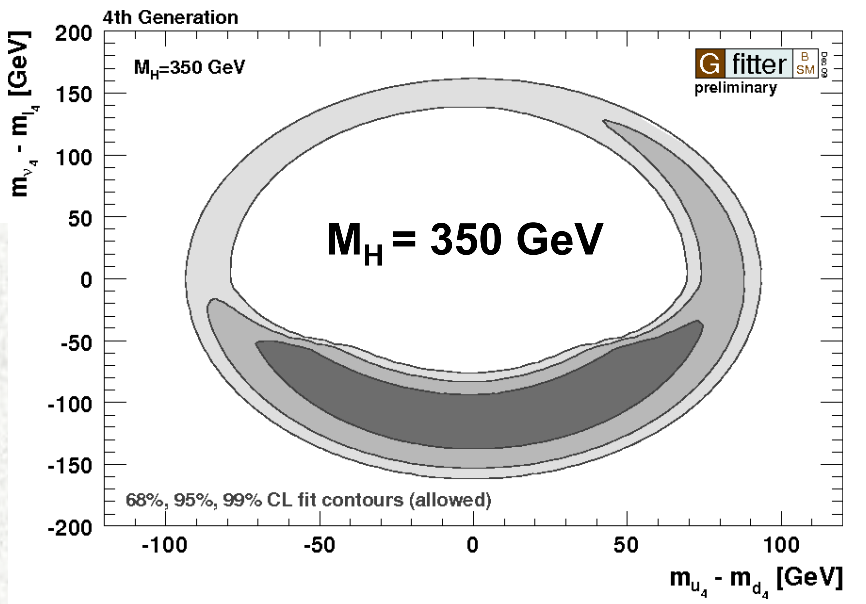


4^{th} fermion generation

- Models with a fourth generation
  - No explanation for *n=3* generations
  - Intr. new states for leptons and quarks
    - $\Psi_L = (\Psi_1, \Psi_2)_L, \ \Psi_{1,R}, \ \Psi_{2,R}$
  - Free parameters: $m_{u_4}, m_{d_4}, m_{e_4}, m_{\nu_4}$
    - masses of new quarks and leptons
    - assume: no mixing of extra fermions
- Contrib. to *STU* from new fermions
  - Discrete shift in S from extra generation
  - Sensitive to mass difference between up- and down-type fields. (not to absolute mass scale)
- CDF+D0 & CMS: SM4G Higgs partially excluded:
  - CDF+D0: 131 > MH > 204 GeV @ 95% CL
  - CMD: 144 > MH > 207 GeV @ 95% CL
- Results:
  - With appropriate mass differences: 4^{th} fermion model consistent with EW data
    - In particular, again a large M_H is allowed
  - 5+ generations disfavored
  - Data prefer a heavier charged lepton / up-type quark (which both reduce size of S)

[H. He et al., Phys. Rev. D 64, 053004 (2001)]

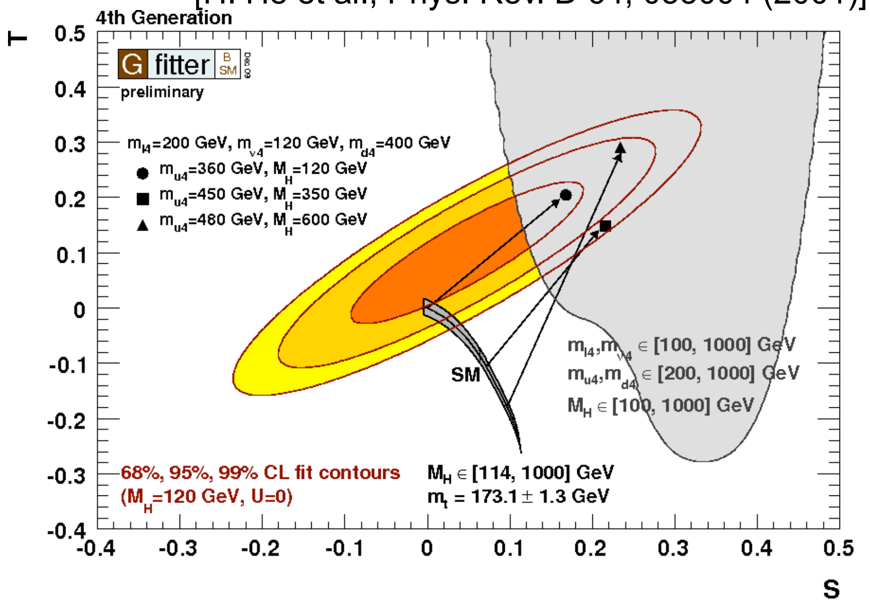




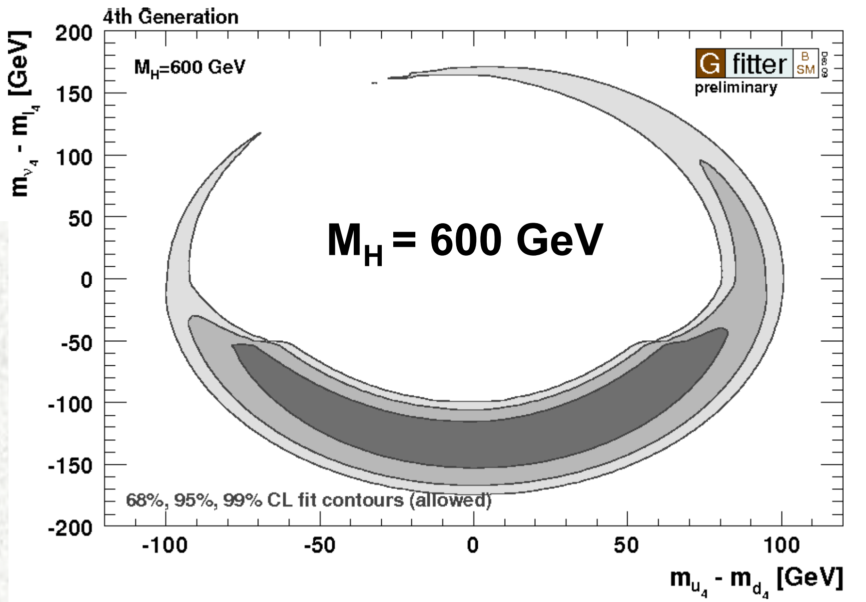
4th fermion generation

- Models with a fourth generation
  - No explanation for *n=3* generations
  - Intr. new states for leptons and quarks
    - $\Psi_L = (\Psi_1, \Psi_2)_L,\ \Psi_{1,R},\ \Psi_{2,R}$
  - Free parameters: $m_{u_4}, m_{d_4}, m_{e_4}, m_{\nu_4}$
    - masses of new quarks and leptons
    - assume: no mixing of extra fermions
- Contrib. to *STU* from new fermions
  - Discrete shift in S from extra generation
  - Sensitive to mass difference between up- and down-type fields. (not to absolute mass scale)
- CDF+D0 & CMS: SM4G Higgs partially excluded:
  - CDF+D0: 131 > MH > 204 GeV @ 95% CL
  - CMD: 144 > MH > 207 GeV @ 95% CL

[H. He et al., Phys. Rev. D 64, 053004 (2001)]



- Results:
  - With appropriate mass differences: 4th fermion model consistent with EW data
    - In particular, again a large M_H is allowed
  - 5+ generations disfavored
  - Data prefer a heavier charged lepton / up-type quark (which both reduce size of S)



Conclusion & Prospects

- **Gfitter** is a powerful framework for HEP model fits.

- Results shown
  - New and updated global fit of the electroweak SM
    - Very happy to see first LHC Higgs results included in EW fit !
    - SM Higgs mass strongly constrained. Light Higgs very much preferred by SM.
  - Oblique parameters (still!) a powerful method to constrain BSM theories
    - Presented constraints on various BSM theories (see more in models backup)
    - Heavy Higgs boson perfectly allowed in many BSM models by EW fit !

- The future
  - Maintain and extend existing fits.
    - Update with latest Tevatron and LHC results
  - Publication for BSM constraints from oblique parameters coming soon!
  - Emphasis this year: SUSY results

- Latest results/updates and new results always available at:
  - http://cern.ch/Gfitter

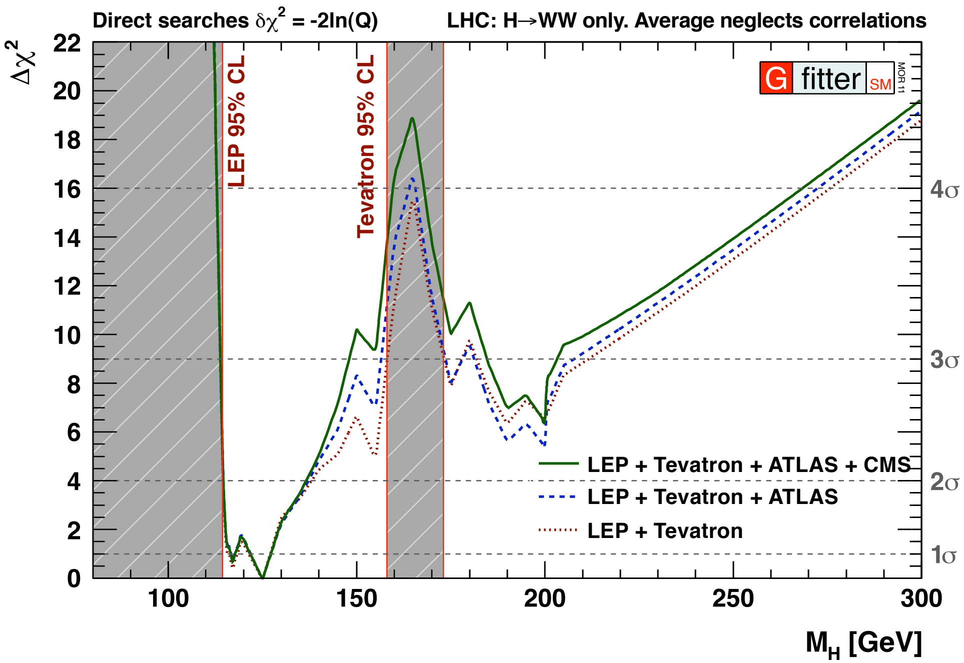
Gfitter

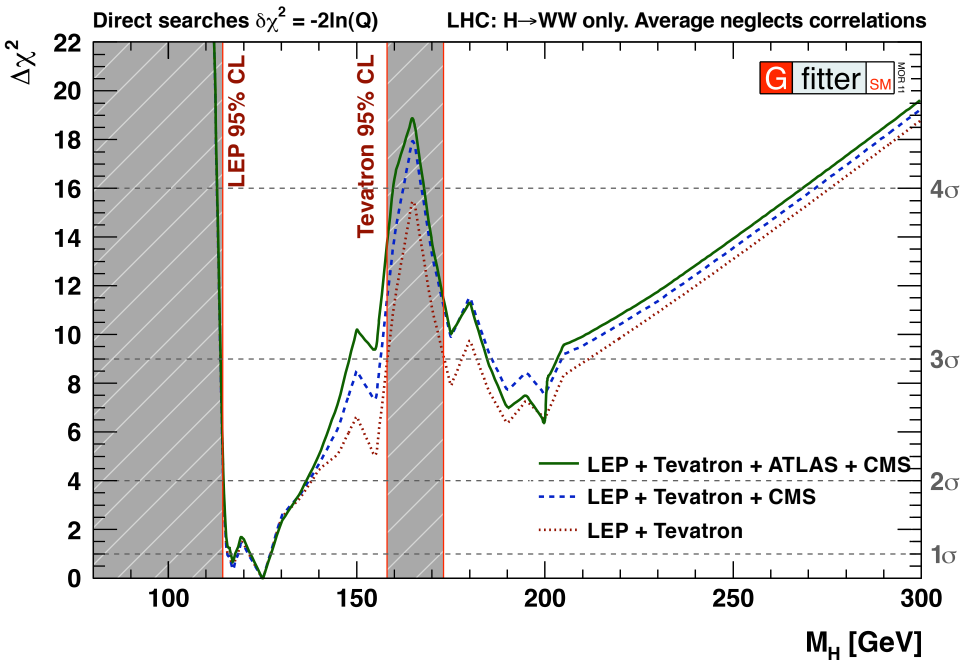
A Generic Fitter Project for HEP Model Testing

Backup

Comparison of ATLAS and CMS

- Results used:
  - Tevatron combination Moriond 2011, upto 8.2 /fb
  - CMS & ATLAS: latest H→WW results, 35 and 36 /pb





Electroweak Fit – Tevatron Higgs Constraints

- M_H from fit w/o Higgs searches:
  - Central value ±1σ:

$$M_H = 95.7^{+30.3}_{-24.2}\ \text{GeV}$$

  - 2σ interval:

$$[52,171]\ \text{GeV}$$

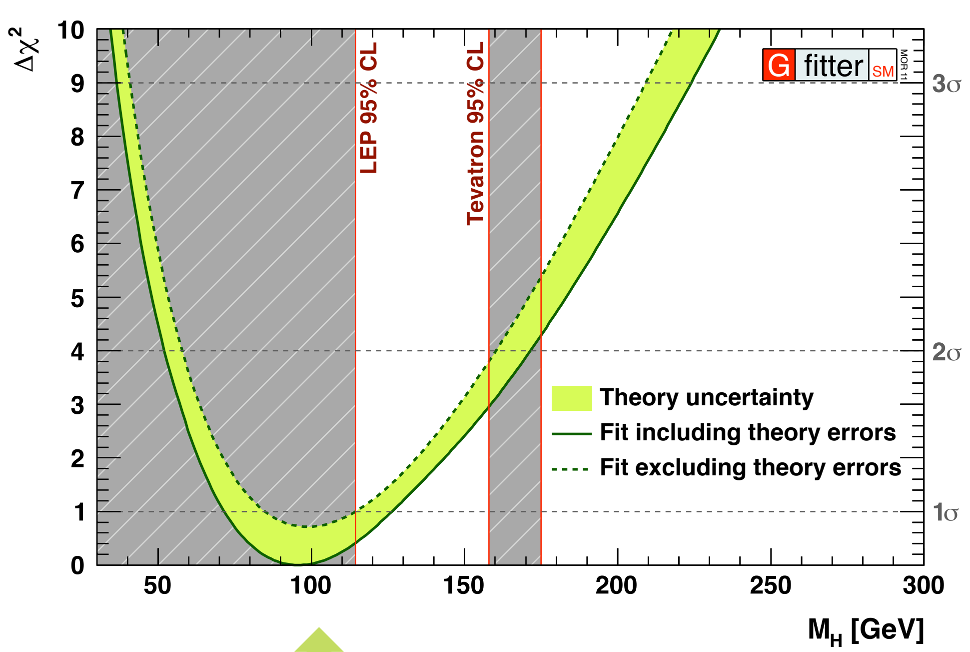
- Fit with LEP & latest Tevatron searches:
  - CL_{s+b}^{2s} central value ±1σ:

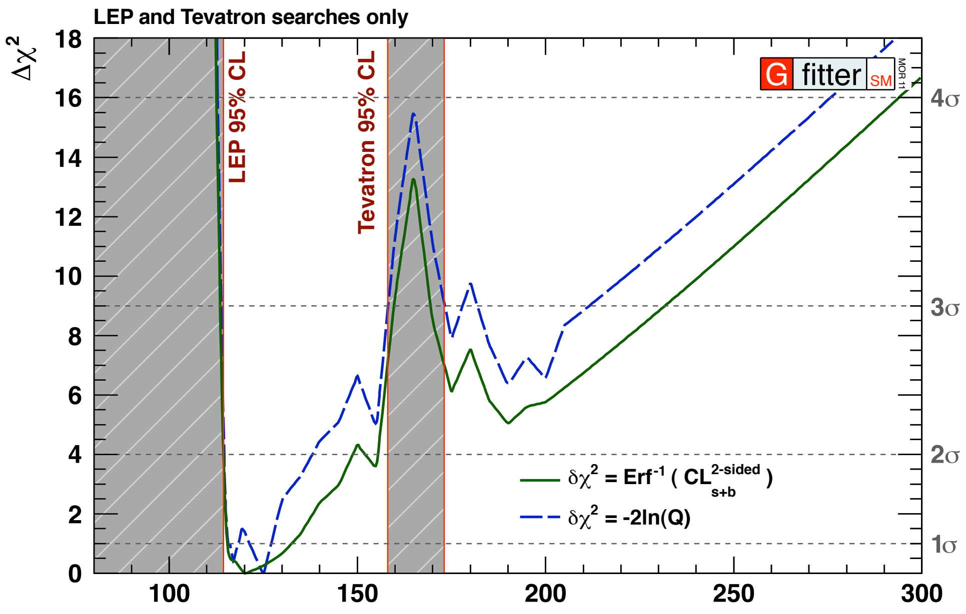
$$M_H = 120.2^{+12.3}_{-4.7}\ \text{GeV}$$

  - 2σ interval:

$$CL_{s+b}^{2-sided}: \ [114,149] \cup [152,155]\ \text{GeV}$$

$$-2\ln Q: \ [115,138]\ \text{GeV}$$



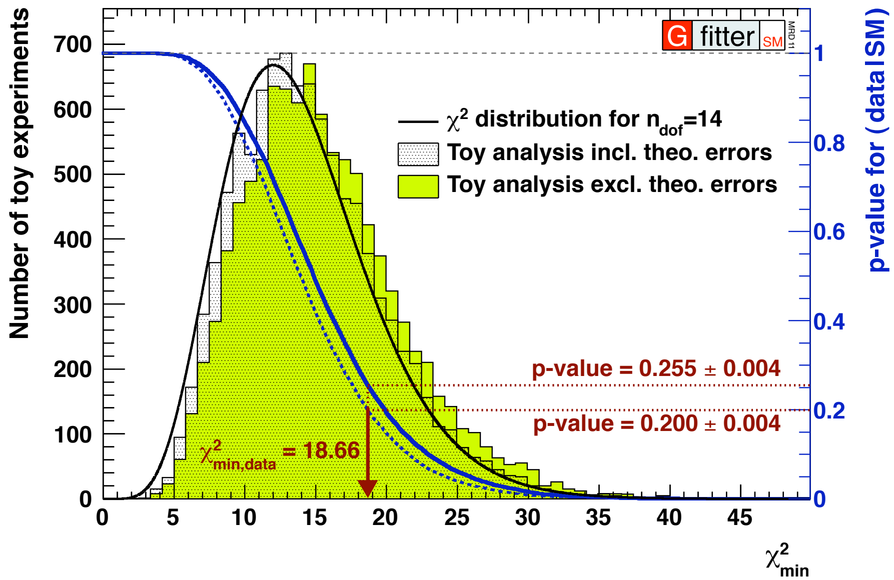


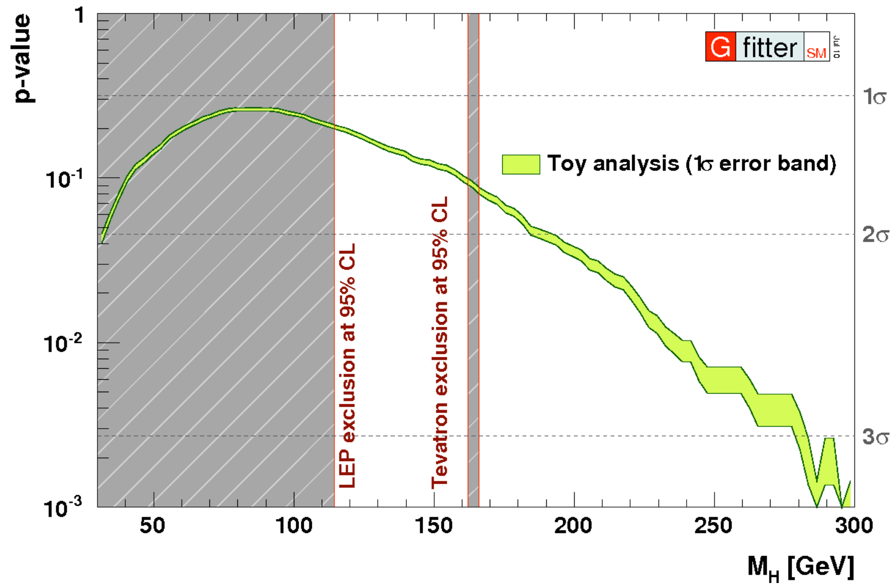
LEP & Tevatron upto 8.2 fb^{-1}

- Green error band from including / excluding theoretical errors in fit
  - Theoretical errors included in χ^2 with "flat likelihood term"

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





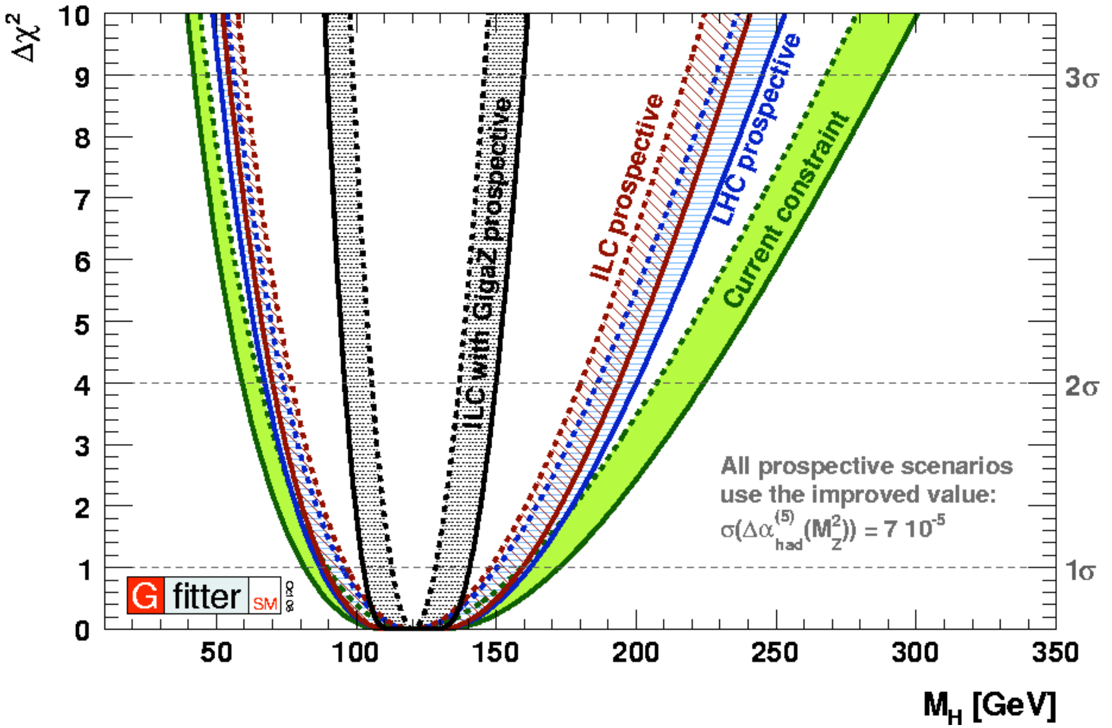
- for each toy complete fit is performed
- p-value = $(25\pm1_{-2})\%$
  - no significant requirement for new physics

- derivation of p-value for standard fit as function of M_H
- small p-values for large Higgs masses (M_H~280 GeV)

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

- 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

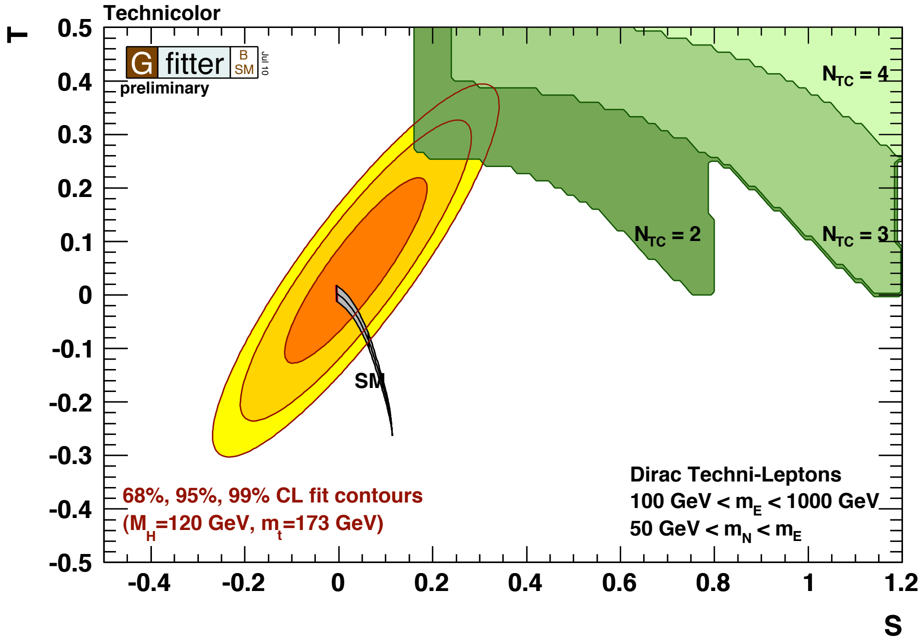


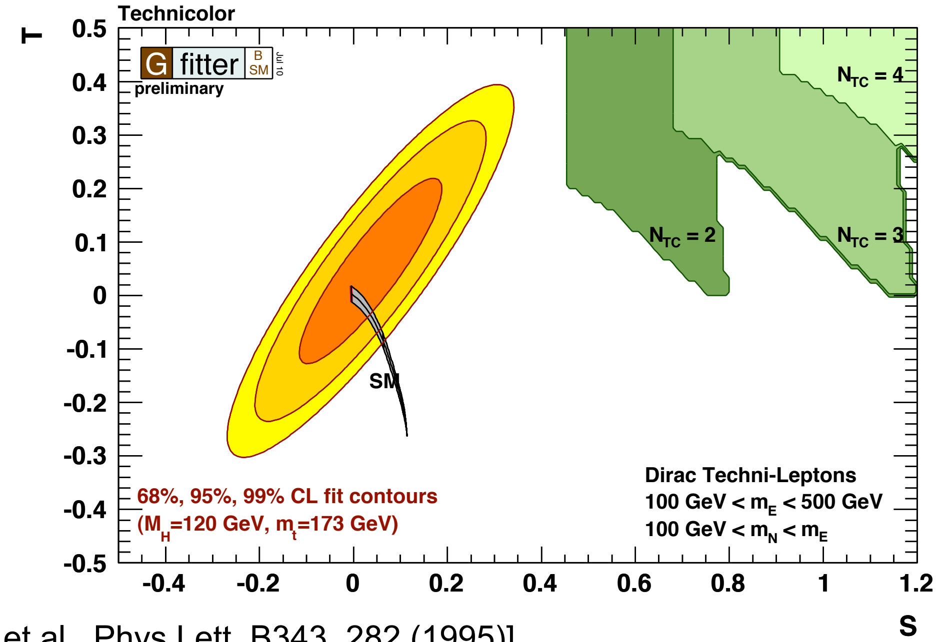
- assume M_H=120 GeV by adjusting central values of observables
- improvement of M_H prediction
  - to be confronted with direct measurement → goodness-of-fit
  - broad minima: Rfit treatment of theo. uncertainties
- GigaZ: significant improvement for M_H and $\alpha_S(M_Z^2)$

*[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]

Minimal Extended Technicolor

- **Extended Technicolor (ETC)**
  - One of first explanations for EWSB and hierarchy problem.
- **Magnitude of rad. corrections scales with number of techni-colors and flavors.**
- **Minimal ETC: with 1 TC quark/ lepton generation, and 2 upto 4 TCs.**
  - One triplet of TC quarks, doublet of TC leptons.
  - Techni-neutrino can be Dirac or Majorana.
  - Parameters: N_{TC}, ratio neutrino/ electrion masses.
- **Results:**
  - Ruled out: well-known incompatibility in S parameter.
  - Large isospin violations in Dirac techni-doublet are disfavored



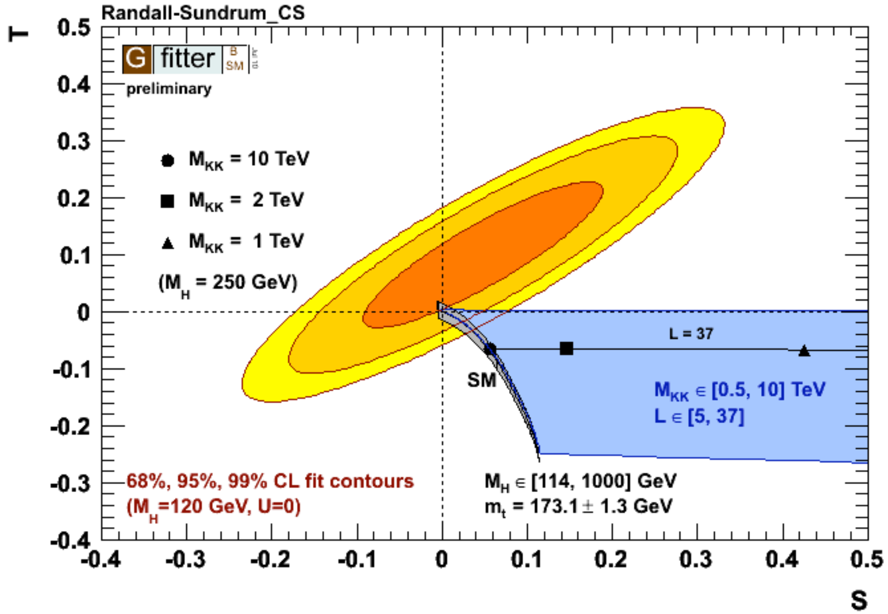


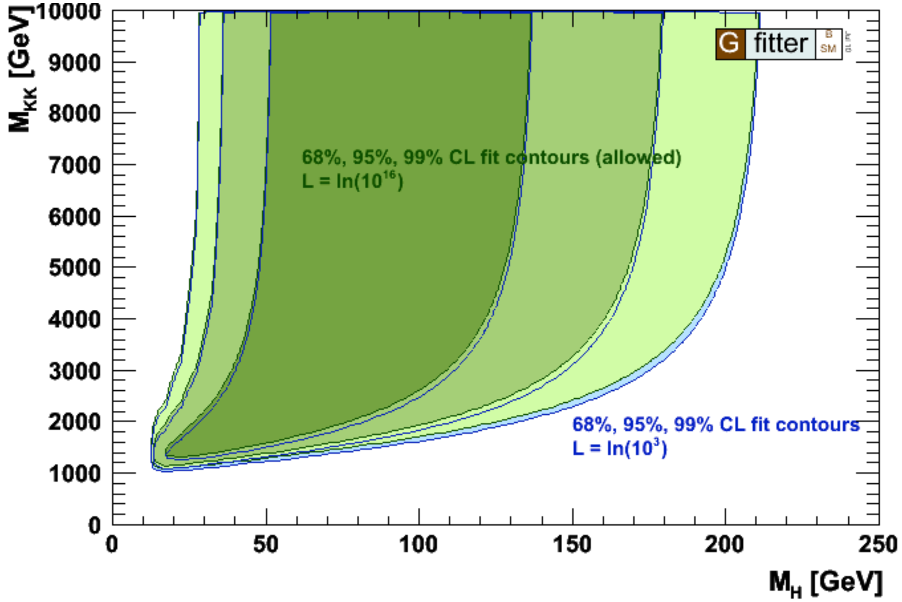
[M.E.Peskin and T. Tacheuchi. Phys Rev. D46 (1992) 381] [J. Ellis et al., Phys.Lett. B343, 282 (1995)]

Warped Extra Dimensions w/ custodial symmetry

[K. Agashe, A. Delgado, M. May, R. Sundrum, hep-ph/0308036v2]

- Goal: “cure” WED with too large T values
- Introduction of so-called **custodial isospin gauge symmetry** in the bulk
- Extension of hypercharge group to $SU(2)_R \times U(1)_X$
  - Bulk symmetry group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$
- Broken to SM $SU(3)_C \times SU(2)_L \times U(1)_Y$ on “UV” brane
- IR brane $SU(2)_R$ symmetric
- Right-handed fermionic fields occur in doublets

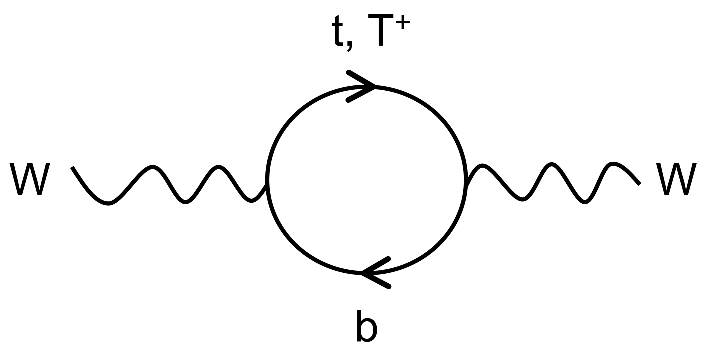


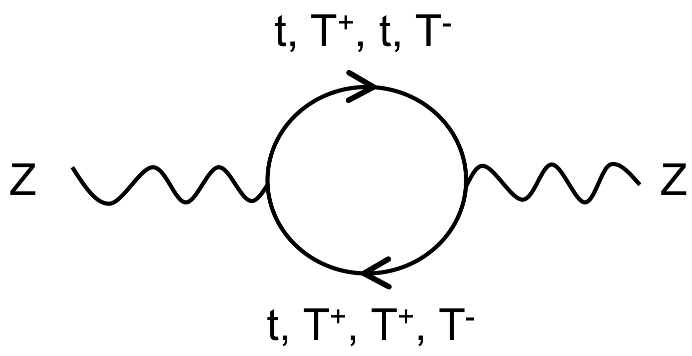


- Results:
  - Almost completely ruled out
  - Only small M_H allowed

Littlest Higgs Model with T-Parity

- LHM: solves hierarchy problem, possible explanation for EWSM
  - SM contributions to Higgs mass cancelled by new particles
- Non-linear sigma model, broken Global SU(5)/SO(5) symmetry
  - Higgs = lightest pseudo-Nambu-Goldstone boson
  - New SM-like fermions and gauge bosons at TeV scale
- T-parity = symmetry like susy R-parity (not time-invariance)
  - Symmetry forbids direct couplings of new gauge bosons (T-odd) to SM particles (T-even)
  - LHM provides natural dark matter candidate
- Two new top states: T-even m_{T+} and T-odd m_{T-}
- Dominant oblique corrections from weak isospin violation:



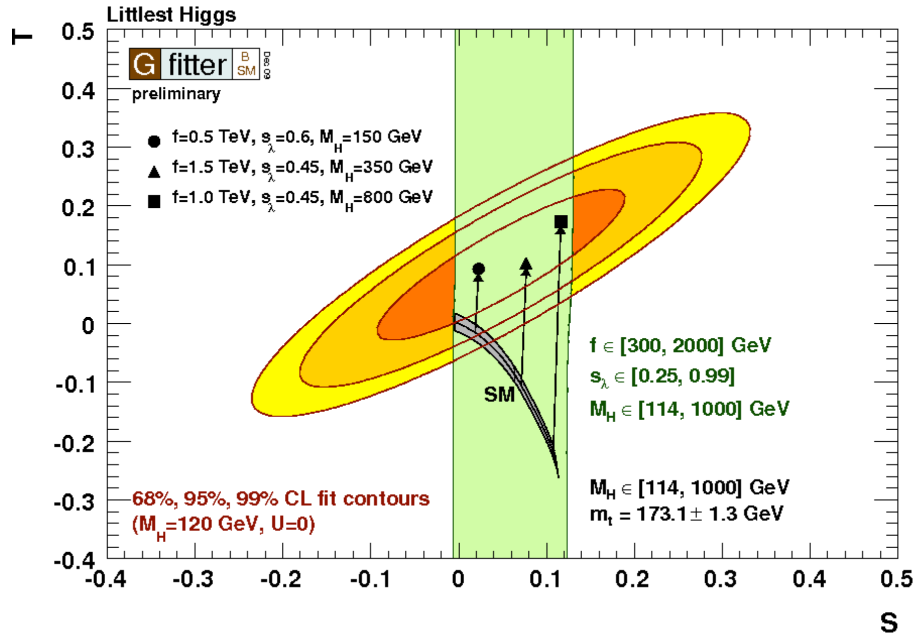


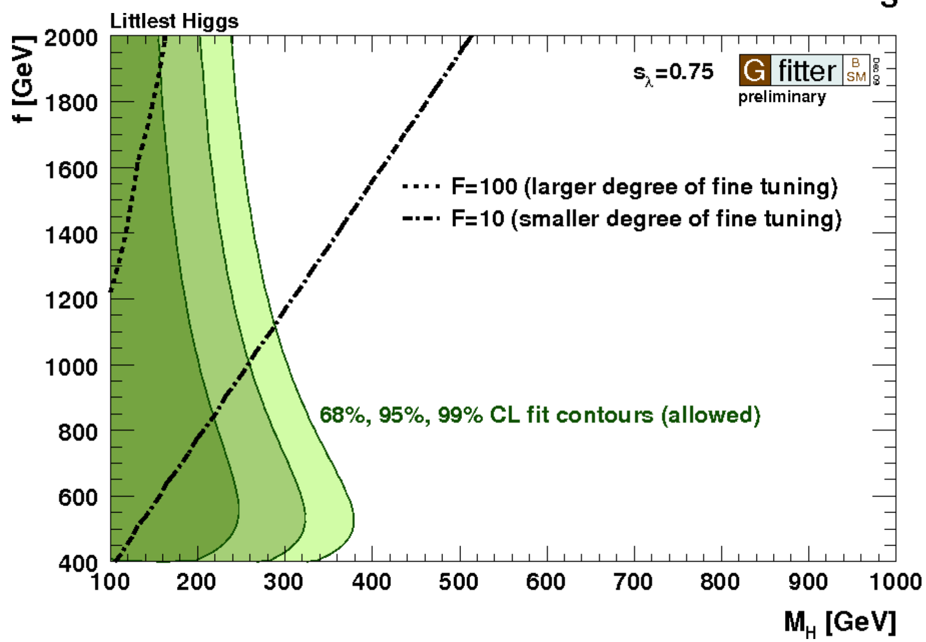
Littlest Higgs with T-Parity

- 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

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



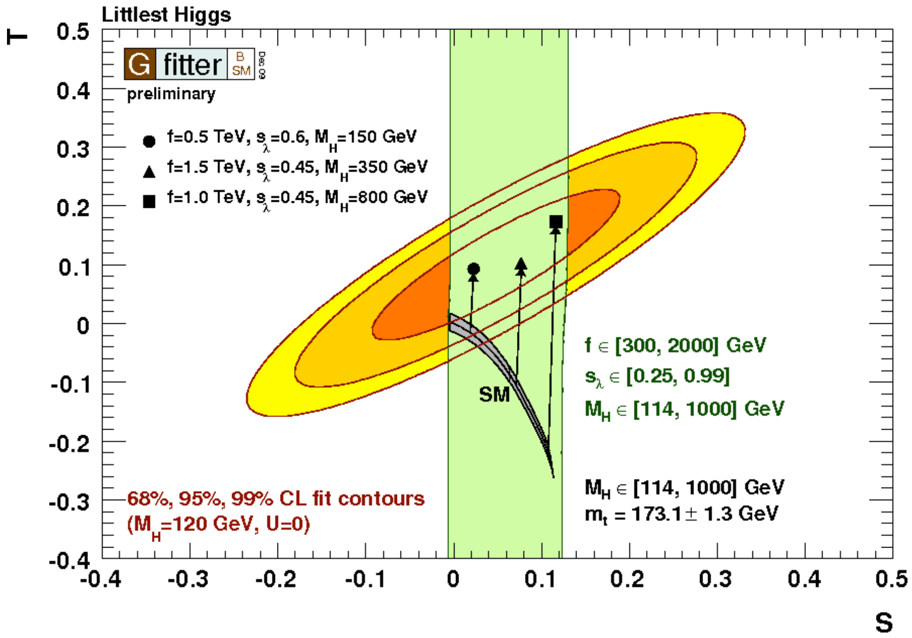


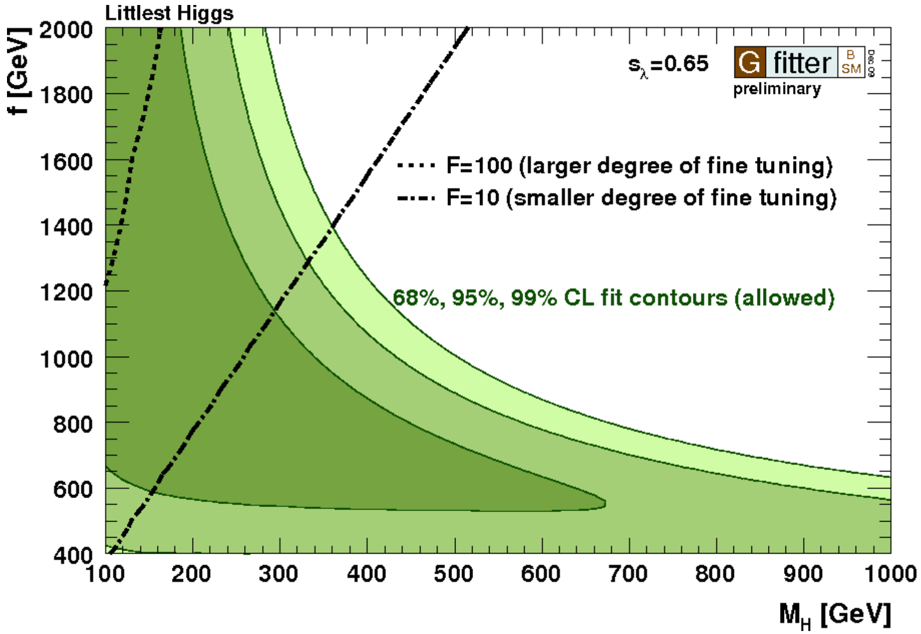
Littlest Higgs with T-Parity

- 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

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



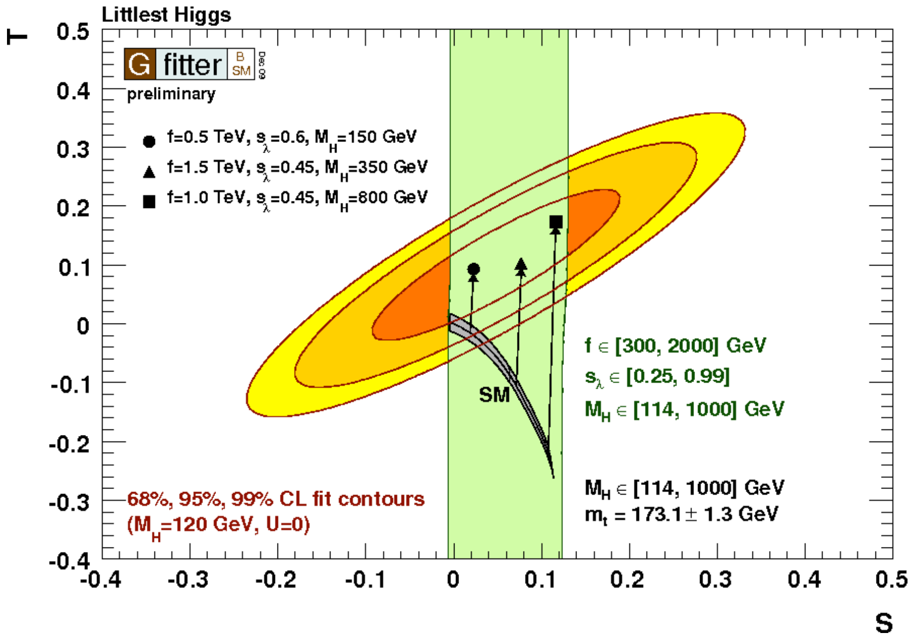


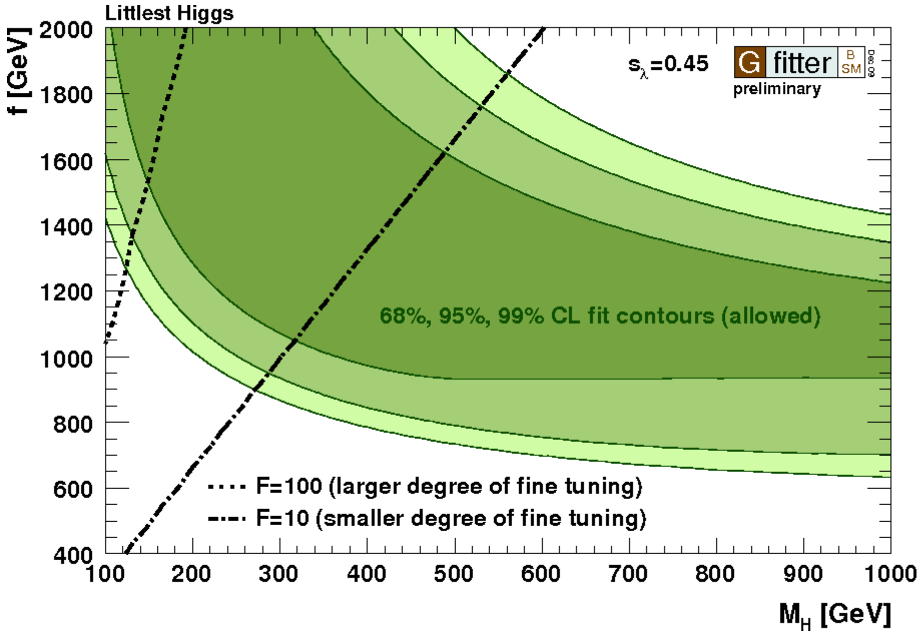
Littlest Higgs with T-Parity

- 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

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





Fit correlations

correlation coefficients between free fit parameters

Parameter	$\ln M_H$	$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	M_Z	$\alpha_S(M_Z^2)$	m_t	$\overline{m}_c$	$\overline{m}_b$
$\ln M_H$	1	-0.395	0.113	0.041	0.309	-0.001	-0.006
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$		1	-0.006	0.101	-0.007	0.001	0.003
M_Z			1	-0.019	-0.015	-0.000	0.000
$\alpha_S(M_Z^2)$				1	0.021	0.011	0.043
m_t					1	0.000	-0.003
$\overline{m}_c$						1	0.000