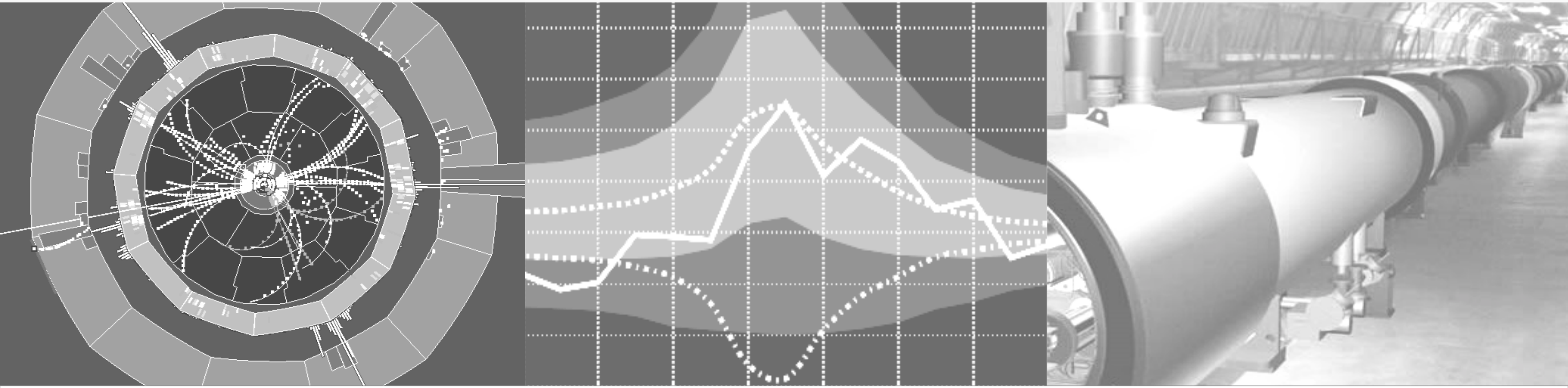
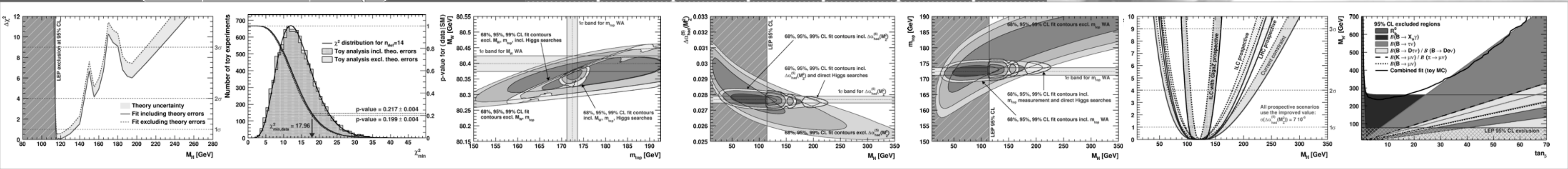
Electroweak Constraints on Higgs Boson

Andreas Hoecker (CERN)

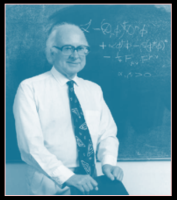
Higgs Hunting Workshop, Orsay, July 29 – 31, 2010

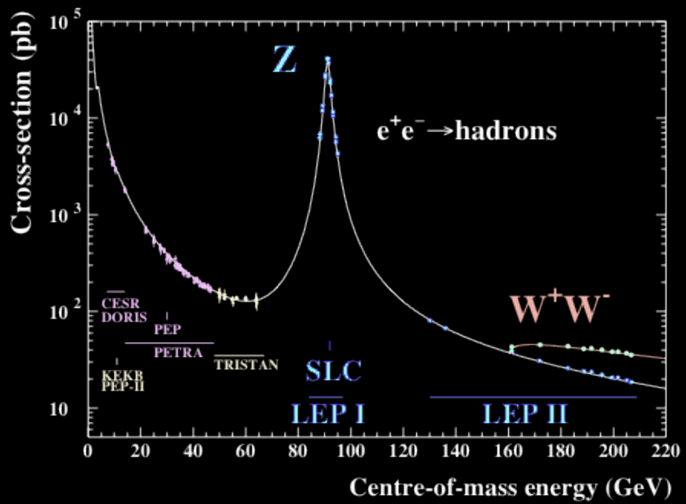




Indirect Constraints on the Higgs

from Electroweak Precision Data





Since the Z^0 boson couples to all fermion-antifermion pairs, it is an ideal laboratory for studying electroweak and strong interactions

Electroweak fits have a long history …

Based on a huge amount of preparatory work

- Needed to understand importance of loop corrections
- Precise Standard Model (SM) predictions and measurements required

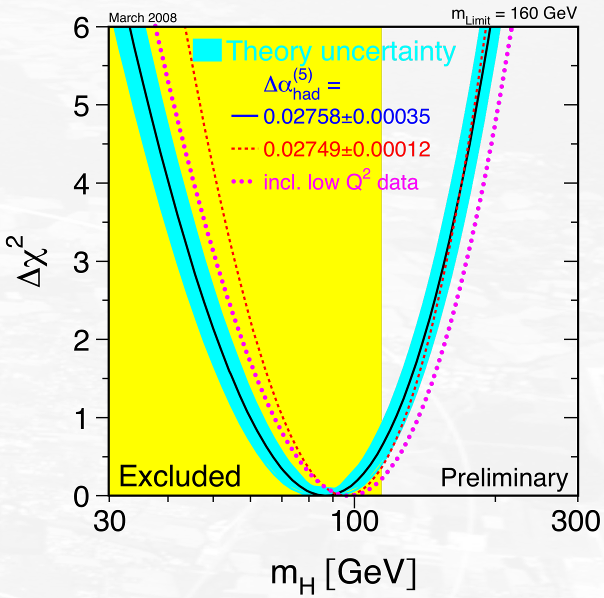
EW fits routinely performed by many groups

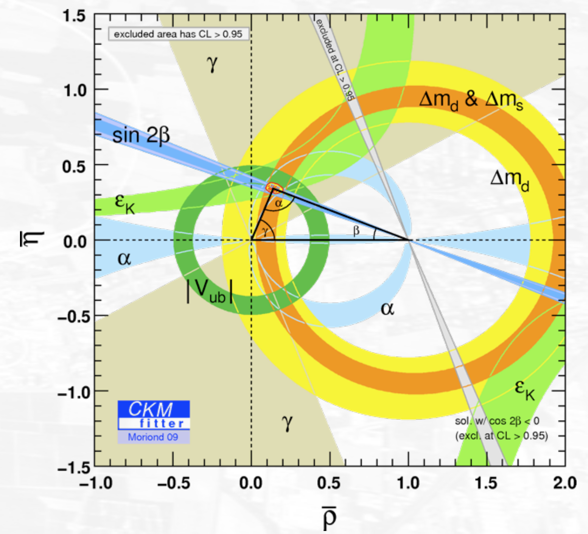
- D. Bardinet al. (ZFITTER), G. Passarinoet al. (TOPAZ0), LEP EW WG (M. Grünewald, K. Mönig *et al*.), J. Erler (GAPP), …
- Important results obtained !

Global SM fits also used at lower energies

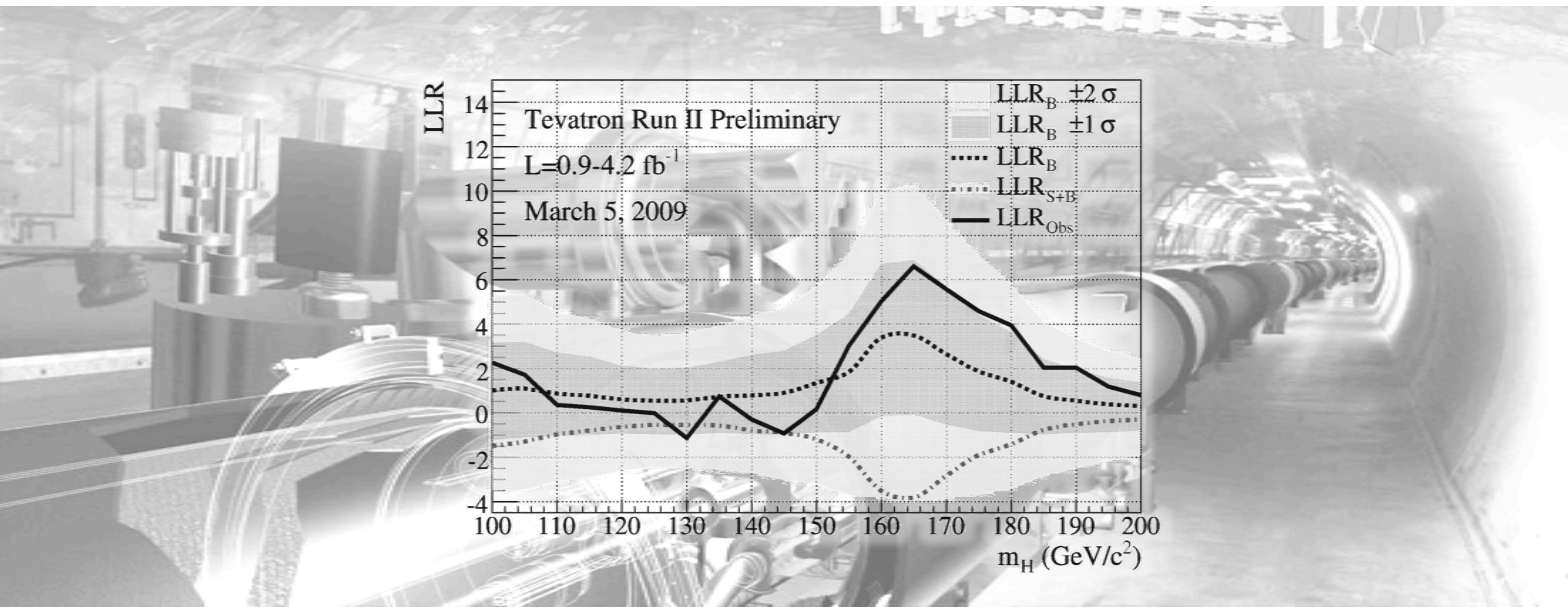
- CKMfitter (J. Charles *et al*.), UTfit (M. Bona *et al*.), …
- Mostly concentrating on CKM matrix

Also many groups pursuing global beyond-SM fits





Fit Inputs


LLR
Tevatron Run II Preliminary
L=0.9-4.2 fb^{-1}
March 5, 2009
LLR_B ±2 σ
LLR_B ±1 σ
LLR_B
LLR_{S+B}
LLR_{Obs}
14 12 10 8 6 4 2 0 -2 -4
100 110 120 130 140 150 160 170 180 190 200
m_H (GeV/c^2)

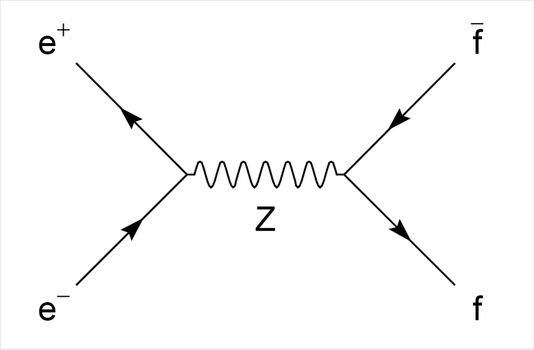
Measurements at the Z Pole

A look at the theory – tree level relations

Vector and axial-vector couplings for $Z \rightarrow f\bar{f}$ in SM:

$$g_{V,f}^{(0)} \equiv g_{L,f}^{(0)} + g_{R,f}^{(0)} = I_3^f - 2Q^f \sin^2\theta_W \qquad \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

$$g_{A,f}^{(0)} \equiv g_{L,f}^{(0)} - g_{R,f}^{(0)} = I_3^f$$



Electroweak unification: relation between weak and electromagnetic couplings:

$$G_F = \frac{\pi\alpha(0)}{\sqrt{2}M_W^2\left(1 - M_W^2/M_Z^2\right)}$$

Since uncertainty on G_F and M_Z small, relation often used to eliminate direct M_W dependence:

$$M_W^2 = \frac{M_Z^2}{2} \cdot \left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$

Gauge sector of SM on tree level is given by 3 free parameters, *e.g.*: α, $\boldsymbol{M_Z}$, $\boldsymbol{G_F}$

Measurements at the Z Pole

Radiative corrections –
modifying propagators and vertices

Significance of radiative corrections can be illustrated by verifying tree level relation:

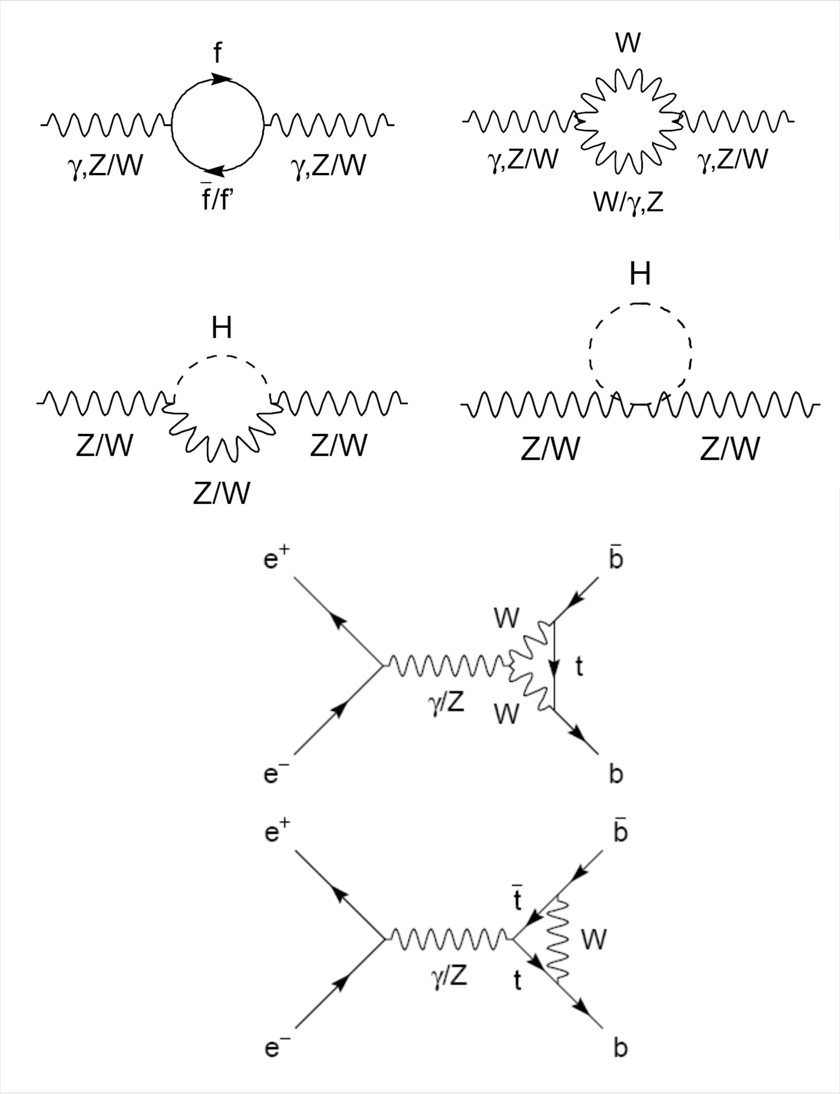
$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

- Using the measurements:

$$M_W = (80.399 \pm 0.023)\ \text{GeV}$$
$$M_Z = (91.1875 \pm 0.0021)\ \text{GeV}$$

one predicts: $\sin^2\theta_W = 0.22284 \pm 0.00045$

which is 19σ away from the experimental value obtained by combining all asymmetry measurements: $\sin^2\theta_W = 0.23151 \pm 0.00011$



Measurements at the Z Pole

Radiative corrections –
modifying propagators and vertices

Parametrisation of radiative corrections:
"electroweak form-factors": ρ, κ, Δr

- Modified ("effective") couplings at the *Z* pole:

$$g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\rm eff}^f\right)$$

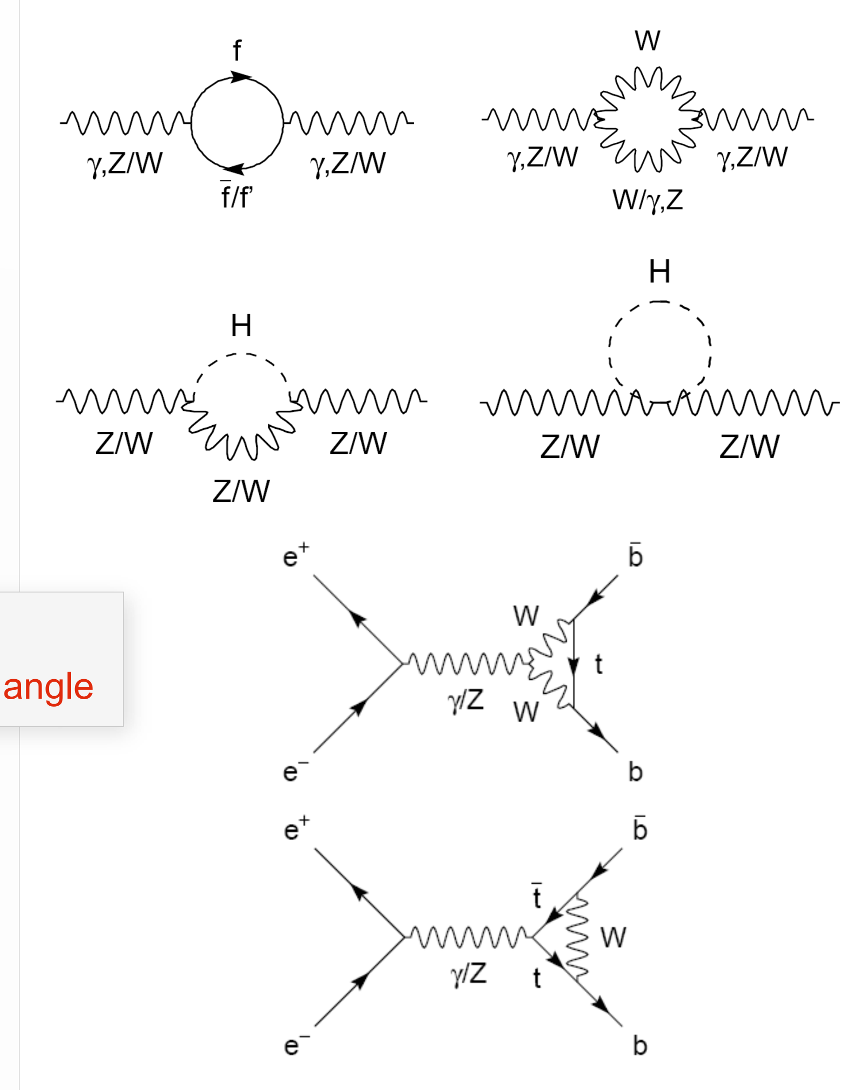
$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$

$$\sin^2\theta_{\rm eff}^f = \kappa_Z^f \sin^2\theta_W$$

ρ : overall scale
κ : on-shell mixing angle

- Modified *W* mass:

$$M_W^2 = \frac{M_Z^2}{2}\cdot\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha\cdot(1-\Delta r)}{G_F M_Z^2}}\right)$$



Measurements at the Z Pole

Radiative corrections – modifying propagators and vertices

Leading order terms ($M_H \ll M_W$)

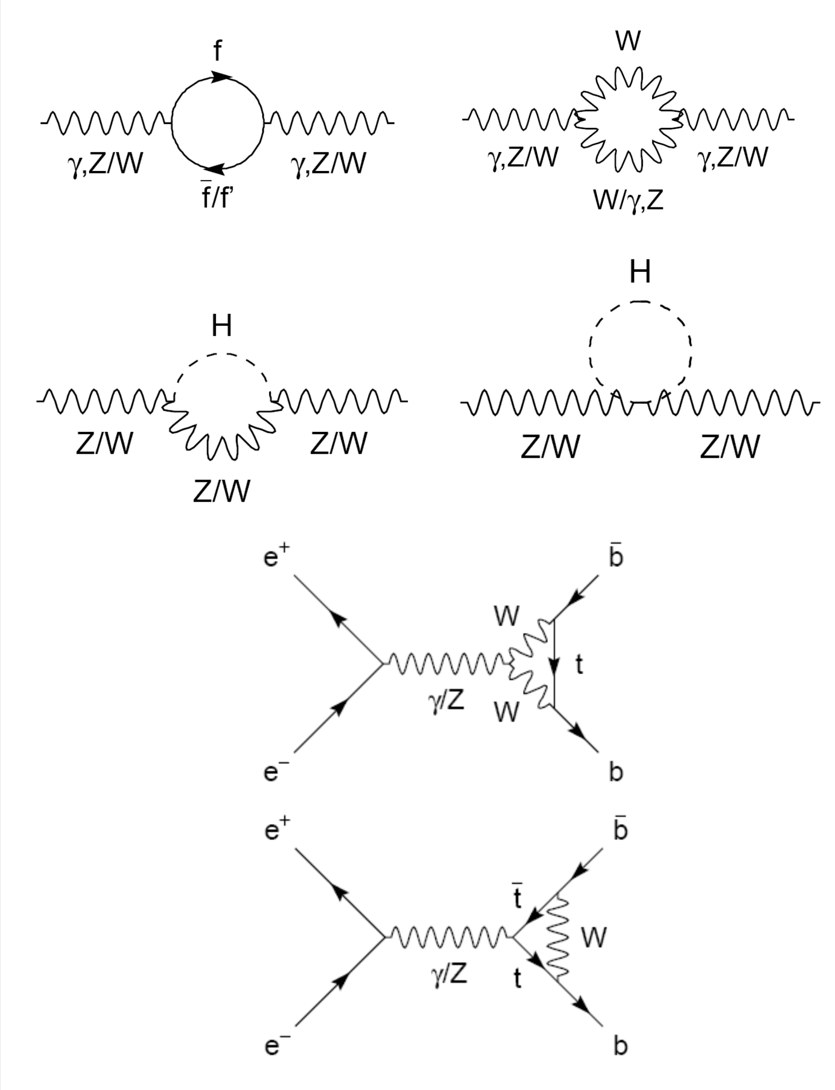
- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:

$$\Delta\rho_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{M_W^2} - \tan^2\theta_W\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \ldots\right]$$

$$\Delta\kappa_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{M_W^2}\cot^2\theta_W - \frac{10}{9}\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \ldots\right]$$

- and flavour-specific vertex corrections, which are very small, except for top quarks, due to large $|V_{tb}|$ CKM element

$$\Delta\rho^f = -2\Delta\kappa^f = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \ldots$$



Measurements at the Z Pole

Radiative corrections –
modifying propagators and vertices

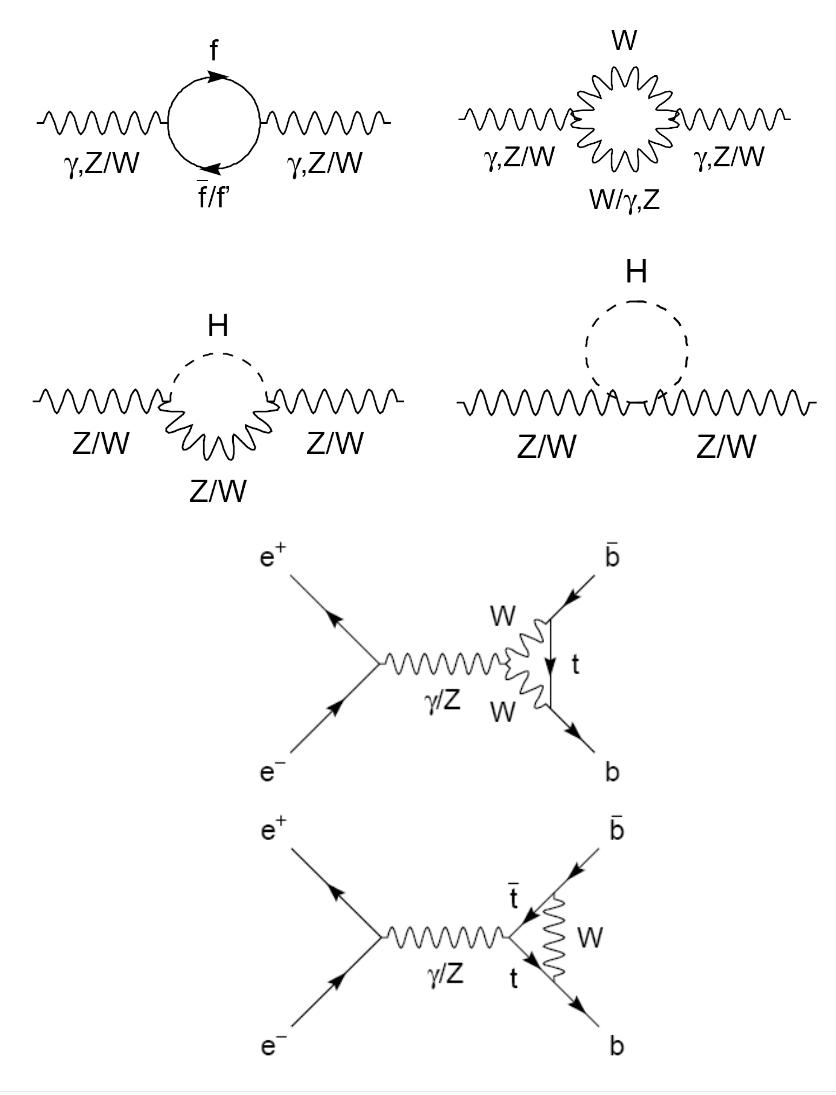
Leading order terms ($M_H \ll M_W$)

- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:

Radiative corrections allow us to test the SM and to constrain unknown SM parameters

- and flavour-specific vertex corrections, which are very small, except for top quarks, due to large $|V_{tb}|$ CKM element

$$\Delta\rho^f = -2\Delta\kappa^f = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \ldots$$



Measurements at the Z Pole

Total hadronic cross section – measurement and prediction

Total cross-section (from $\cos\theta$ symmetric terms) expressed in Breit-Wigner form:

$$\sigma_{f\bar{f}}^{Z} = \sigma_{f\bar{f}}^{0} \cdot \frac{s \cdot \Gamma_Z^2}{\left(s - M_Z^2\right)^2 + s^2\Gamma_Z^2 / M_Z^2} \cdot \frac{1}{R_{\text{QED}}} \qquad \sigma_{f\bar{f}}^{0} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

Corrected for QED radiation

Partial widths add up to full width: $\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadronic}} + \Gamma_{\text{invisible}}$

- Measured cross sections depend on products of partial and total widths
- Highly correlated set of parameters !

Instead: use less correlated set of six measurements

- *Z* mass and width: M_Z, Γ_Z
- Hadronic pole cross section: σ^0_{had}
- Three leptonic ratios (use lepton-univ.): $R_\ell^0 = R_e^0 = \Gamma_{\text{had}}/\Gamma_{ee} = R_\mu^0 = R_\tau^0$
- Hadronic width ratios: R_b^0, R_c^0

Taken from LEP:
- precise $\sqrt{s}$
- high statistics

Include also SLD:
- higher effi./purity for heavy quarks

Measurements at the Z Pole

Partial width – sensitive to QCD and QED corrections

Partial width are defined **inclusively**, *i.e.*, they contain final state QED and QCD vector and axial-vector corrections via “radiator functions”: $R_{A,f}$, $R_{V,f}$

$$\Gamma_{f\bar{f}} = N_c^f \frac{G_F M_Z^3}{6\sqrt{2}\pi}\left(\left|g_{A,f}\right|^2 R_{A,f} + \left|g_{V,f}\right|^2 R_{V,f}\right)$$

QCD corrections only affect final states with quarks

- To first order in α_S corrections are flavour independent and identical for *A* and *V*

$$R_{V,\mathrm{QCD}} = R_{A,\mathrm{QCD}} = R_{\mathrm{QCD}} = 1 + \frac{\alpha_S(M_Z^2)}{\pi} + \ldots = 1 + 0.038 + \ldots$$

- 3NLO (!) calculation available [P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]

QED corrections similar: $R_{V,\mathrm{QED}} = R_{A,\mathrm{QED}} = R_{\mathrm{QED}} = 1 + \underbrace{\frac{3}{4} Q_f^2 \frac{\alpha(M_Z^2)}{\pi}}_{0.0019 \times Q_f^2} + \ldots$

(though much smaller due to $\alpha \ll \alpha_S$)

Measurements at the Z Pole

Asymmetry and polarisation – quantify parity violation

Distinguish vector and axial-vector couplings of the *Z* (*i.e.*, $\sin^2\theta^f_{\rm eff}$)

Convenient to use "asymmetry parameters":

$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = 2\frac{g_{V,f}/g_{A,f}}{1+\left(g_{V,f}/g_{A,f}\right)^2}$$

dependent on $\sin^2\theta^f_{\rm eff}$: $\frac{\mathrm{Re}(g_{V,f})}{\mathrm{Re}(g_{A,f})} = 1 - 4\left|Q_f\right|\sin^2\theta^f_{\rm eff}$

Via *final state (FS) angular distribution* in unpolarised scattering (LEP)

- Forward-backward asymmetries: $A^f_{\rm FB} = \frac{N_F - N_B}{N_F + N_B}$, $A^{0,f}_{\rm FB} = \frac{3}{4}A_e A_f$
- LEP measurements: $A^{0,l}_{\rm FB}$, $A^{0,c}_{\rm FB}$, $A^{0,b}_{\rm FB}$

Via *IS polarisation* (SLC): $A_{\rm LR} = \frac{N_L - N_R}{N_L + N_R}\frac{1}{\langle |P|_e\rangle}$, $A_{\rm LRFB} = \frac{(N_F - N_B)_L - (N_F - N_B)_R}{(N_F + N_B)_L + (N_F + N_B)_R}\frac{1}{\langle |P_e|\rangle}$

- Left-right, and left-right forward-backward asymmetries: $A^0_{\rm LR} = A_e$, $A^{0,f}_{\rm LRFB} = \frac{3}{4}A_f$

Measurements at the Z Pole

Asymmetry and polarisation – quantify parity violation

Distinguish vector and axial-vector couplings of the Z (*i.e.*, $\sin^2\theta^f_{\text{eff}}$)

Convenient to use "asymmetry parameters":

$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = 2\frac{g_{V,f}/g_{A,f}}{1+\left(g_{V,f}/g_{A,f}\right)^2}$$

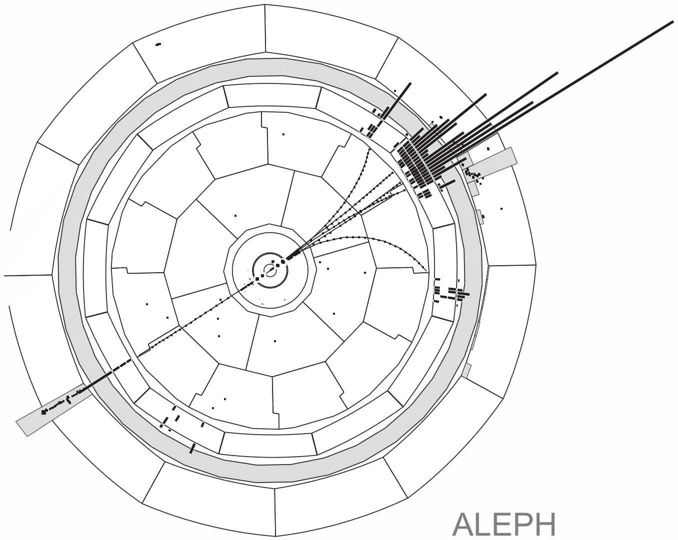
dependent on $\sin^2\theta^f_{\text{eff}}$: $\frac{\text{Re}(g_{V,f})}{\text{Re}(g_{A,f})} = 1-4|Q_f|\sin^2\theta^f_{eff}$

Via *final state polarisation* (LEP):

- Tau polarisation:

$$P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta)+2A_e\cos\theta}{1+\cos^2\theta+2A_\tau A_e\cos\theta}$$

- Measure τ spin versus from energy and angular correlations in τ decays
- Fit at LEP determines: A_τ, A_e



ALEPH
$Z \rightarrow \tau^+\tau^-$ candidate

Measurements at the Z Pole

Asymmetry and polarisation – quantify parity violation

Distinguish vector and axial-vector couplings of the *Z* (*i.e.*, $\sin^2\theta^f_{\rm eff}$)

Convenient to use "asymmetry parameters":

$$A_f = \frac{g^2_{L,f} - g^2_{R,f}}{g^2_{L,f} + g^2_{R,f}} = 2\frac{g_{V,f}/g_{A,f}}{1+\left(g_{V,f}/g_{A,f}\right)^2}$$

dependent on $\sin^2\theta^f_{\rm eff}$: $\dfrac{\mathrm{Re}(g_{V,f})}{\mathrm{Re}(g_{A,f})} = 1-4|Q_f|\sin^2\theta^f_{eff}$

The measured asymmetries are corrected for QED radiation, γ–Z interference to give "pole" quantities $^{(0)}$.

In case of e^+e^- final state, must also take into account t-channel scattering.

Measurements at the Z Pole

Initial and final state QED radiation

Measured cross-section and asymmetries are modified by initial and final state QED radiation

- Effects are corrected for by the collaborations (using the programs TOPAZ0 and ZFITTER)

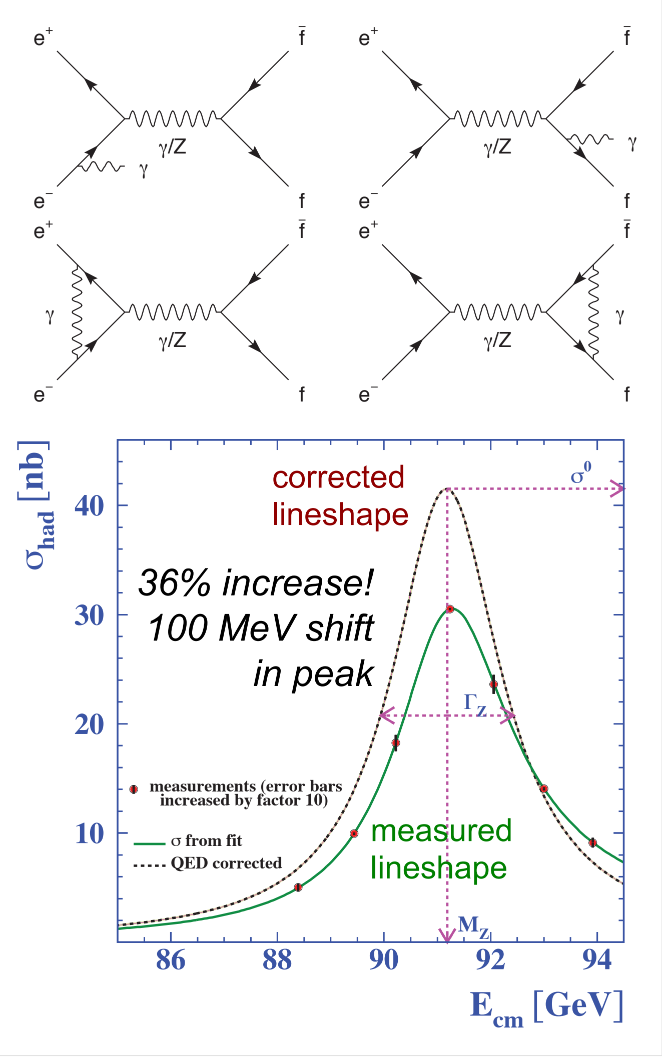
$$\sigma(s) = \int_{4m_f^2/s}^{1} dz \cdot H_{\text{QED}}^{\text{tot}}(z,s) \cdot \sigma(zs)$$

Convolution of kernel cross section by QED radiator function

- *Very large corrections applied in some cases!*
- Measured observables become “pseudo-observables”
- *E.g.*, hadronic pole-cross section σ^0_{had}

In the electroweak fit the published “pseudo-observables” are used

Important: these QED corrections are independent of the electroweak corrections discussed before!



All Observables Entering the Fit

Experimental results:

- *Z*-pole observables: LEP/SLD results (corrected for ISR/FSR QED effects)
  [ADLO & SLD, Phys. Rept. 427, 257 (2006)]
  - Total and partial cross sections around *Z*: M_Z, Γ_Z, σ^0_{had}, R_l^0, R_c^0, R_b^0
    Sensitive to the total coupling strength of the *Z* to fermions
  - Asymmetries on the *Z* pole: $A_{\mathrm{FB}}^{0,l}$, $A_{\mathrm{FB}}^{0,b}$, $A_{\mathrm{FB}}^{0,c}$, A_l, A_c, A_b, $\sin^2\theta^l_{\mathrm{eff}}\,(Q_{\mathrm{FB}})$
    Sensitive to the ratio of the *Z* vector to axial-vector couplings (*i.e.* $\sin^2\theta_{\mathrm{eff}}$) → parity violation
- M_W and Γ_W: LEP + Tevatron average
  [ADLO, hep-ex/0612034] [CDF, Phys. Lett. 100, 071801 (2008)]
  [CDF & D0, Phys. Rev. D 70, 092008 (2004)] [CDF & D0, arXiv:0908.1374v1]
- m_t: latest Tevatron average [CDF & D0, new combination for ICHEP 2010, arXiv:1007.3178]
- $\overline{m}_c$, $\overline{m}_b$: world averages [PDG, Phys. Lett. B667, 1 (2008) and 2009 partial update for the 2010 edition]
- $\Delta\alpha_{\mathrm{had}}(M_Z)$: [K. Hagiwara et al., Phys. Lett. B649, 173 (2007)] + rescaling mechanism to account for α_s dependency
- Direct Higgs searches at LEP and Tevatron (2009 Tev. average, *and ICHEP 2010 average*)
  [ADLO: Phys. Lett. B565, 61 (2003)] [CDF & D0: arXiv:0911.3930] [FERMILAB-CONF-10-257-E]

Experimental Input

Parameter	Input value	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP, SLC
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	SLC
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
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

Parameter	Input value	
M_H [GeV] $^{(\circ)}$	Likelihood ratios	LEP & Tevatron
M_W [GeV]	80.399 ± 0.023	LEP & Tevatron
Γ_W [GeV]	2.098 ± 0.048	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
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2769 ± 22	
$\alpha_s(M_Z^2)$	$-$	
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	
$\delta_{\rm th} \rho^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	
$\delta_{\rm th} \kappa^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	

Correlations for observables from Z lineshape fit

	M_Z	Γ_Z	$\sigma^0_{\rm had}$	R^0_ℓ	$A^{0,\ell}_{\rm FB}$
M_Z	1	-0.02	-0.05	0.03	0.06
Γ_Z		1	-0.30	0.00	0.00
$\sigma^0_{\rm had}$			1	0.18	0.01
R^0_ℓ				1	-0.06
$A^{0,\ell}_{\rm FB}$					1

Correlations for heavy-flavour observables at Z pole

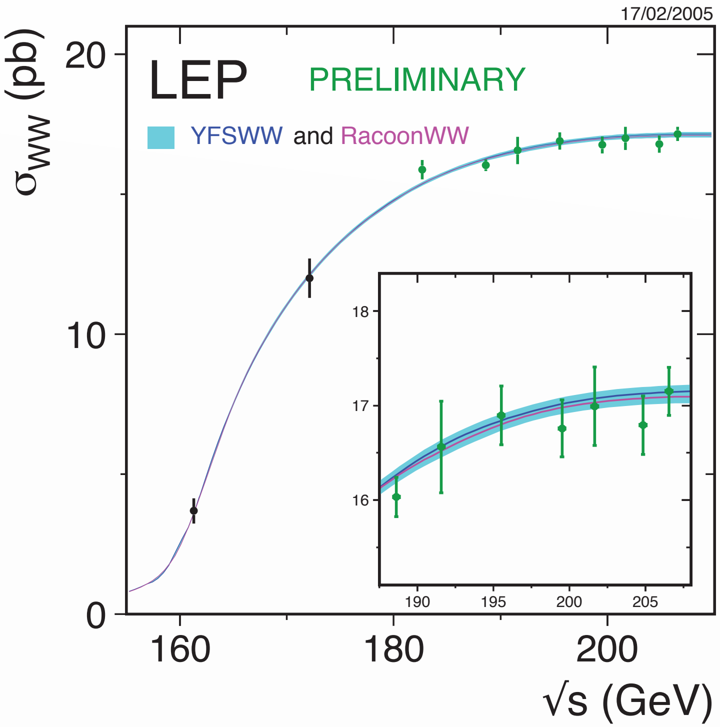
	$A^{0,c}_{\rm FB}$	$A^{0,b}_{\rm FB}$	A_c	A_b	R^0_c	R^0_b
$A^{0,c}_{\rm FB}$	1	0.15	0.04	-0.02	-0.06	0.07
$A^{0,b}_{\rm FB}$		1	0.01	0.06	0.04	-0.10
A_c			1	0.11	-0.06	0.04
A_b				1	0.04	-0.08
R^0_c					1	-0.18

Precision Measurement of the *W* mass

Results from LEP-2:

- 10 pb^{-1} per experiment recorded close to the *WW* threshold
  - M_W from σ_{WW} measurements
  - Much less precise result than kinematic *W* reconstruction (200 MeV statistical error)
- 700 pb^{-1} per experiment above the threshold
  - M_W directly reconstructed from invariant mass of observed leptons (dominant) and jets
  - Large "colour reconnection" systematics in hadronic channel (35 MeV)
  - Combination: M_W = (80.376 ± 0.025 ± 0.022) GeV

4 × 700 pb^{-1} taken for $\sqrt{s}$ = 161–209 GeV between 1996 and 2000 at LEP-2



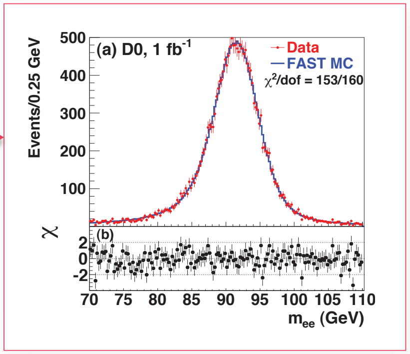
Results from Tevatron:

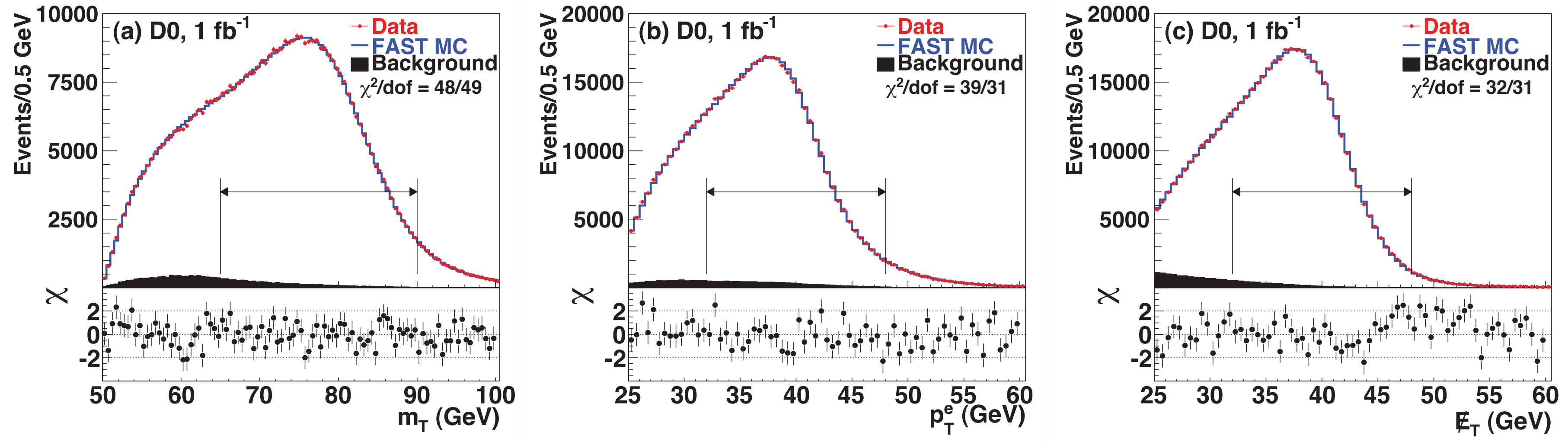
- Using leptonic *W* decays
  - M_W from template fits to the transverse mass or transverse momentum of lepton
  - Extremely challenging, systematics dominated measurement (energy calibration)
  - Combination (2009): M_W = (80.420 ± 0.031) GeV

Precision Measurement of the W mass

Recent D0 measurement of M_W in $W \rightarrow e\nu$

- Analysis relies on energy calibration with $Z \rightarrow ee$
- Result: $M_W = (80.401 \pm 0.021 \pm 0.038)$ GeV
- Greatly deserves the label *"precision measurement"*



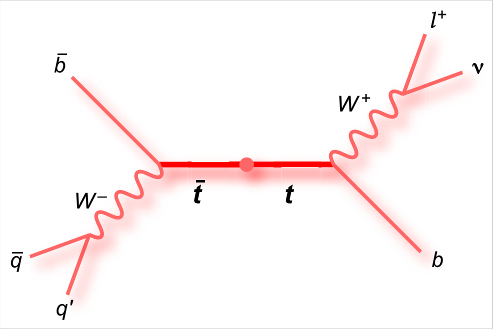


The (a) m_T , (b) $p^e{}_T$, and (c) $E_{T,miss}$ distributions for data and fastmc simulation with backgrounds. The χ values are shown below each distribution where $\chi_i = [N_i - (\text{fastmc}_i)]/\sigma_i$ for each point in the distribution, N_i is the data yield in bin i and only the statistical uncertainty is used. The fit ranges are indicated by the double-ended horizontal arrows.

Measurement of the top mass

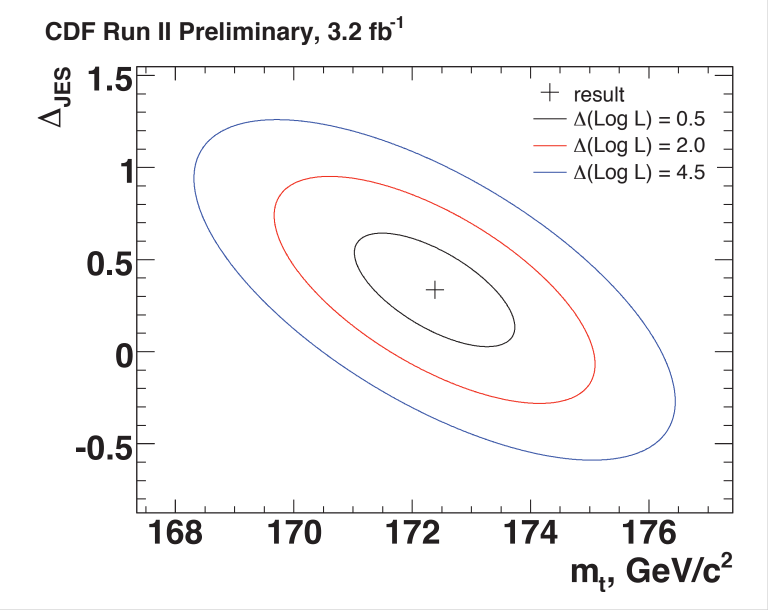
Top quark mass is measured in di-lepton (4%), lepton-jets (30%), and jets-jets (46%) modes

- Analysis relies strongly on identification of *b*-jets for background suppression and reduction of jet combinatorics
- Use multivariate methods to suppress backgrounds
- "In situ" jet energy scale (JES) calibration in modes with jets



The lepton-jets channel provides most precise m_t measurment

Fit method: parameterise templates depending on top mass and JES for sensitive variables (e.g., $M_{\text{jet-jet}}$, $M_{letp\text{-}jet}$, …), construct and maximise overall likelihood function



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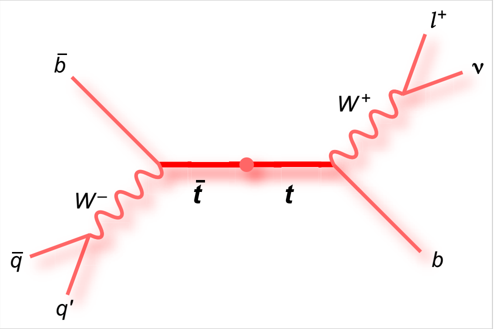

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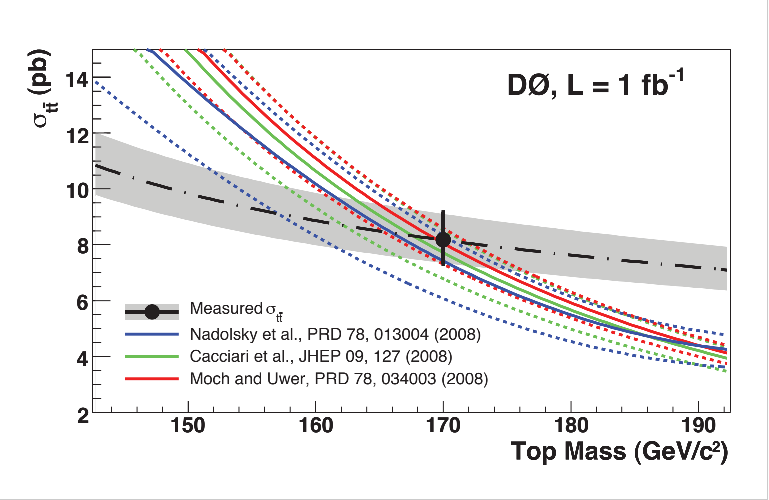
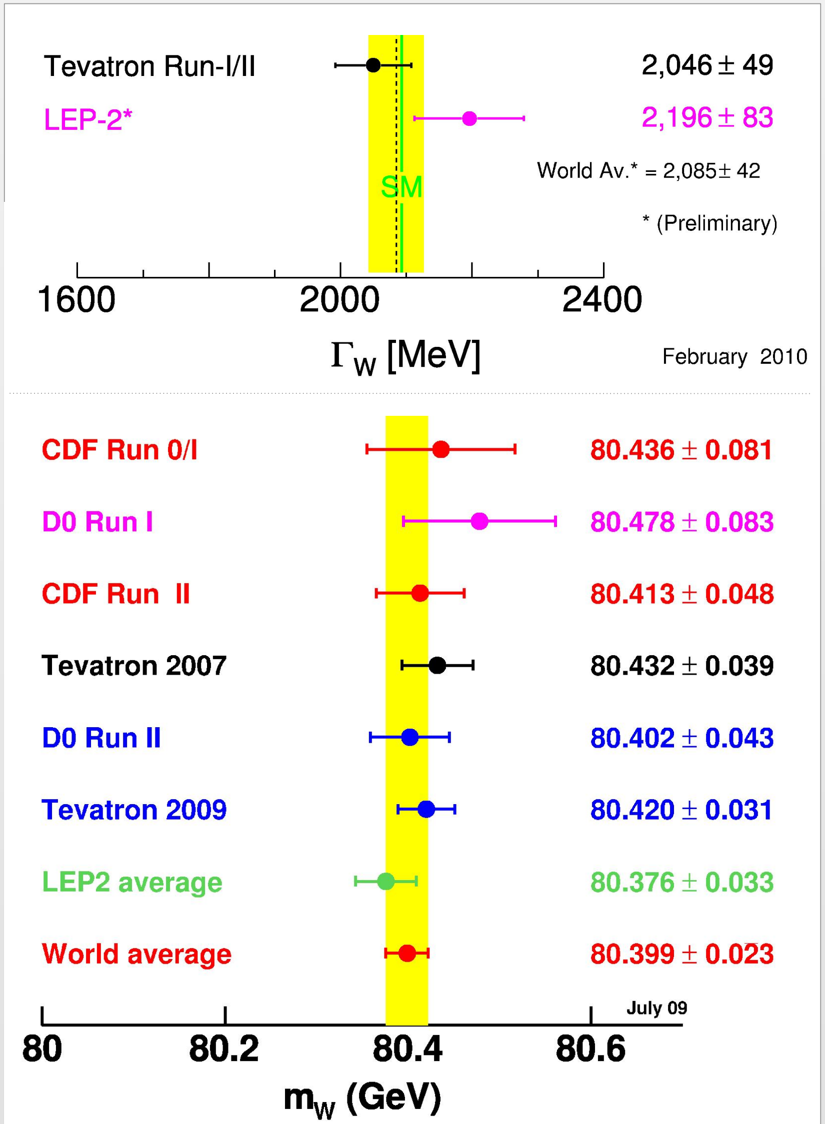
Can also extract m_t from top cross section measurement

- Complementary method [PRD 80, 071102 (2009)]
- **Unambiguous** definition of running top mass, but limited by precision on luminosity

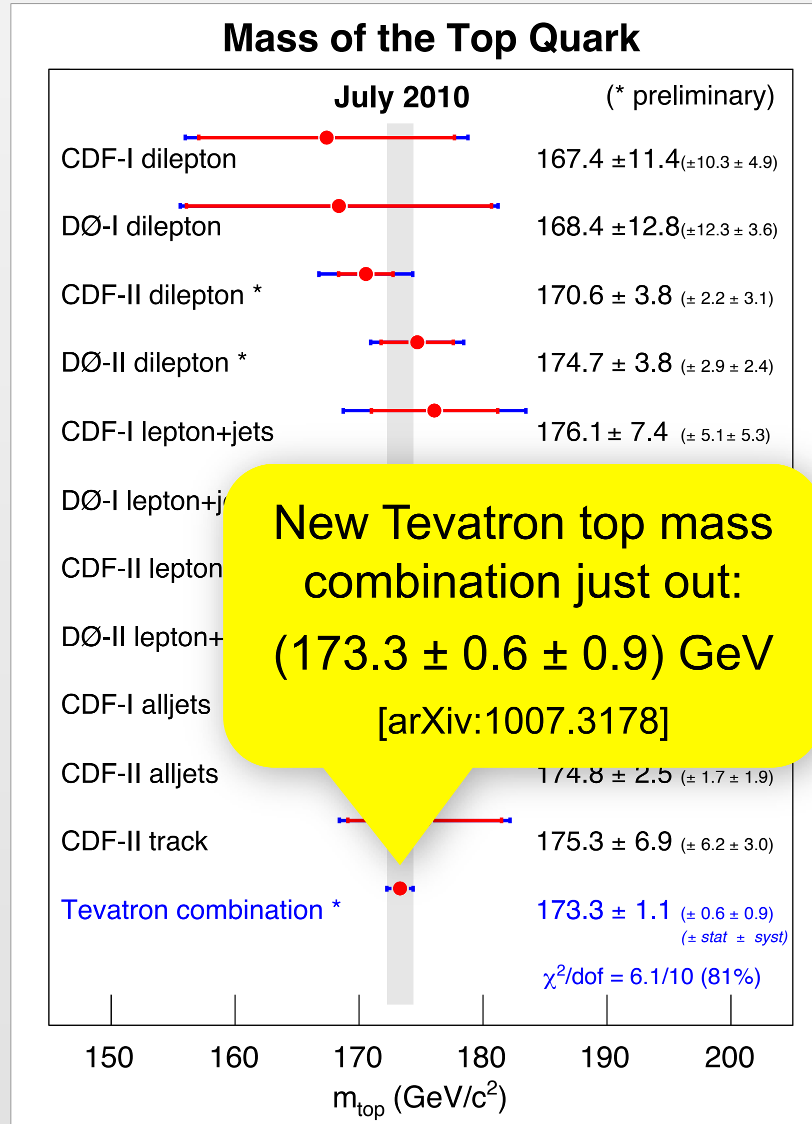


2009 Γ_W, M_W (left) and m_{top} (right) world averages

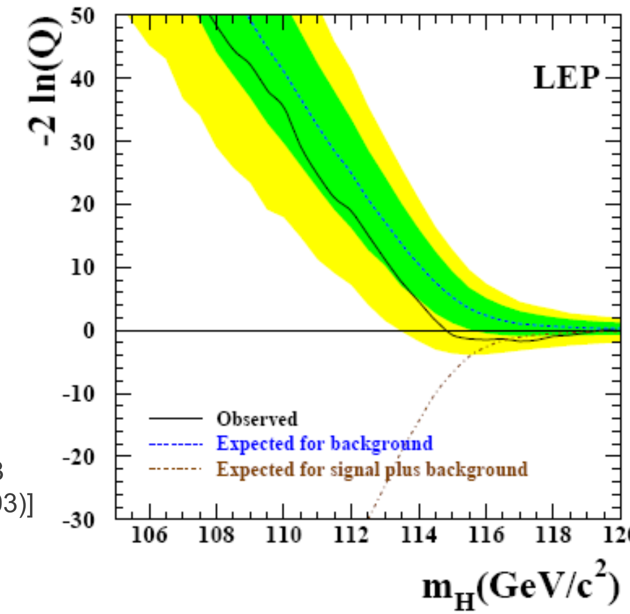
[CDF + D0, up to 1 fb–1, 0908.1374, width: D0 Note 6041-CONF]



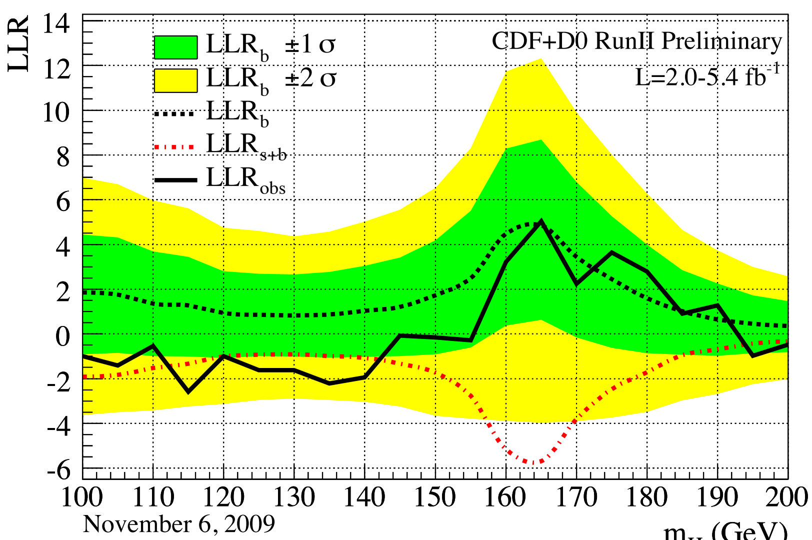
[CDF + D0, up to 5.6 fb^{-1}, arXiv:1007.3178]



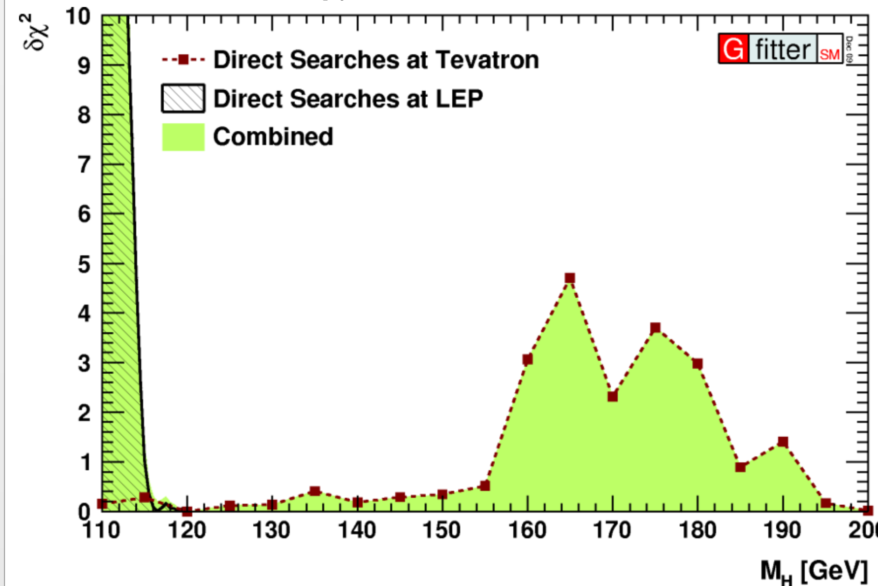
Direct Higgs Searches



[ADLO: Phys. Lett. B 565, 61 (2003)]



Combined $\delta\chi^2$ input to EW fit:



Statistical interpretation in fit: *two-sided CL_{s+b}*

- Experiments measure test statistics LLR = –2ln$Q$, where $Q = L_{s+b} / L_b$
- LLR is transformed by experiments into CL_{s+b}
- We transform 1-sided CL_{s+b} into 2-sided CL_{s+b}

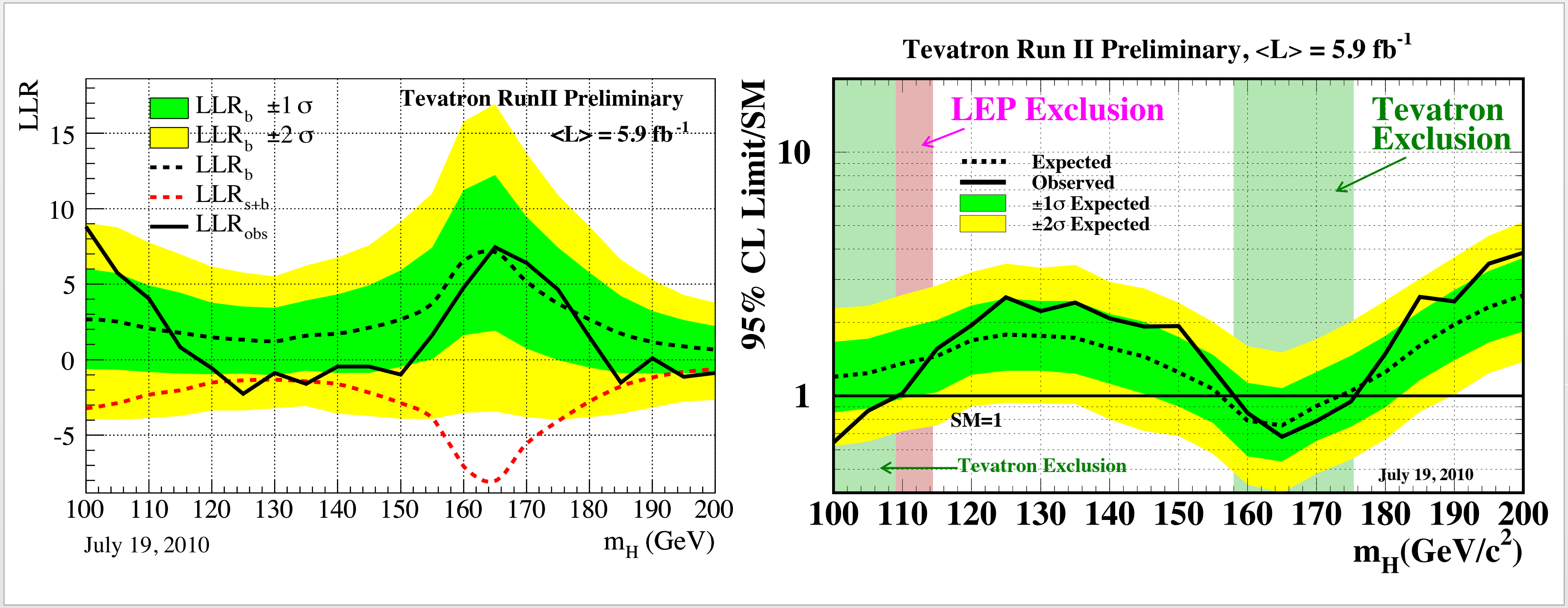
$$\Delta\chi^2 = \mathrm{Erf}^{-1}\left(1 - CL_{s+b}^{2\text{-sided}}\right)$$ (measure *deviation* from SM)

– Alternatively also directly use $\Delta\chi^2 \approx$ LLR: Bayesian interpretation, lacks pseudo-MC information

Direct Higgs Searches – New Combined Result from Tevatron

Up to 6.7 fb^{-1}. Conference Note FERMILAB-CONF-10-257-E

95% CL exclusion: $158 < M_H < 175$ GeV



Main fit results based on 2009 combination (CL_{s+b} values not yet available). Will show impact of new result.

The Global Electroweak Fit

Theory predictions – state-of-the art calculations, in particular:

- M_W and $\sin^2\theta^f_{eff}$: full two-loop + leading beyond-two-loop form factor corrections
  [M. Awramik et al., Phys. Rev D69, 053006 (2004) and ref.] [M. Awramik et al., JHEP 11, 048 (2006) and refs.]
- Radiator functions: 3NLO prediction of the massless QCD cross section
  [P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]
- Theoretical uncertainties: M_W ($\delta_{theo}(M_H)$ = 4–6 GeV), $\sin^2\theta^l_{eff}$ (δ_{theo} = $4.7\cdot10^{-5}$)

Fit parameters

- In principle, all parameters used in theory predictions are varying freely in fit
- Masses of leptons and light quarks fixed to world-averages from PDG
- Free are running charm, bottom and top masses → m_t strongest impact on fit !

→ List of freely varying parameters in the SM fit:
$\Delta\alpha_{had}^{(5)}(M_Z)$, $\alpha_S(M_Z)$, M_Z, M_H, $\overline{m}_c$, $\overline{m}_b$, m_t

http://cern.ch/Gfitter

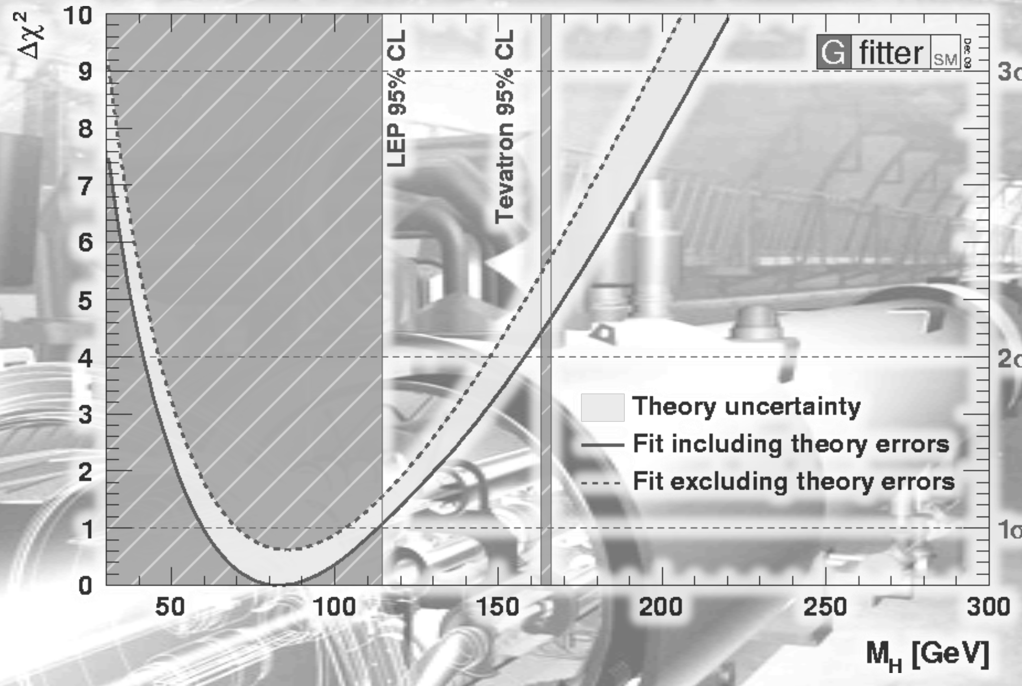
Fit Results(*)

(*) Status: July 2010

Distinguish two fit types:

Standard Fit: all data except for direct Higgs searches

Complete Fit: all data including direct Higgs searches



Experimental Input and Fit Results

Parameter	Input value	Free in fit	Results from global EW fits: *Standard fit*	*Complete fit*	*Complete fit w/o exp. input in line*
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.1974^{+0.0146}_{-0.0159}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4959 ± 0.0015	$2.4954^{+0.0016}_{-0.0013}$	$2.4954^{+0.0008}_{-0.0012}$
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.478 ± 0.014	41.472 ± 0.001	41.469 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.742 ± 0.018	20.741 ± 0.018	20.718 ± 0.027
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01638 ± 0.0002	0.01624 ± 0.0002	0.01618 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1478 ± 0.0010	0.1472 ± 0.0009	–
A_c	0.670 ± 0.027	–	$0.6682^{+0.00045}_{-0.00044}$	$0.6679^{+0.00043}_{-0.00037}$	$0.6679^{+0.00044}_{-0.00034}$
A_b	0.923 ± 0.020	–	0.93469 ± 0.00009	$0.93464^{+0.00006}_{-0.00007}$	$0.93463^{+0.00006}_{-0.00007}$
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0741^{+0.0006}_{-0.0005}$	0.0737 ± 0.0005	0.0738 ± 0.0005
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1036 ± 0.0007	0.1032 ± 0.0006	$0.1037^{+0.0004}_{-0.0005}$
R^0_c	0.1721 ± 0.0030	–	0.17225 ± 0.00006	0.17226 ± 0.00006	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	$0.21579^{+0.00004}_{-0.00006}$	0.21577 ± 0.00005	0.21577 ± 0.00005
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23145^{+0.00011}_{-0.00016}$	0.23151 ± 0.00011	$0.23148^{+0.00013}_{-0.00010}$
M_H [GeV] $^{(\circ)}$	Likelihood ratios	yes	$82.8^{+30.2[+75.2]}_{-23.2[-41.5]}$	$119.1^{+13.4[+37.9]}_{-4.0[-4.9]}$	$82.8^{+30.2[+75.2]}_{-23.2[-41.5]}$
M_W [GeV]	80.399 ± 0.023	–	$80.384^{+0.014}_{-0.015}$	$80.370^{+0.008}_{-0.010}$	$80.365^{+0.009}_{-0.026}$
Γ_W [GeV]	2.098 ± 0.048	–	2.092 ± 0.001	2.091 ± 0.001	2.092 ± 0.001
$\overline{m}_c$ [GeV]	1.25 ± 0.09	yes	1.25 ± 0.09	1.25 ± 0.09	–
$\overline{m}_b$ [GeV]	4.20 ± 0.07	yes	4.20 ± 0.07	4.20 ± 0.07	–
m_t [GeV]	173.1 ± 1.3	yes	173.2 ± 1.2	173.6 ± 1.2	$177.9^{+11.2}_{-3.5}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2769 ± 22	yes	2772 ± 22	2764 ± 22	2733^{+57}_{-46}
$\alpha_s(M_Z^2)$	–	yes	$0.1192^{+0.0028}_{-0.0027}$	0.1193 ± 0.0028	0.1193 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	4.7	0.8	–
$\delta_{\rm th}\rho^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	yes	2	2	–
$\delta_{\rm th}\kappa^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	yes	2	2	–

Correlation coefficients of 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

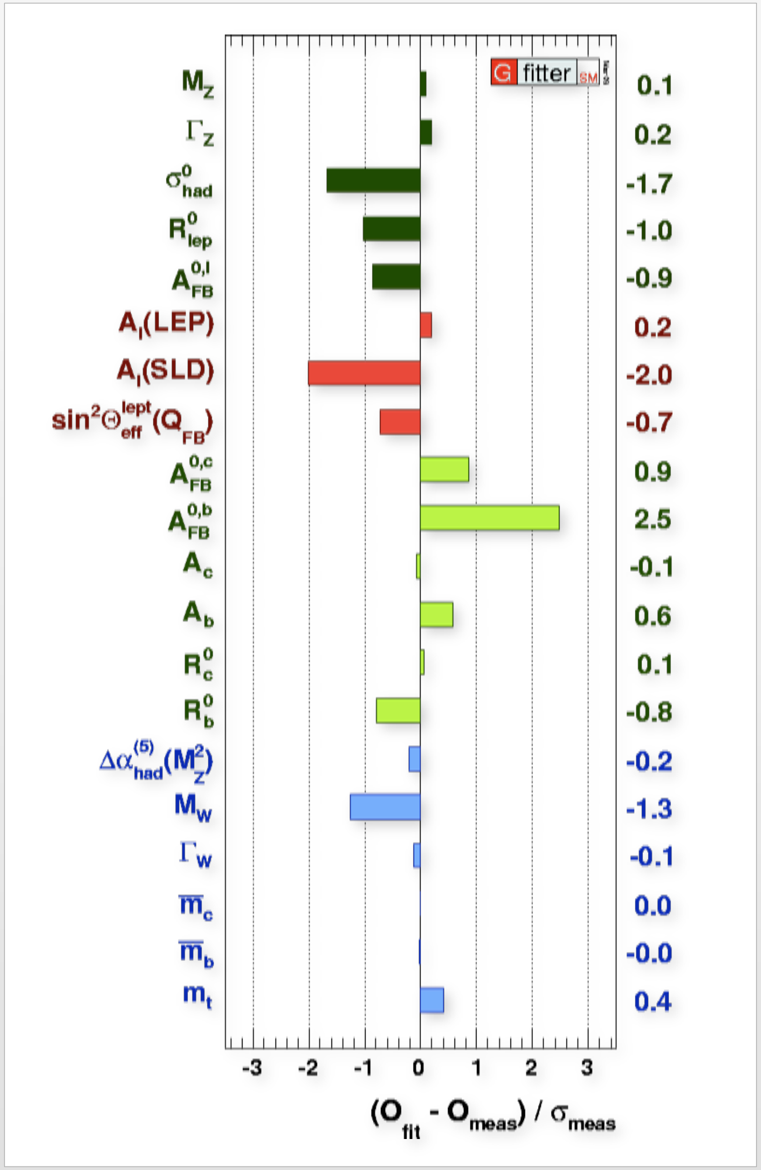
Goodness-of-Fit

Goodness-of-fit:

- *Standard fit*: $\chi^2_{min} = 16.4 \rightarrow \text{Prob}(\chi^2_{min},13) = 0.23$
- *Complete fit*: $\chi^2_{min} = 17.9 \rightarrow \text{Prob}(\chi^2_{min},14) = 0.21$
- ➠ *No requirement for new physics*

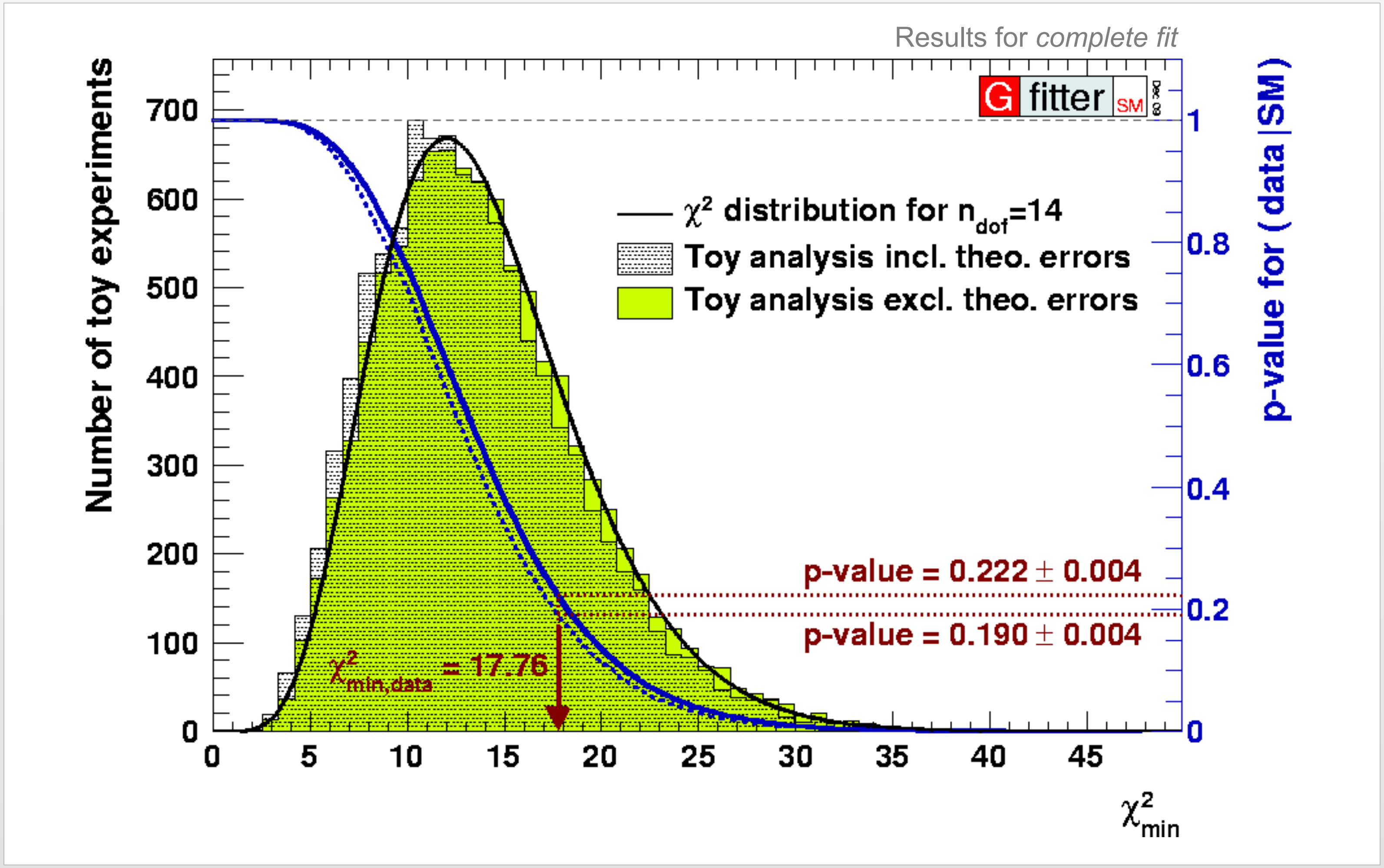
Pull values for complete fit *(right figure →)*

- No individual pull exceeds 3σ
- FB(b) asymmetry largest contributor to χ^2_{min}
- Small contributions from M_Z, $\Delta\alpha^{had}(M_Z)$, m_c, m_b indicate that their input accuracies exceed fit requirements → parameters could have been fixed in fit
- Can describe data with only two floating parameters (α_S, M_H)



Goodness-of-Fit

Toy analysis: p-value for wrongly rejecting the SM = 0.23 ± 0.01–0.02$_{theo}$



Higgs Mass Constraints

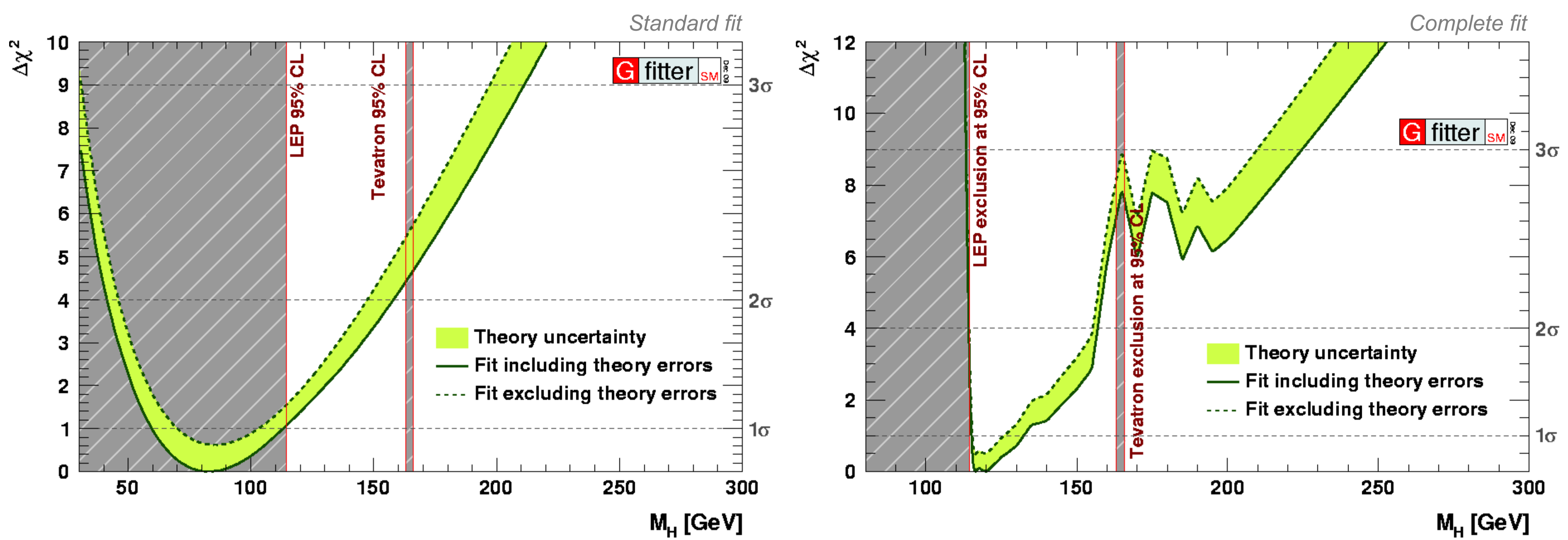
M_H from *Standard fit*:

- Central value ±1σ: $M_H = 83^{+30}_{-23}$ GeV
- 2σ interval: [42, 158] GeV

Green band due to *R*fit treatment of theory errors, fixed errors lead to larger χ^2_{min}

M_H from *Complete fit*:

- Central value ±1σ: $M_H = 119^{+13}_{-4.0}$ GeV
- 2σ interval: [114, 157] GeV



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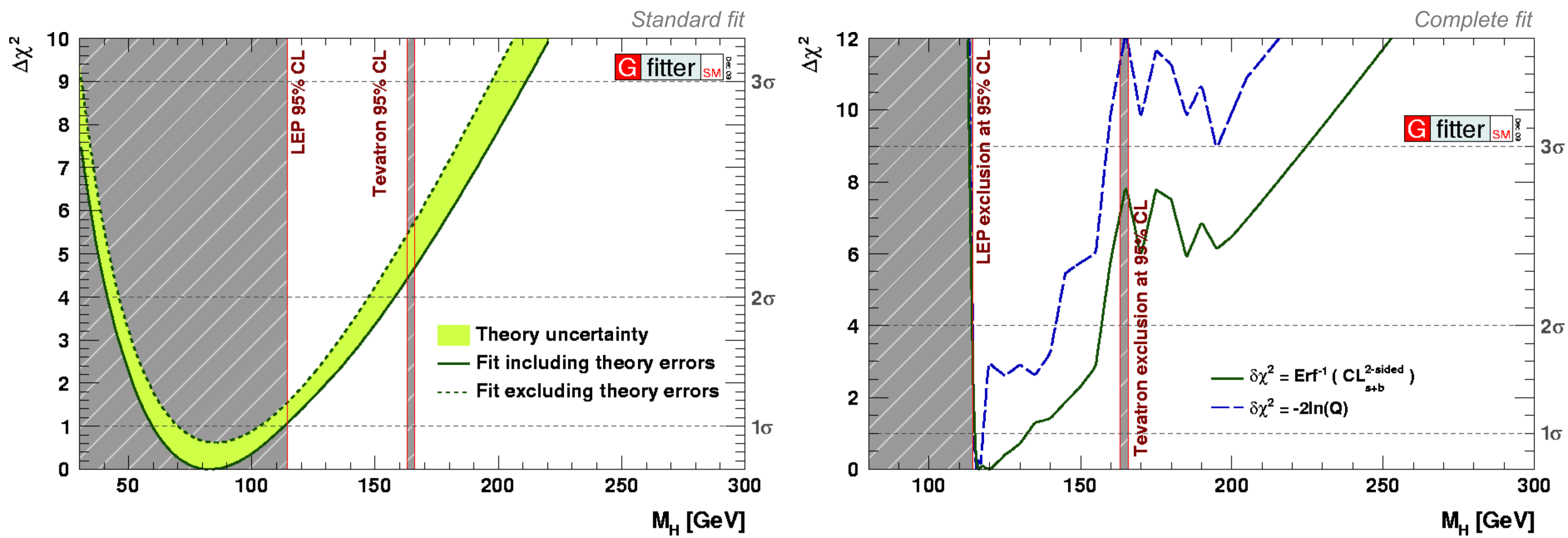
Comparison with Bayesian interpretation of LLR



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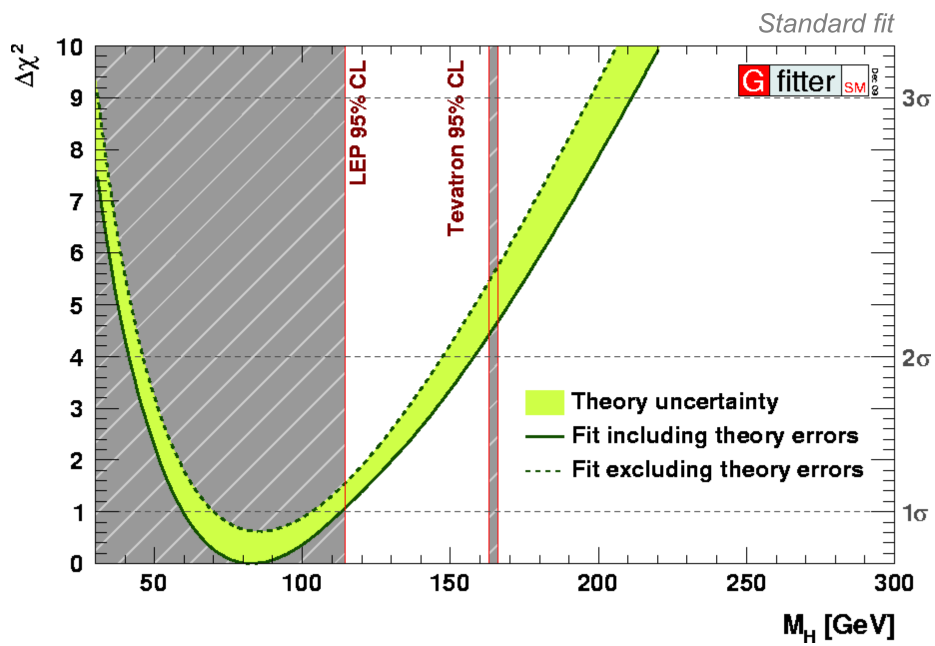

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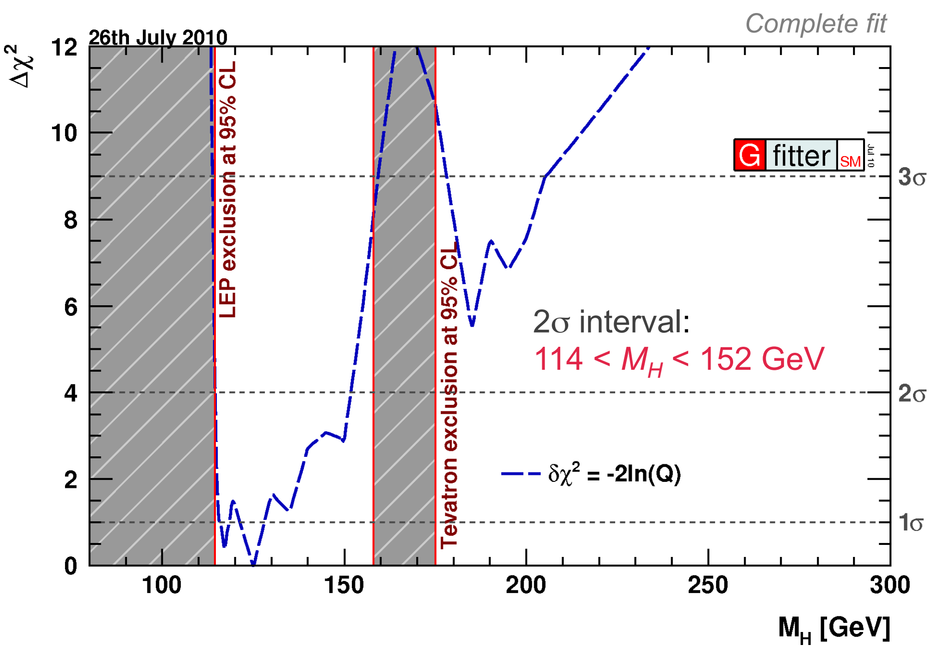
New Tevatron combination, ICHEP 2010



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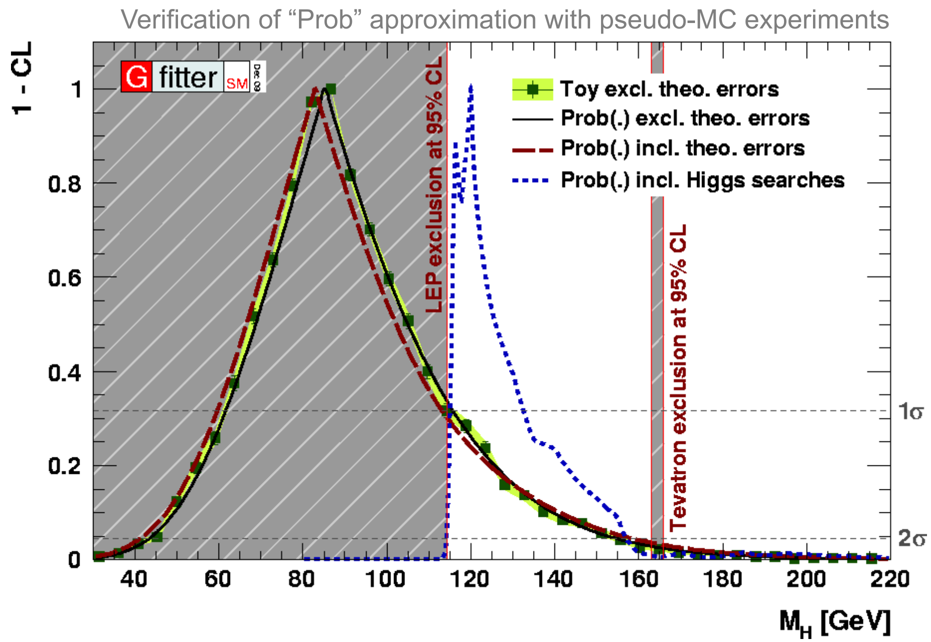

Verify Gaussian Prob($\Delta\chi^2$,1) approximation

- Fix M_H, perform two fits and calculate Prob($\Delta\chi^2(M_H) = \chi^2_{min}(M_H) - \chi^2_{min}$,1)
- Generate pseudo experiments ("toy MC") using fitted values for M_H with experimental errors
- For each toy experiment perform two fits and compute $\Delta\chi^2_{toy}(M_H)$ exactly as in real data
- Compute 1−CL at M_H by integrating normalised $\Delta\chi^2_{toy}(M_H)$ distribution from $\Delta\chi^2(M_H)$ to infinity
- **Assumes that $\Delta\chi^2_{toy}(M_H)$ distribution is independent of nuisance parameters !**

Higgs Mass Constraints

M_H from *Standard fit*:

- Central value ±1σ: $M_H = 83^{+30}_{-23}$ GeV
- 2σ interval: [42, 158] GeV

Green band due to *R*fit treatment of theory errors, fixed errors lead to larger χ^2_{min}

M_H from *Complete fit*:

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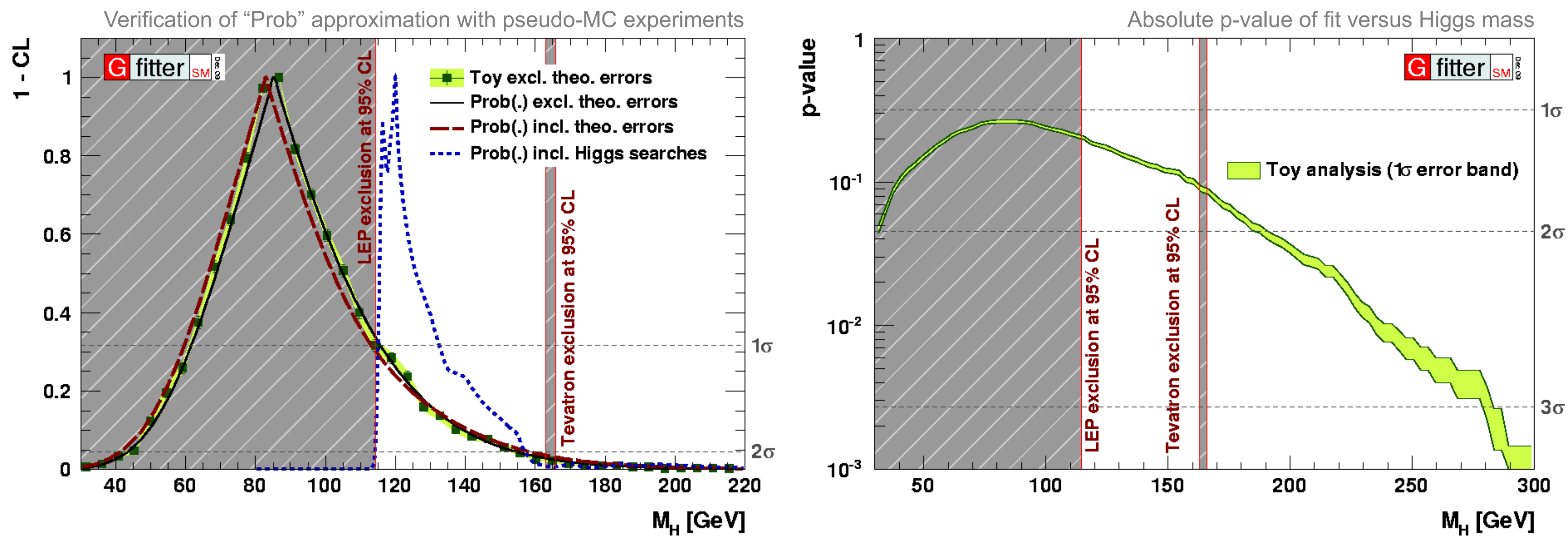
- 2σ interval: [114, 157] GeV

Curve gives the probability of wrongly rejecting SM hypothesis assuming a certain value for M_H

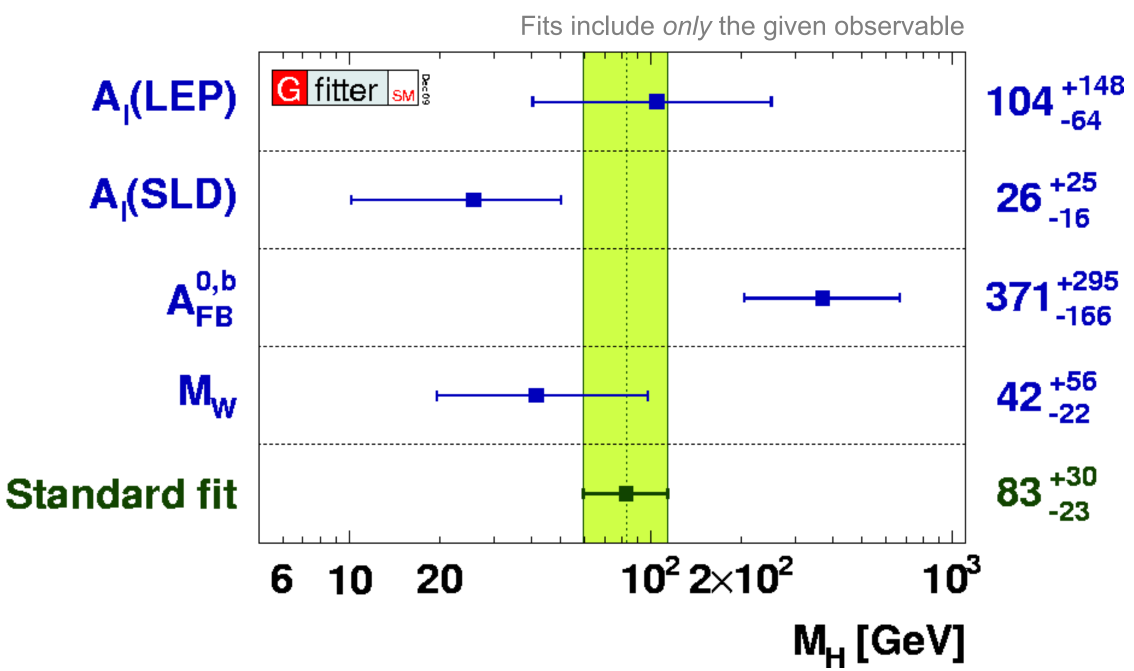


Higgs Mass Constraints

Known tension between $A^{0,b}_{FB}$ and A_{lep}(SLD) and M_W:

- Pseudo-MC analysis to evaluate
  "Probability to observe a $\Delta\chi^2$ = 8.0 when removing the least compatible input"
  → accounts for "look-elsewhere effect"

- Find: 1.4% (2.5σ)



Top Mass

Quadratic sensitivity to m_{top}

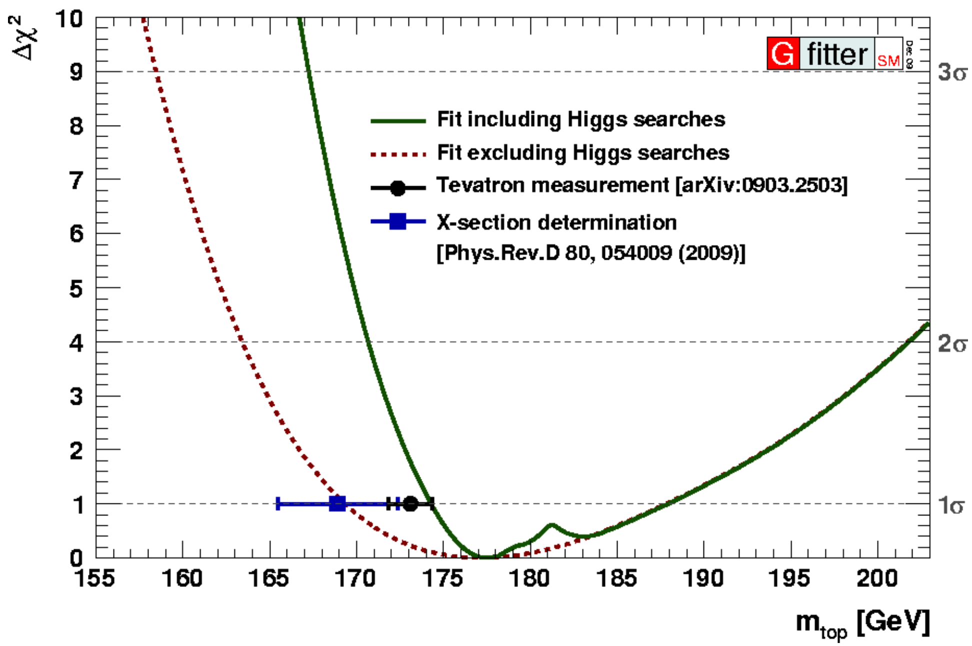
- *Standard fit*: $m_{top} = 177.2\,^{+10.5}_{-7.8}$ GeV
- *Complete fit*: $m_{top} = 177.9\,^{+11.2}_{-3.5}$ GeV

Tevatron average: (173.1 ± 1.3) GeV

For Standard fit with free m_{top} find: $m_H = 116\,^{+184}_{-61}$ GeV

Note: profile of the *standard fit* exhibits an asymmetry opposite to the naïve expectation from $\sim m_t^2$ dependence of loop corrections

Reasons: floating Higgs mass and its positive correlation with m_t



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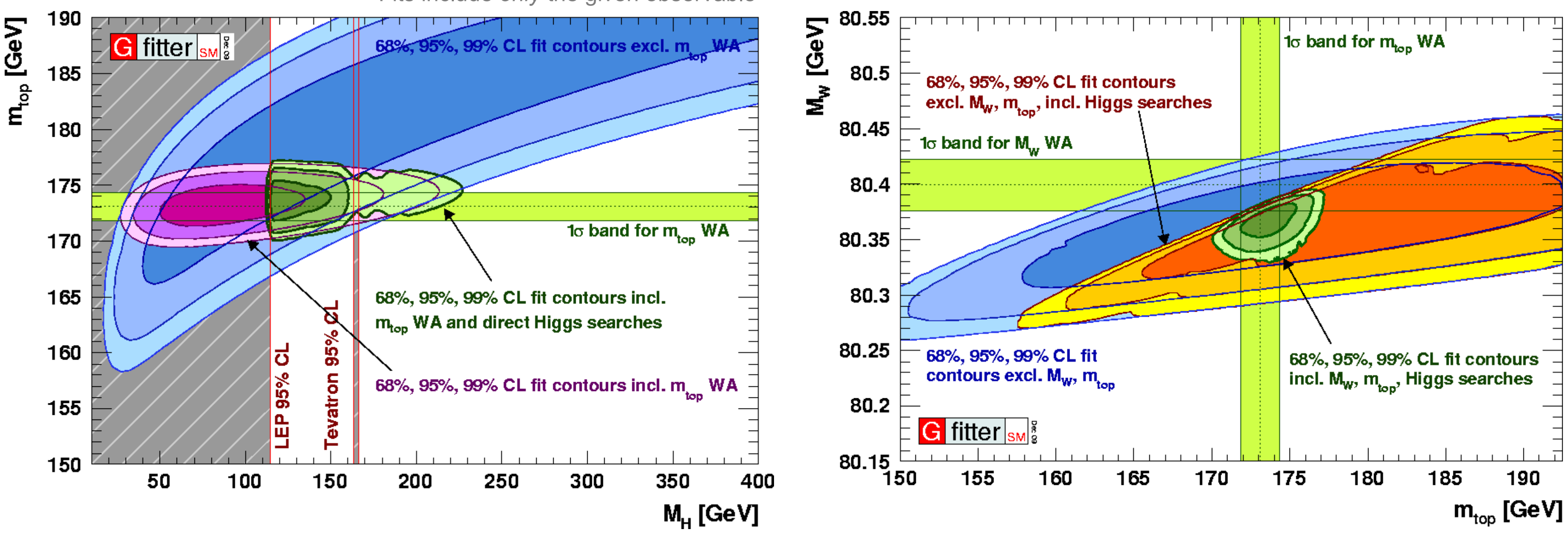
Fit (*i.e.* excluding the Higgs searches and the respective measurements)

Fit + Higgs searches

Fit + Higgs searches + direct measurements → best knowledge of SM

Fits include *only* the given observable



$\Delta\alpha_{\text{had}}(M_Z)$

Strong sensitivity to $\Delta\alpha_{\text{had}}(M_Z)$

- *Complete fit*: $\Delta\alpha_{\text{had}}^{(5)}(M_Z^2) = (273.3\ ^{+5.7}_{-4.6}) \cdot 10^{-4}$

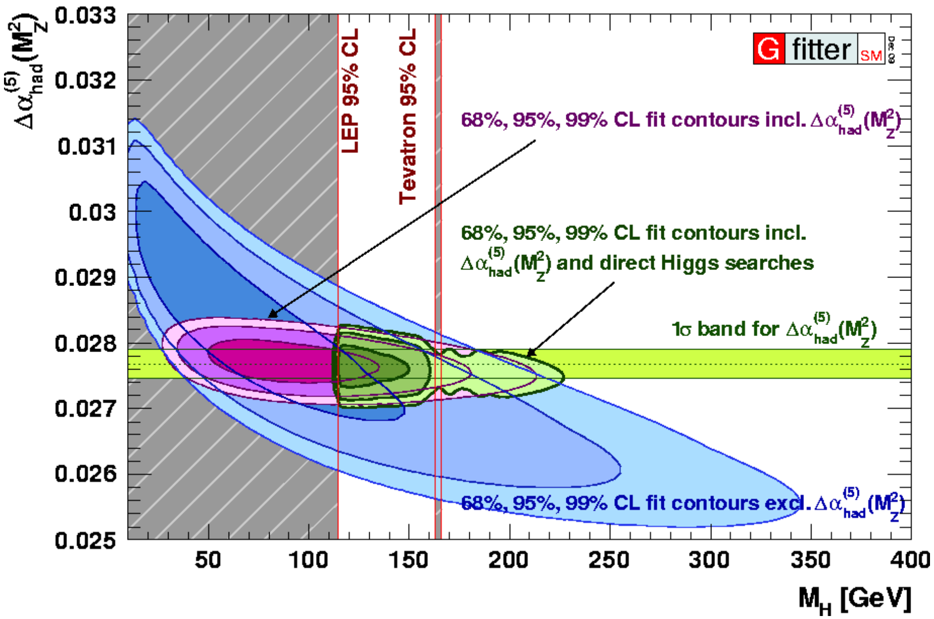
Phenomenological value: $(277.2 \pm 2.2)\ 10^{-4}$

Fit (*i.e.* excluding the Higgs searches and the respective measurements)

Fit + Higgs searches

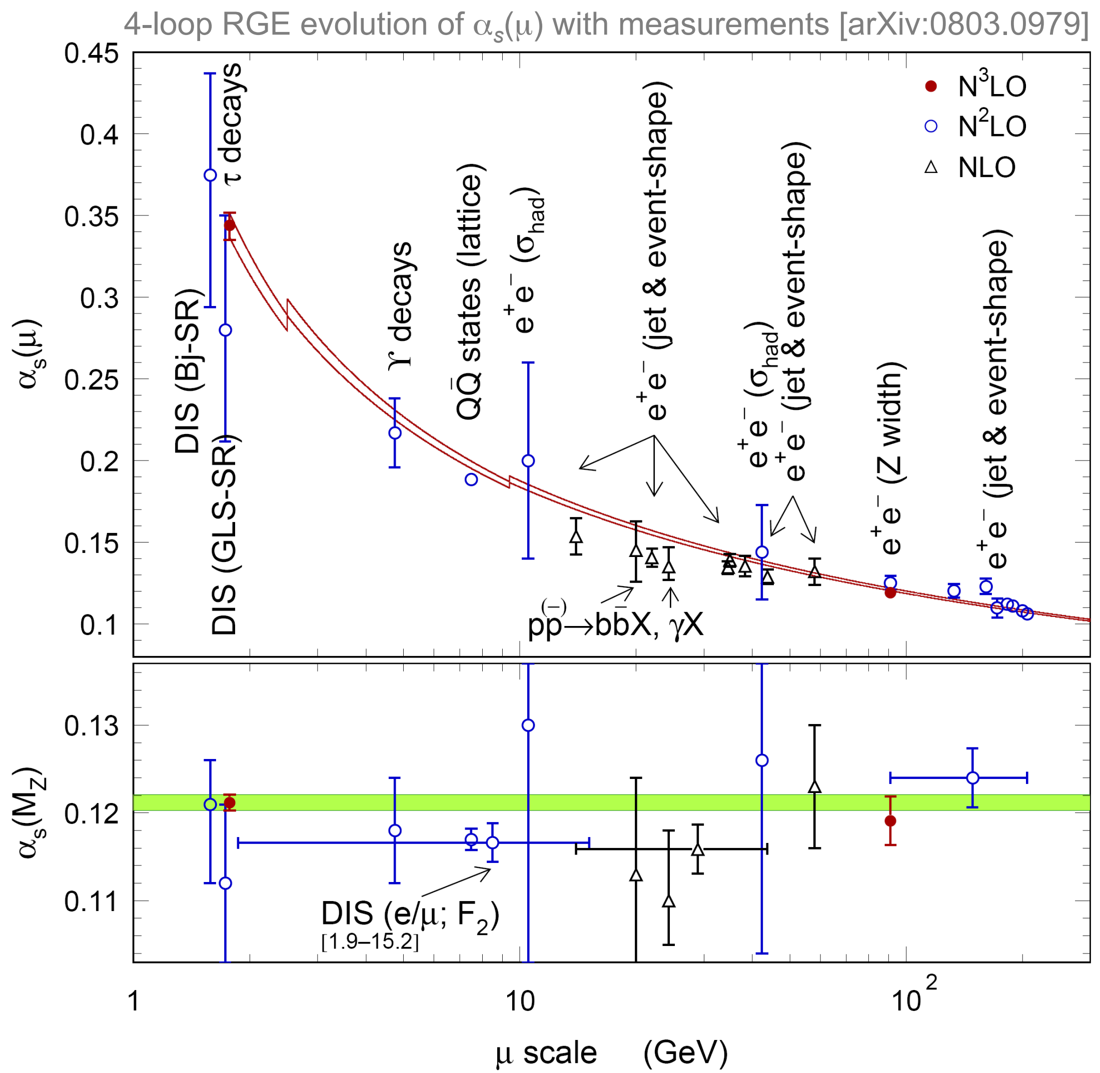
Fit + Higgs searches + direct measurements
→ best knowledge of SM

Fits include *only* the given observable



- The structures reflect presence of local minima in ($\Delta\chi^2$ vs. M_H)-plot
- Today's precision in m_t and $\Delta\alpha_{\text{had}}(M_Z)$ sufficient for the EW fit

3NLO Determination of α_s



From Complete Fit:

$\alpha_s(M_Z) = 0.1193 \pm 0.0028 \pm 0.0001$

- First error experimental
- Second error theoretical (!)
  [incl. variation of renorm. scale from $M_Z/2$ to $2M_Z$ and massless terms of order/beyond $a_S^5(M_Z)$ and massive terms of order/beyond $a_S^4(M_Z)$]
- Excellent agreement with N³LO result from hadronic τ decays
  [M. Davier et al., arXiv:0803.0979]

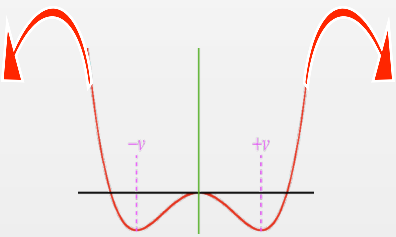
  $\alpha_s(M_Z) = 0.1212 \pm 0.0005_{exp} \pm 0.0008_{theo} \pm 0.0005_{evol}$
- Best current test of asymptotic freedom property of QCD !

The Fate of the Standard Model

Driving the SM to M_{Planck}

The behaviour of the quartic Higgs couplings as function of the cut-off scale Λ puts bounds on M_H

- **For too large M_H,** the couplings become non-perturbative ("triviality" or "blow-up" scenario)
- **For too small M_H,** the vacuum becomes unstable



(Absolute) stability criterion:

$\lambda(\mu) > 0, \ \forall\mu < \Lambda_{\text{cut-off}}$

Driving the SM to M_{Planck}

The behaviour of the quartic Higgs couplings as function of the cut-off scale Λ puts bounds on M_H

- **For too large M_H,** the couplings become non-perturbative ("triviality" or "blow-up" scenario)
- **For too small M_H**, the vacuum becomes unstable

The "unstable" region is not necessarily incompatible with our existence, as long as the electroweak vacuum survives for a time longer than the age of the universe, before quantum tunneling.

Its probability is given by

$$p = \max_{h<\Lambda}\left\{V_U h^4 \cdot \exp\left(-\frac{8\pi^2}{3\,|\lambda(h)|}\right)\right\}, \text{ where } V_U = \tau_U^4$$

and V_U is space-time volume of the past light cone of the observable universe, and τ_U = 13.7 Gyrs. For the bound, one requires $p < 1$.

Driving the SM to M_{Planck}

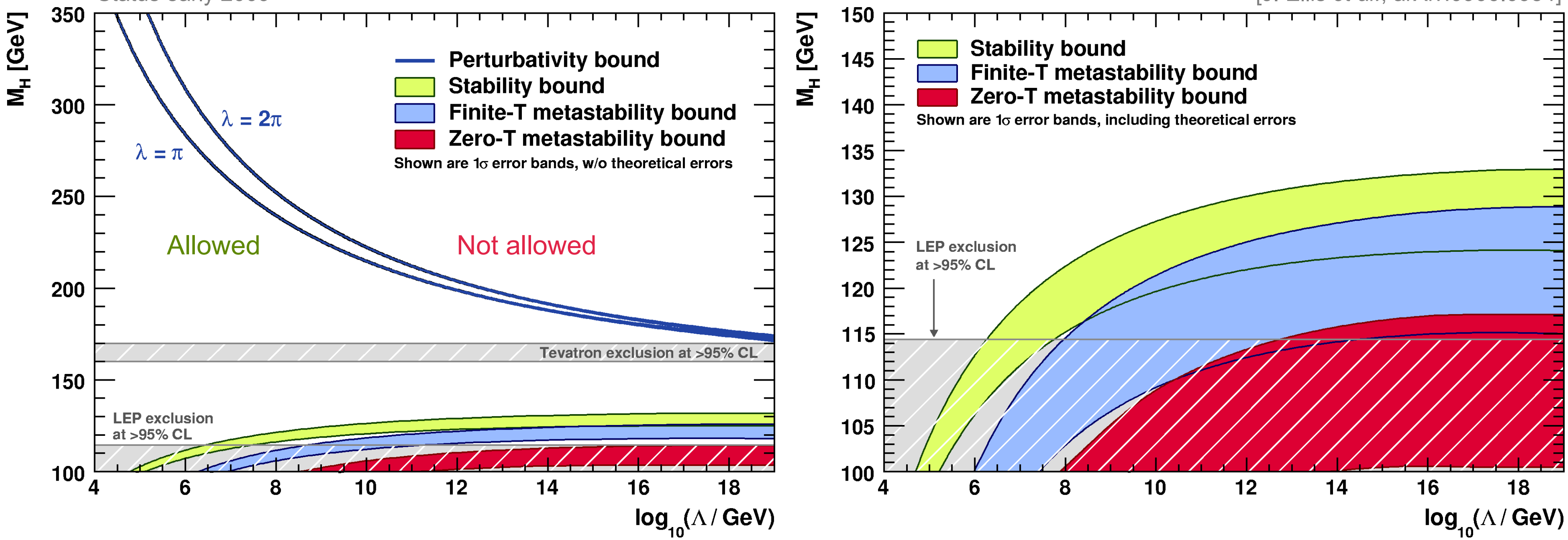
The behaviour of the quartic Higgs couplings as function of the cut-off scale Λ puts bounds on M_H

- **For too large M_H,** the couplings become non-perturbative ("triviality" or "blow-up" scenario)
- **For too small M_H,** the vacuum becomes unstable

→ obtain three lower bounds on M_H from different requirement: **absolute stability, finite-*T* and zero-*T* metastability**

Status early 2009

[J. Ellis *et al.*, arXiv:0906.0954]



Driving the SM to M_{Planck}

- Requiring that the SM cannot develop a minimum deeper than the electroweak vacuum up to the Planck scale (i.e., $\lambda(\mu) > 0$, for all $\mu < \Lambda$) gives the ***stability bound*** :

$$M_H > 128.6\ \text{GeV} + 2.6\ \text{GeV} \cdot \left(\frac{m_t - 173.1\ \text{GeV}}{1.3\ \text{GeV}} \right) - 2.2\ \text{GeV} \cdot \left(\frac{\alpha_S(M_Z) - 0.1193}{0.0028} \right) \pm 1\ \text{GeV}$$

Theoretical error from missing higher order corrections in the RGE

Driving the SM to M_{Planck}

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- Requiring that the local EW vacuum survives for a time longer than the age of the universe, before quantum tunneling into the deeper vacuum, gives ***zero-T metastability bound*** :

$$M_H > 108.9\ \text{GeV} + 4.0\ \text{GeV} \cdot \left(\frac{m_t - 173.1\ \text{GeV}}{1.3\ \text{GeV}} \right) - 3.5\ \text{GeV} \cdot \left(\frac{\alpha_S(M_Z) - 0.1193}{0.0028} \right) \pm 3\ \text{GeV}$$

- Requiring the local SM minimum to be stable against thermal fluctuations up to temperatures as large as the Planck scale translates into ***finite-T metastability bound*** :

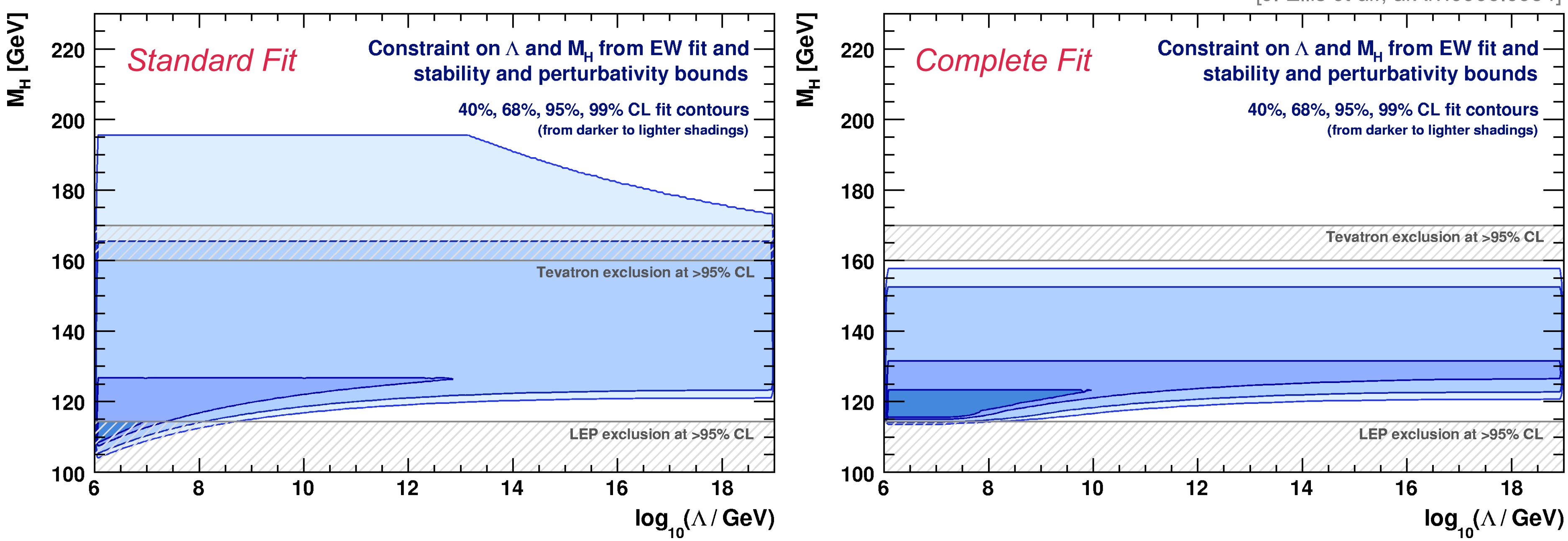
$$M_H > 122.0\ \text{GeV} + 3.0\ \text{GeV} \cdot \left(\frac{m_t - 173.1\ \text{GeV}}{1.3\ \text{GeV}} \right) - 2.3\ \text{GeV} \cdot \left(\frac{\alpha_S(M_Z) - 0.1193}{0.0028} \right) \pm 3\ \text{GeV}$$

Convolve Bounds with M_H Constraints

Can we obtain likelihoods on vacuum stability (or, likewise, the cut-off = new physics scale Λ) from constraint on M_H ?

- Non-perturbativity excluded at 95.7% CL → raise to 99.1% with Tevatron Higgs searches !
- Cannot distinguish between vacuum stability, metastability or collapse scenarios
  → requires M_H > 122 GeV to exclude collapse scenario at 95% CL

[J. Ellis *et al.*, arXiv:0906.0954]

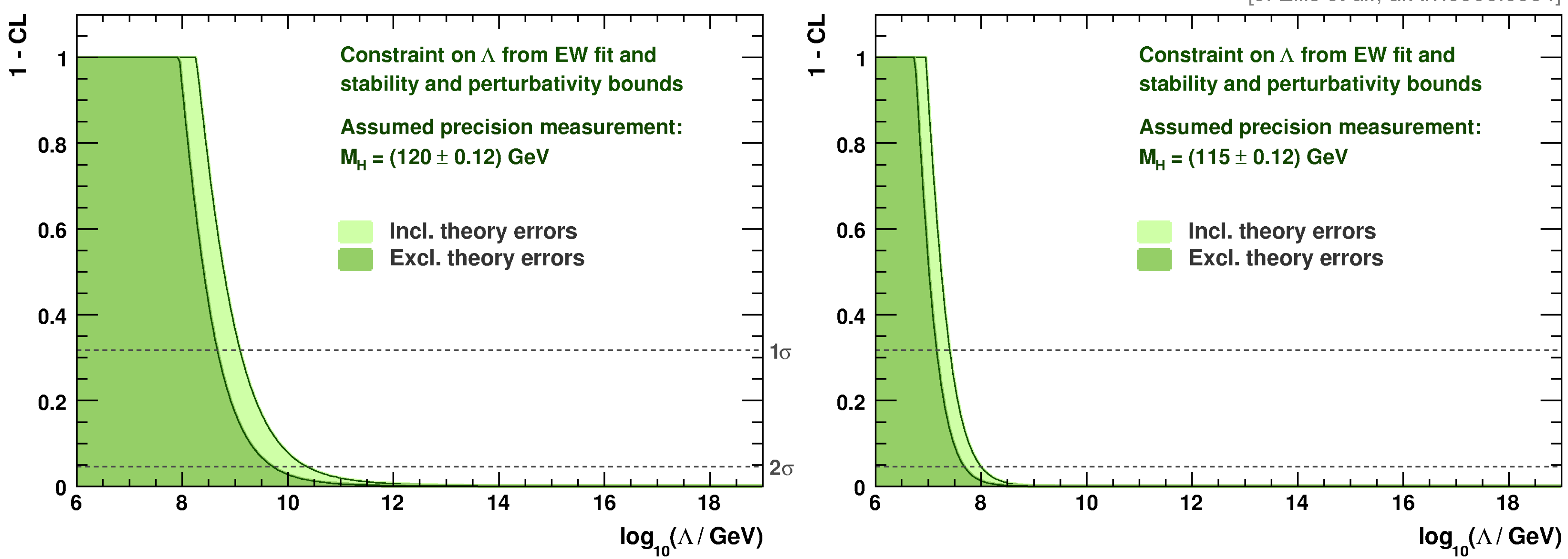


Convolve Bounds with M_H Constraints

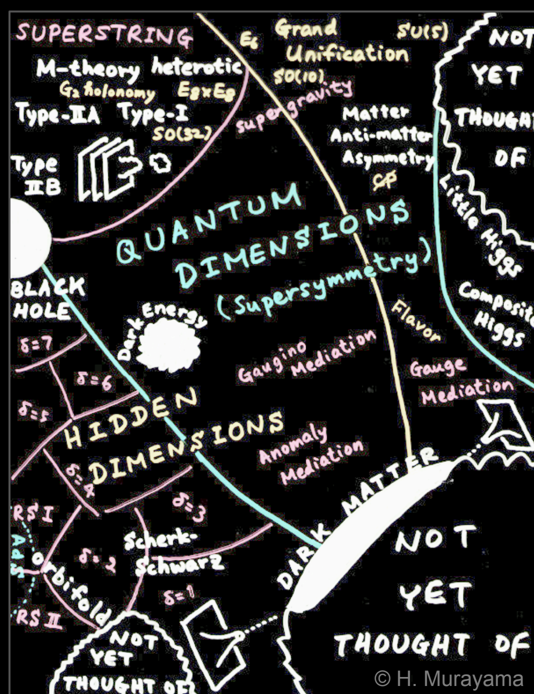
Can we obtain likelihoods on vacuum stability (or, likewise, the cut-off = new physics scale Λ) from constraint on M_H ?

- Requiring absolute vacuum stability (at all times), one can obtain upper bound Λ
  - Left plot: case for precise M_H measurement of **120 GeV**
  - Right plot: case for precise M_H measurement of **115 GeV**

[J. Ellis *et al.*, arXiv:0906.0954]

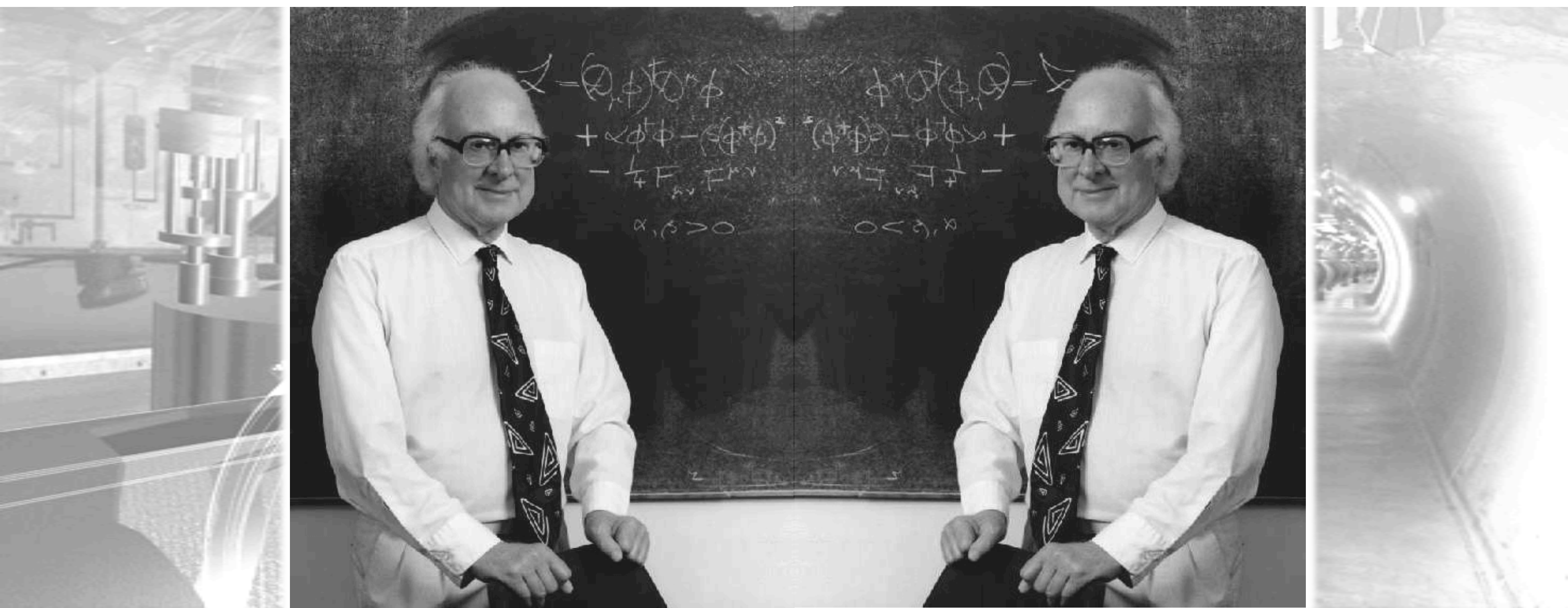


Precision Tests and Higgs Beyond the SM



In the same way as the EW precision data constrain unknown SM parameters, they can be used to constrain beyond the SM models

The Two-Higgs-Doublet Model (2HDM)



Two-Higgs-Doublet Model

Extend SM by adding another scalar Higgs doublet (2HDM)

- *Type-II* 2HDM: one doublet couples to up-type and the other one to down-type fermions only
- 6 free parameters: $\underline{M_h}$, M_{A0}, M_{H0}, $M_{H\pm}$, $\tan\beta = v_2 / v_1$, α (governing h–H^0 mixing)
- Resembles Higgs sector of MSSM

Look, *e.g.*, at processes sensitive to charged Higgs: $M_{H\pm}$

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

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

Sensitive observables mostly from *B*-physics sector, but also *c* and *s*

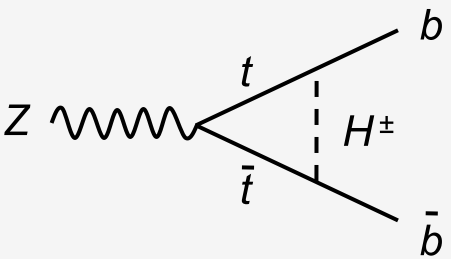
Two-Higgs-Doublet Model

Observables used to constrain charged Higgs in 2HDM

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 $(B \to X_s\gamma)$	$(3.52 \pm 0.23 \pm 0.09)\cdot 10^{-4}$	[HFAG, latest update]	[M. Misiak et al., Phys. Rev. Lett. 98, 022002 (2007)]
BR $(B \to \tau\nu)$	$(1.73 \pm 0.33)\cdot 10^{-4}$	[P.Chang, Talk at ICHEP 2008]	[W. S. Hou, Phys. Rev. D48, 2342 (1993)]
BR $(B \to \mu\nu)$	$(-5.7\pm6.8\pm7.1)\cdot 10^{-4}$	[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]

R_b^0 and $B \to X_s\gamma$

Z-vertex correction $\propto \cot^2\beta$

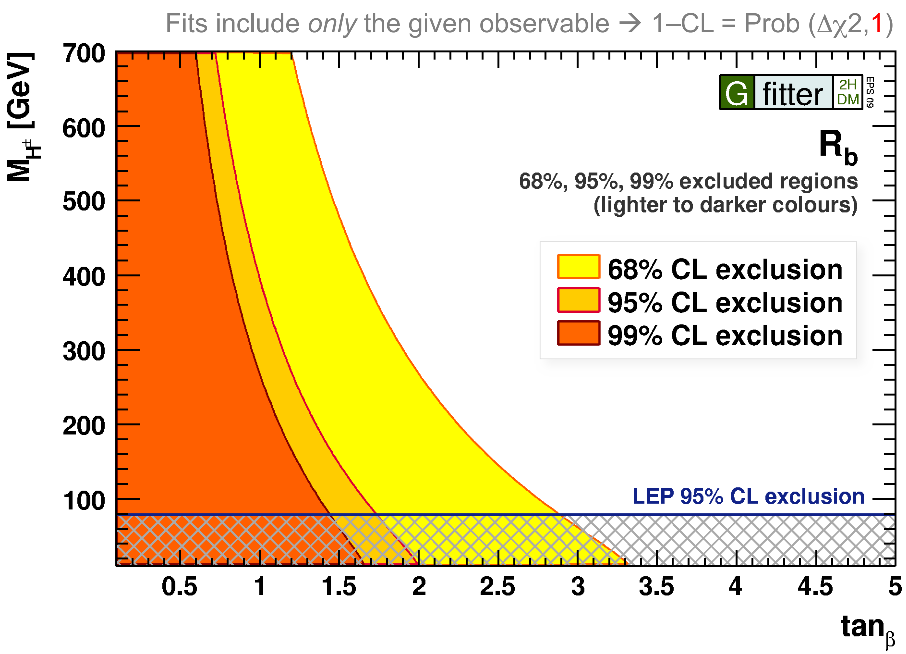


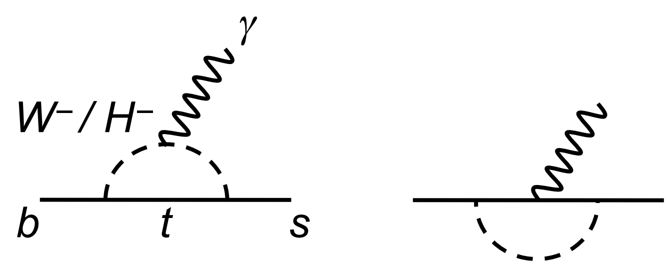
R_b^0 sensitive to small $\tan\beta$ only

Penguin dipole-moment of $B \to X_s\gamma$ allows combination of left and right-handed Higgs couplings.

Wilson coefficient:

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





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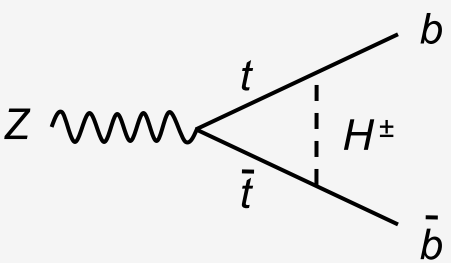

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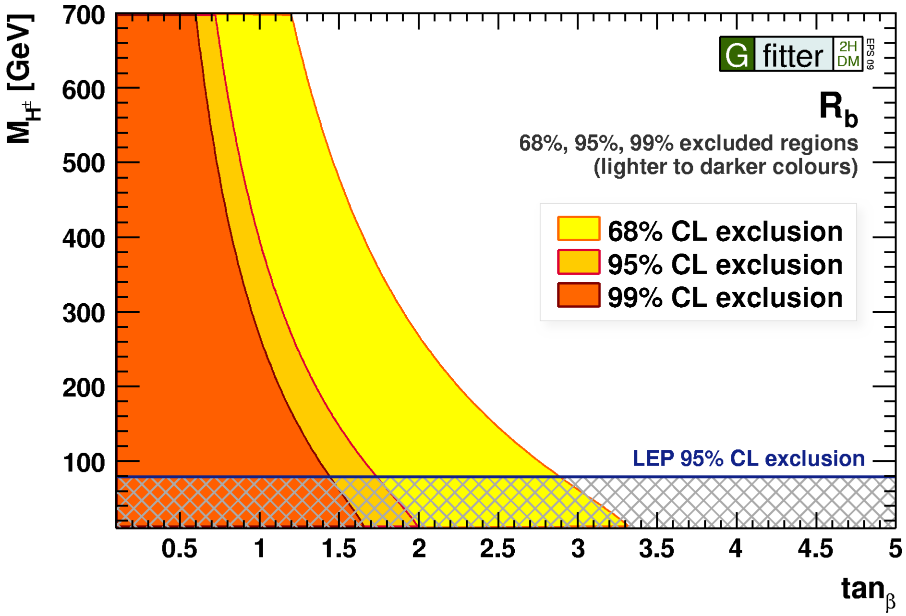
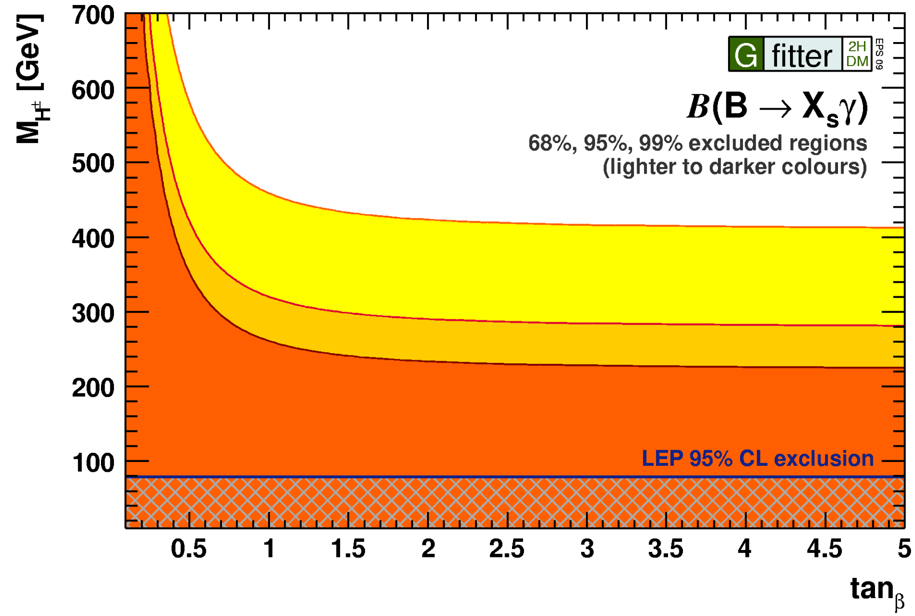
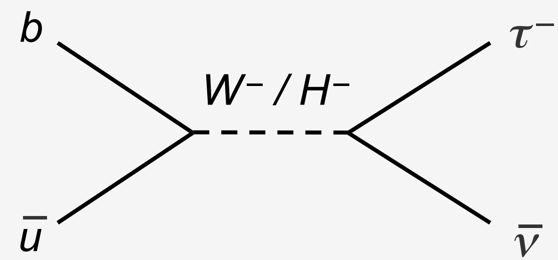
Fits include *only* the given observable → 1–CL = Prob (Δχ2,1)





$B \to \tau\nu$

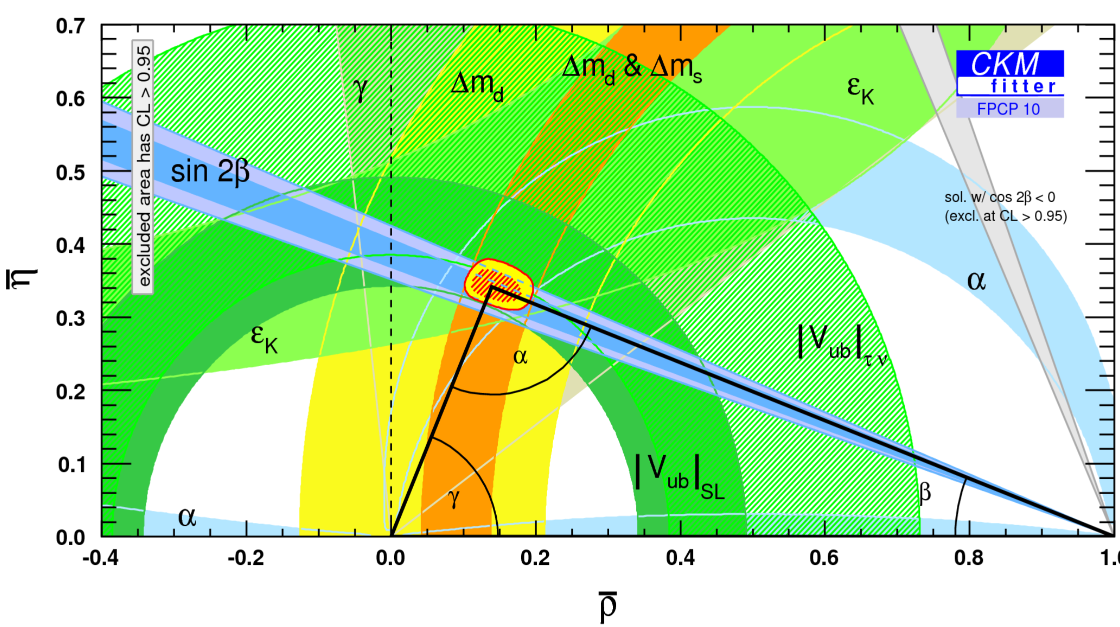


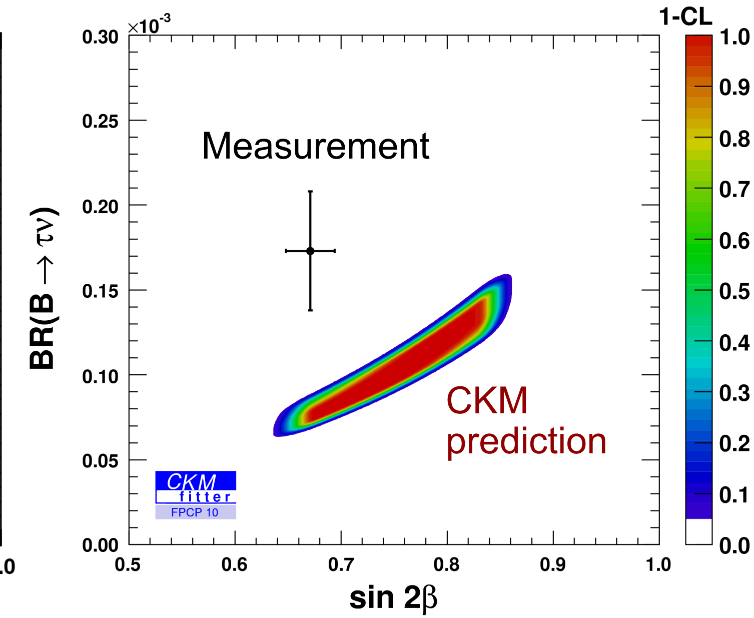
Weak annihilation process. BR proportional to $|V_{ub}|^2$ and B decay constant-squared f_B^2

$$\Gamma(B \to \tau\nu) = \frac{G_F}{8\pi} \cdot m_{B^+} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 \cdot f_B^2 \left|V_{ub}\right|^2 \cdot \left(1 - \frac{m_{B^+}^2}{M_{H^\pm}^2} \tan^2\beta\right)^2$$

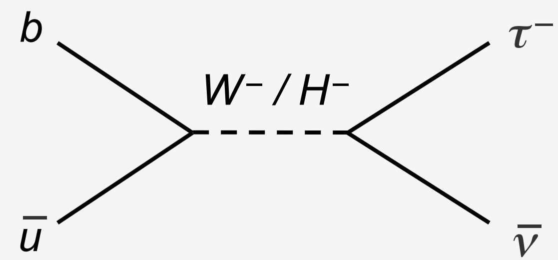
Quadratic solution
Strength of effect $\propto \tan\beta$

Conflict (2.6σ) between direct BR measurement and SM prediction governed by CKM angle β





$B \rightarrow \tau\nu$



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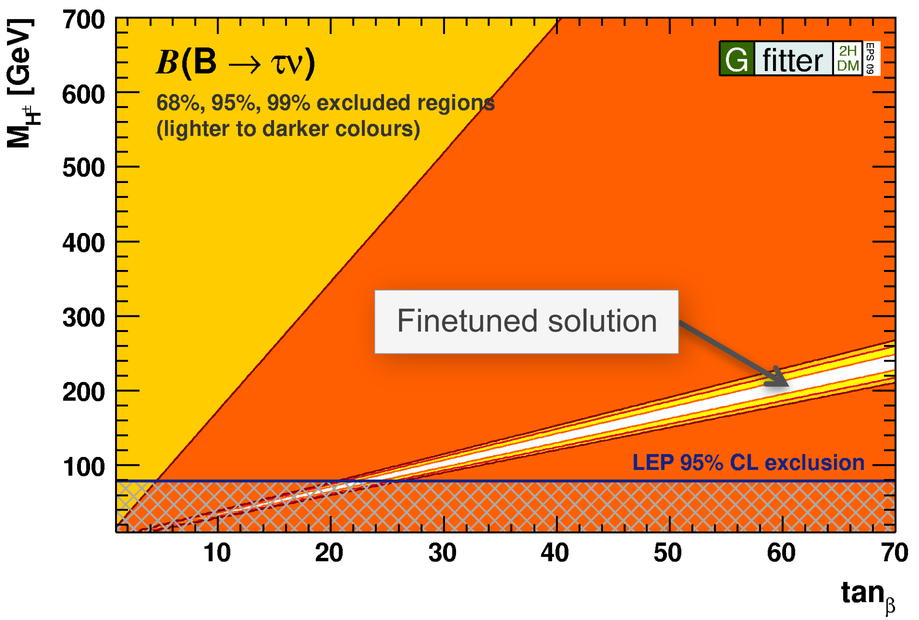
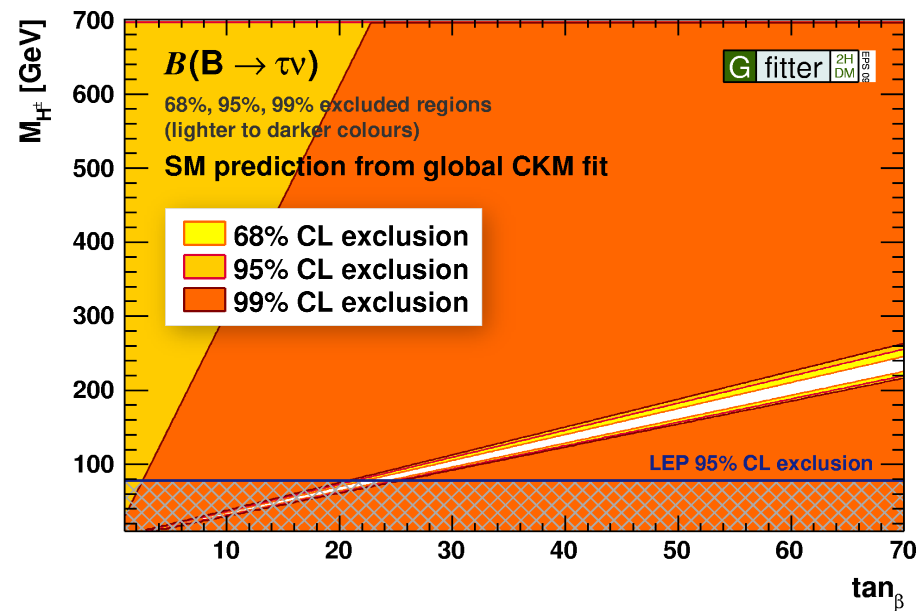
Quadratic solution
Strength of effect $\propto \tan\beta$

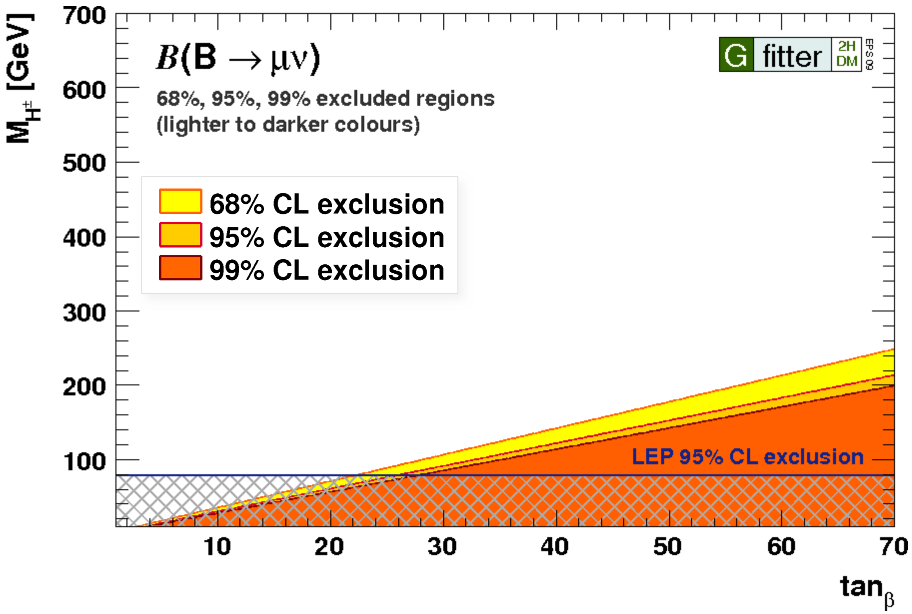
Compare BR predictions based on direct measurements of $|V_{ub}|$ (left) with CKM fit (right)

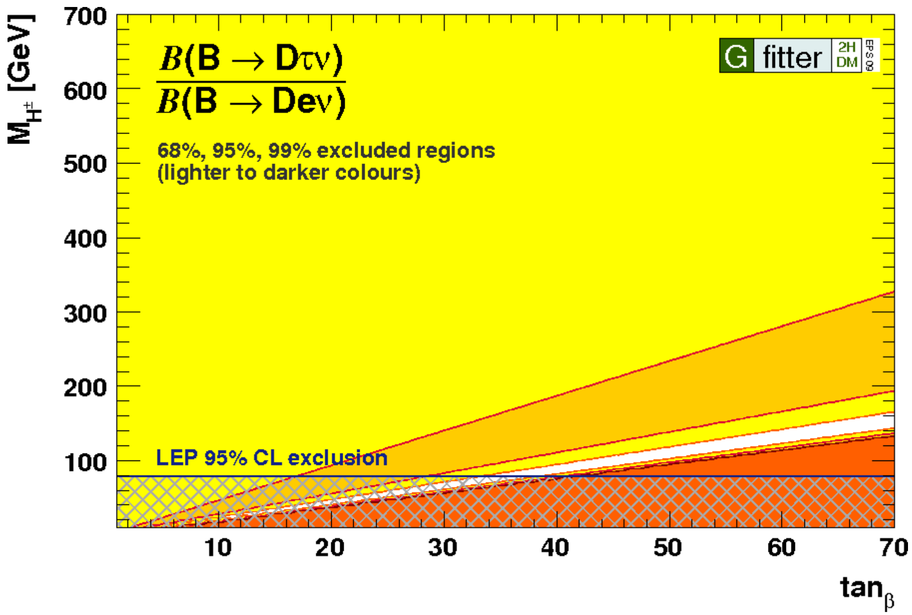




Other measurements with tree level contributions

- Weak upper limit on BR($B \rightarrow \mu\nu$)
- Favored solution of BR($B \rightarrow \tau\nu$) excluded by combination of:
  - BR($B \rightarrow X_s\gamma$)
  - BR($B \rightarrow D\tau\nu$) / BR($B \rightarrow De\nu$)
  - BR($K \rightarrow \mu\nu$) / BR($\pi \rightarrow \mu\nu$)





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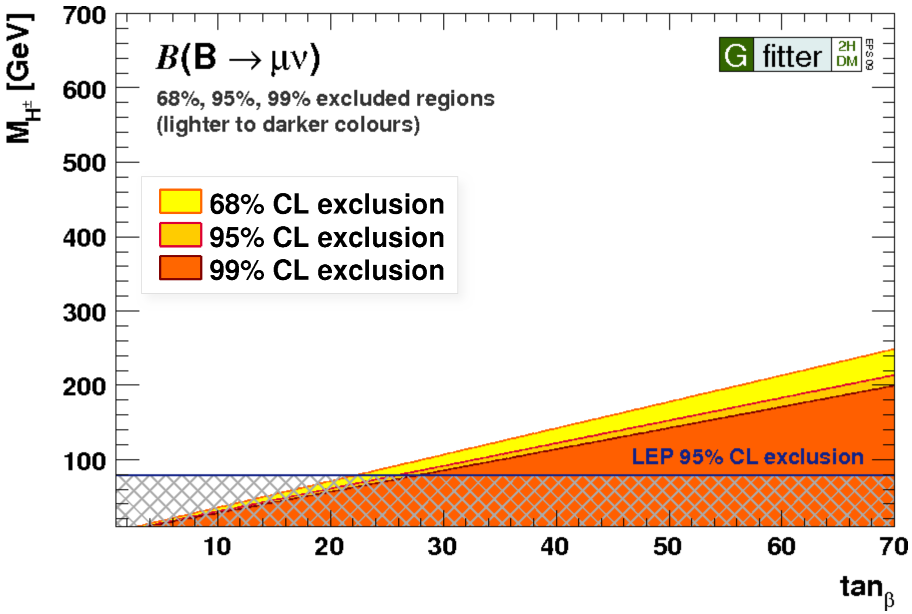
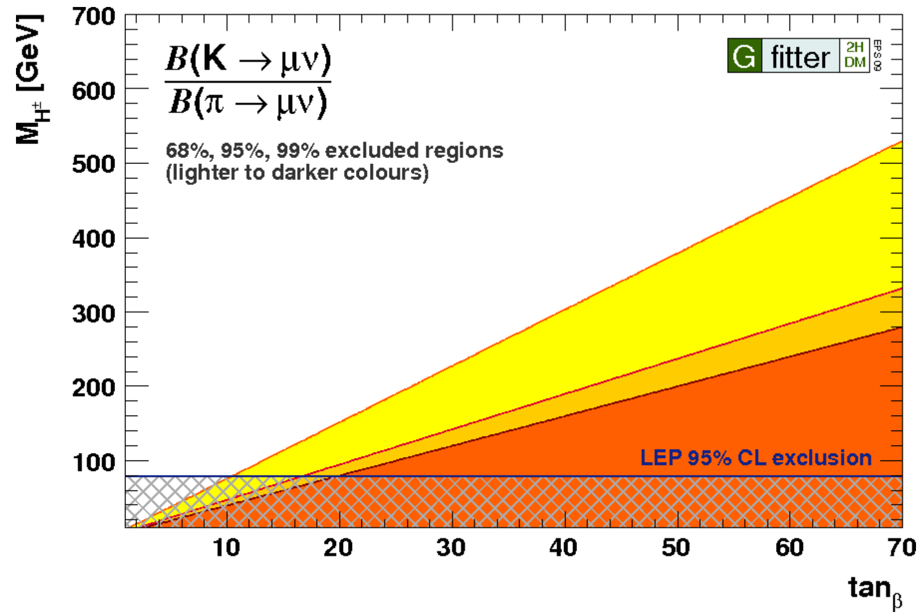


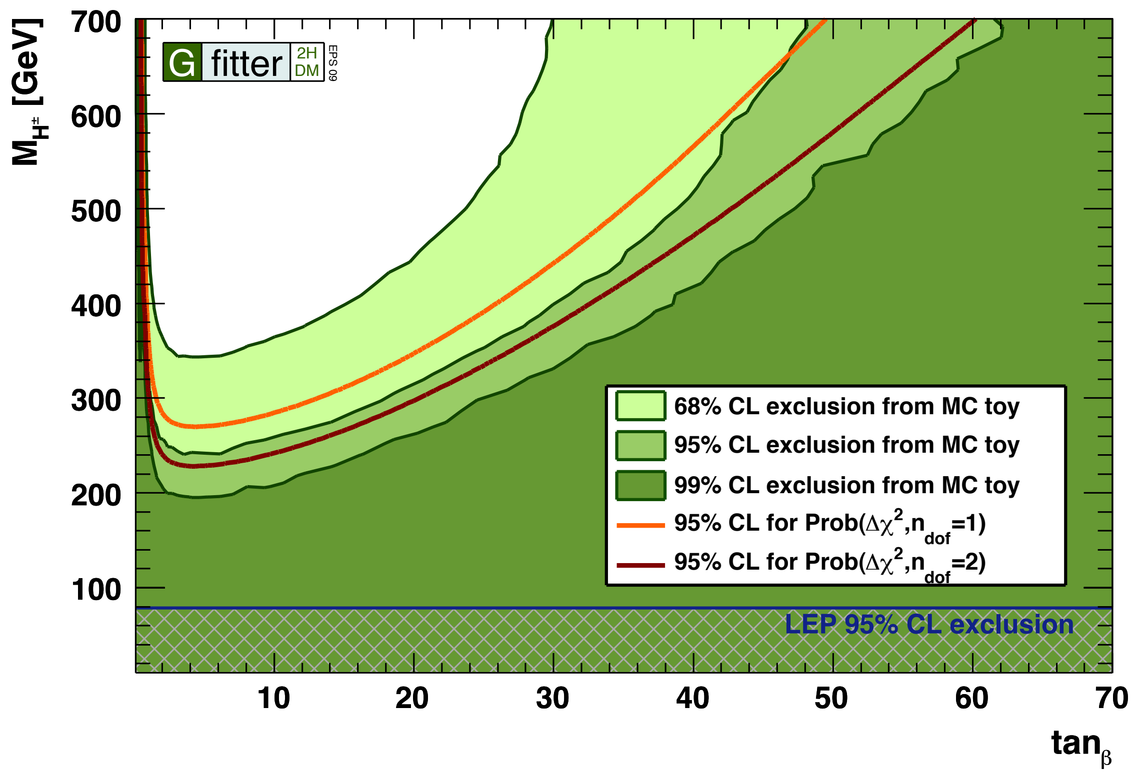


2HDM – Combined Fit

Fit minimum: χ^2 = 3.9 for $M_{H\pm}$ = 858 GeV and tanβ = 6.8

Excluded at 95% CL

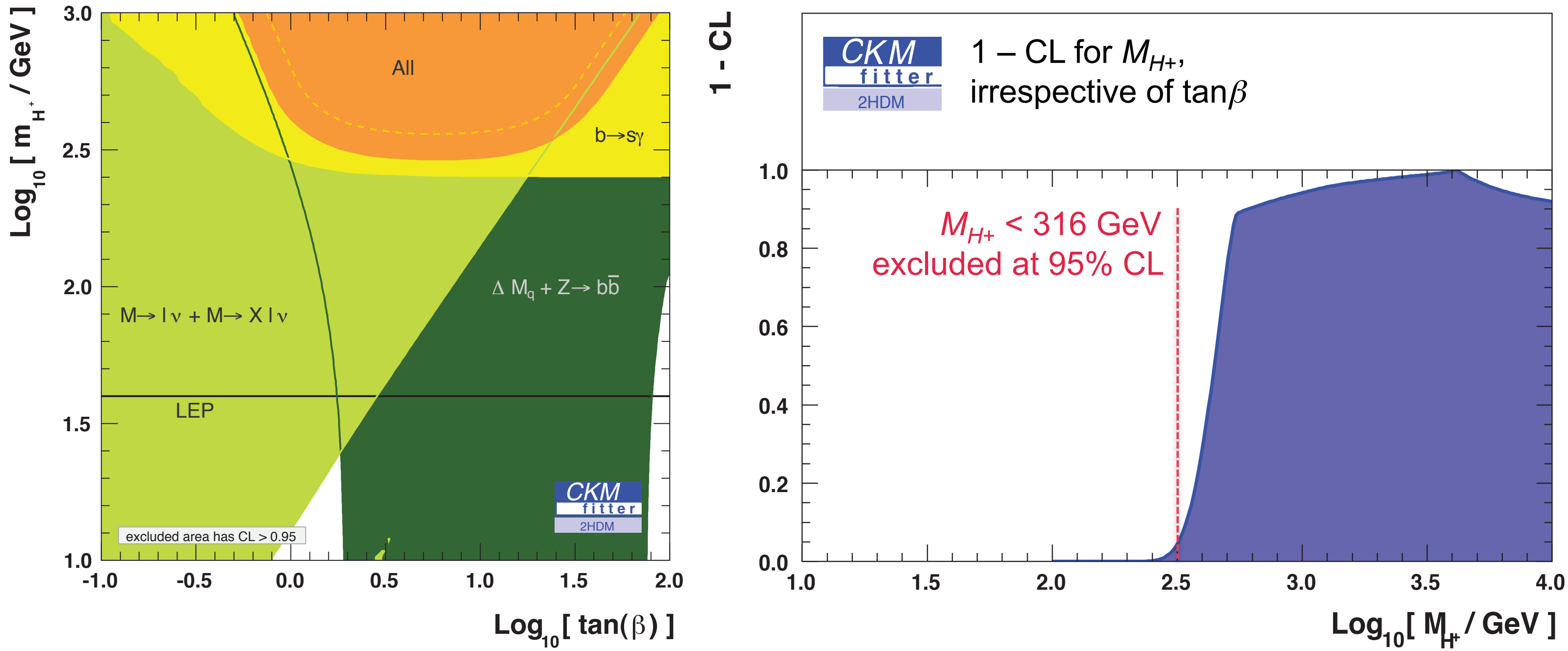
- Small tanβ
- M_{H+} < 240 GeV for all tanβ
- M_{H+} < 780 GeV for tanβ = 70 (mostly from $B \to \tau\nu$)



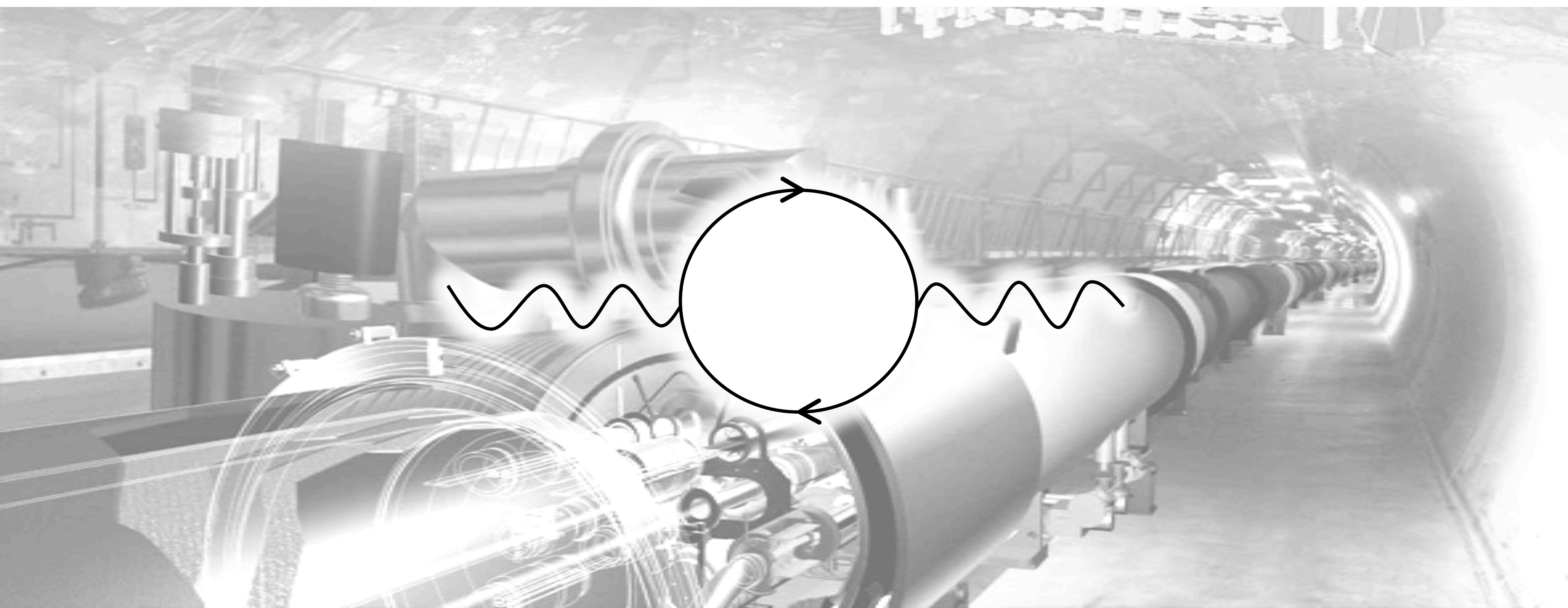
2HDM – Combined Fit

Full 2HDM analysis also performed by **CKMfitter** group: arXiv:0907.5135

- → Include also neutral *B*-meson mixing (similar as R_b, excludes very small tanβ values)
- → Similar results as Gfitter analysis



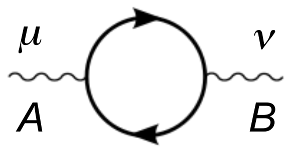
New Physics via Oblique Corrections



Oblique Corrections

At low energies, BSM physics appears dominantly through vacuum polarisation

- Aka, *oblique corrections*



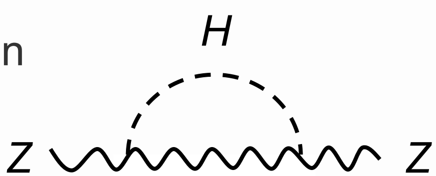
$$= i\Pi^{\mu\nu}_{AB=\{W,Z,\gamma\}}(q)$$

- Direct corrections (vertex, box, brems-strahlung) generally suppressed by m_f / Λ

Oblique corrections reabsorbed into electroweak parameters $\Delta\rho$, $\Delta\kappa$, Δr

Electroweak fit sensitive to BSM physics through oblique corrections

- In direct competition with Higgs loop corrections



- Oblique corrections from New Physics described through ***STU*** **parameters**
  [Peskin-Takeuchi, Phys. Rev. D46, 381 (1992)]

$$O_{\rm meas} = O_{\rm SM,ref}(M_H,m_t) + c_S S + c_T \boldsymbol{T} + c_U \boldsymbol{U}$$

S : (S+U) New Physics contributions to neutral (charged) currents

T : Difference between neutral and charged current processes – sensitive to weak isospin violation

U : Constrained by M_W and Γ_W. Usually very small in NP models (often: U=0)

- Also considered: correction to $Z \rightarrow bb$ coupling, and extended parameters (VWX)
  [Burgess et al., PLB 326, 276 (1994), PRD 49, 6115 (1994)]

The Oblique Parameters in the Standard Model

STU references in SM obtained from fit to EW observables

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

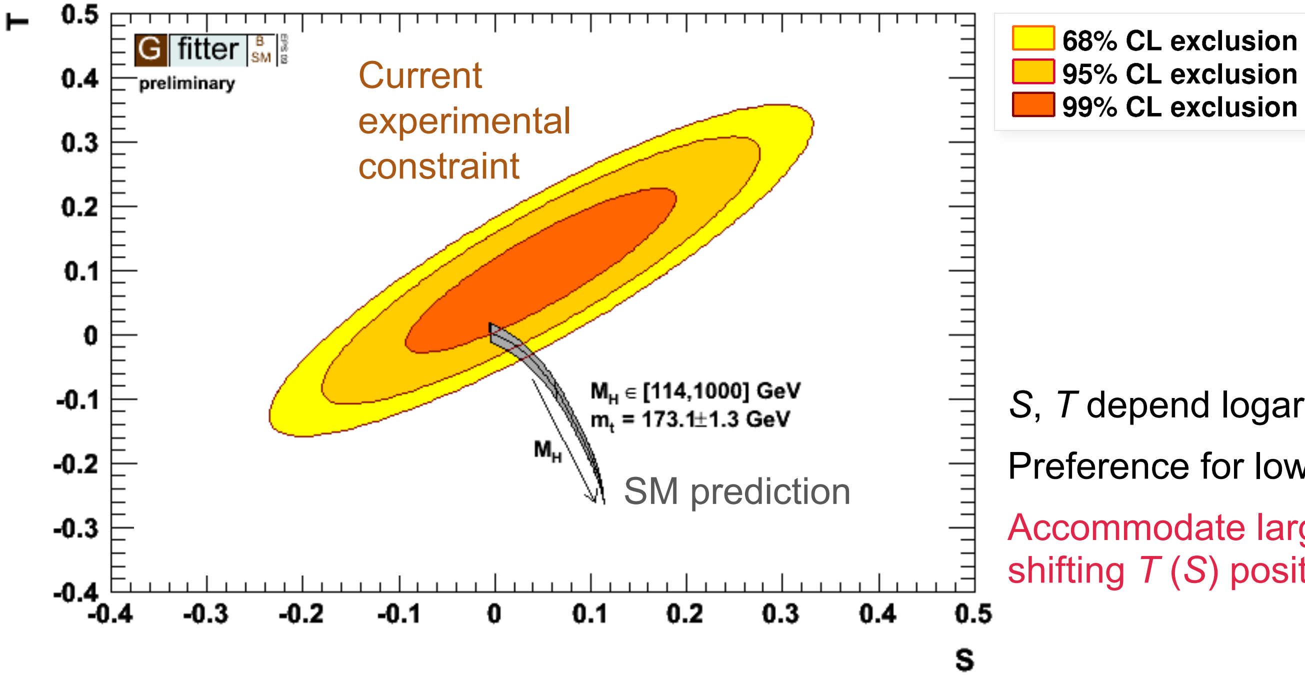
Results from Standard Model fit:

$S = 0.02 \pm 0.11$

$T = 0.05 \pm 0.12$

$U = 0.07 \pm 0.12$

	S	*T*	*U*
S	1	0.88	–0.47
T		1	–0.72
U			1



S, *T* depend logarithmically on M_H

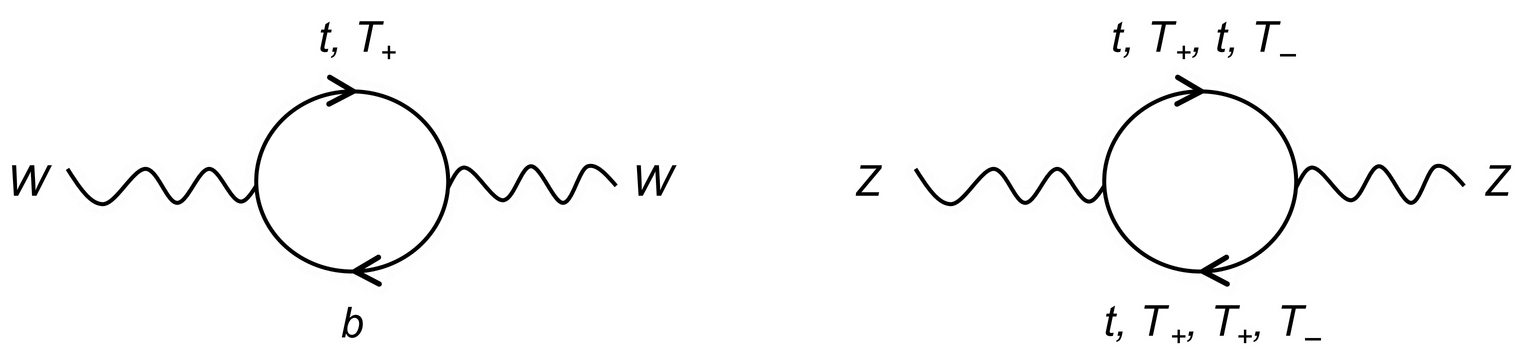
Preference for low M_H values

Accommodate large M_H values by shifting *T* (*S*) positive (negative)

Little Higgs Models (LHM)

- 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 similar to SUSY *R*-parity (note: not *time-invariance* !)
  - Forbids tree-level couplings of new gauge bosons (*T*-odd) to SM particles (*T*-even)
  - LHM provides natural dark matter candidate
- Two new top states: *T*-even T_+ and *T*-odd T_-

One-loop oblique corrections from LH top sector with *T*-parity:



Little Higgs Models (LHM)

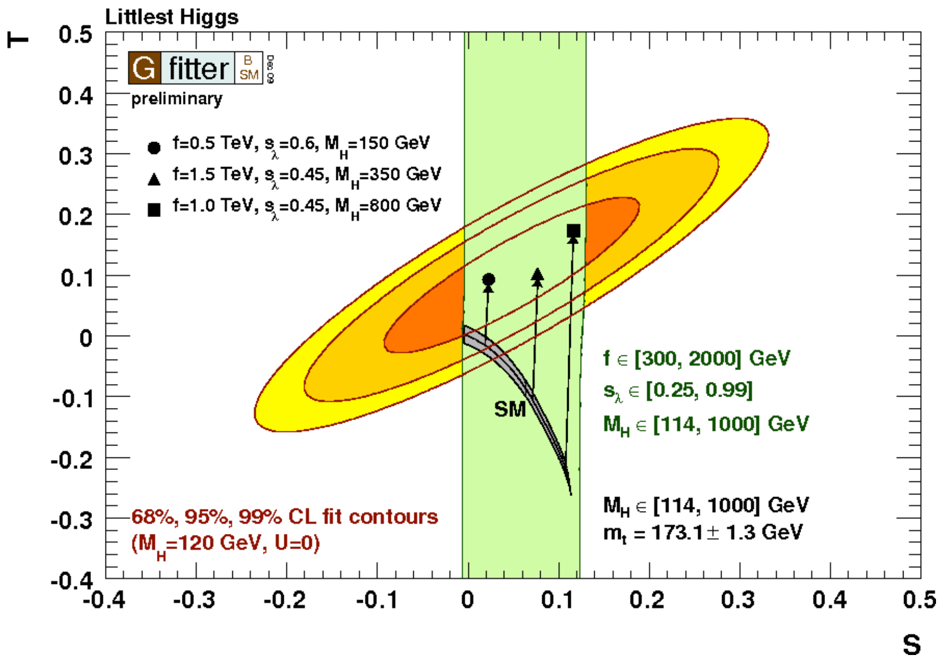
STU predictions (oblique corrections) inserted for **Littlest Higgs model**

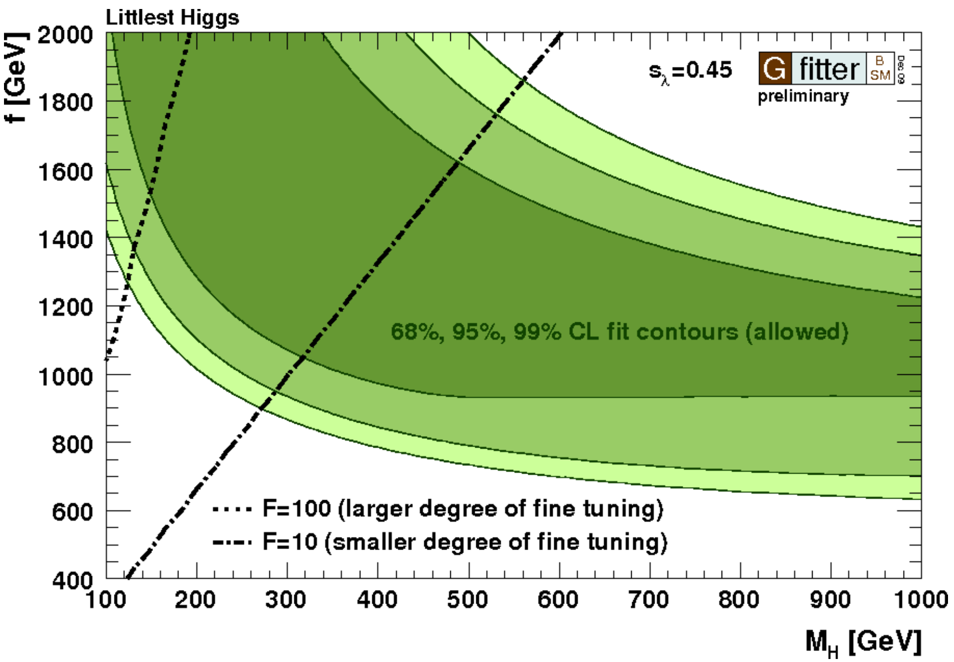
[Hubisz et al., JHEP 0601:135 (2006)]

Parameters of LH model:

- *f* : symmetry breaking scale (new particles)
- $s_\lambda \cong m_{T-} / m_{T+}$
- Coefficient δ_c – depends on detail of UV physics. Treated as theory uncertainty in fit: δ_c= [–5,5]
- *F* : degree of finetuning

Results: **Large *f*** : LH approaches SM and SM M_H constraints. **Smaller *f*** : M_H can be large. Due to strong s_λ dependence, no absolute exclusion limit





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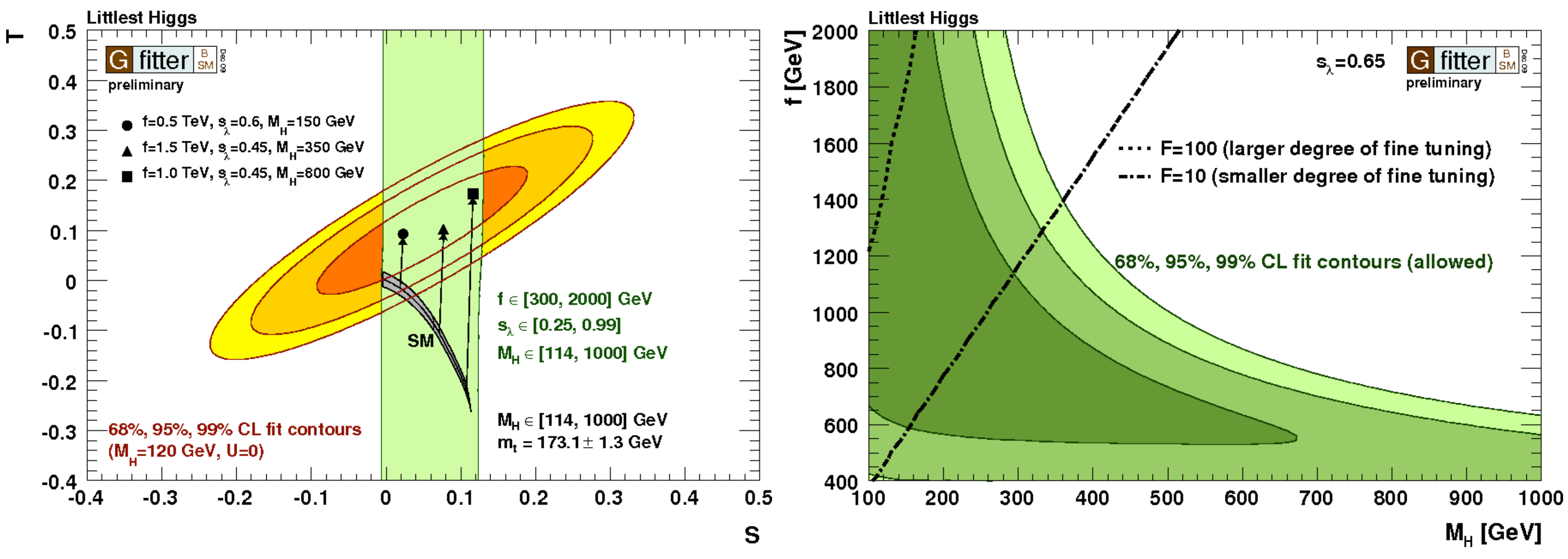

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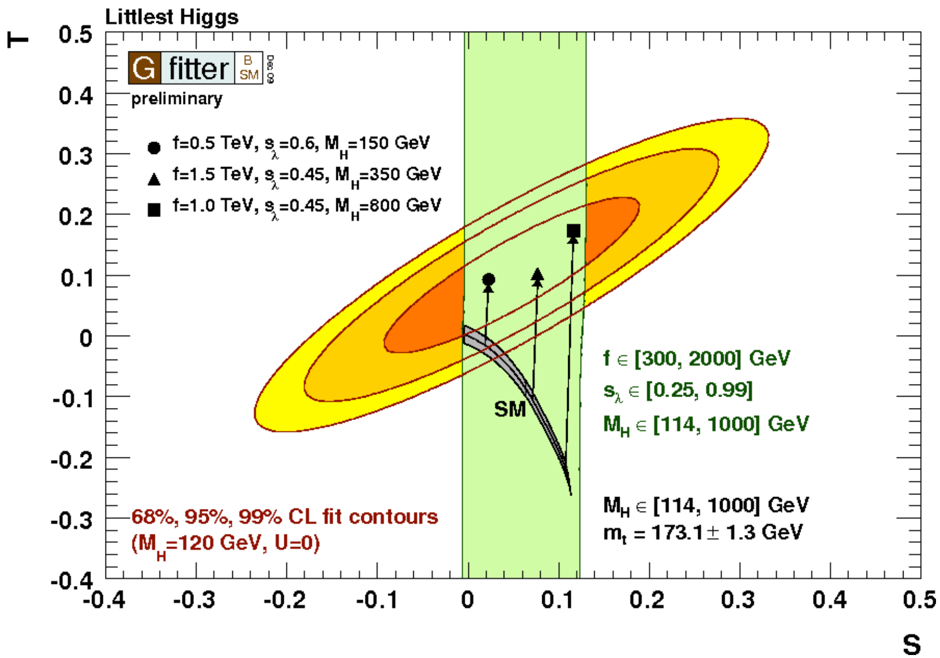
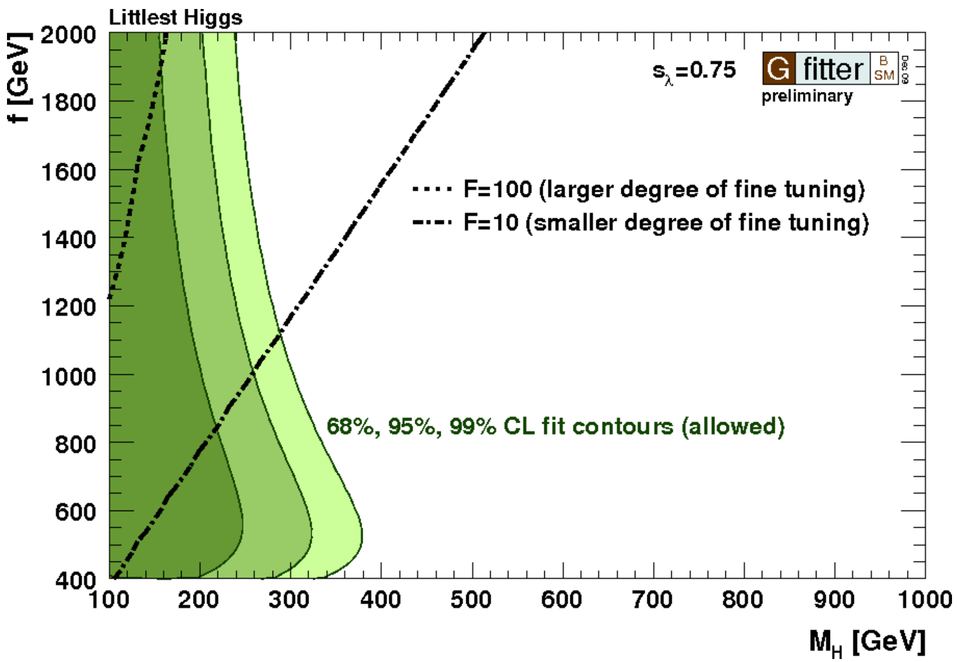




MSSM (SUSY) with mSUGRA

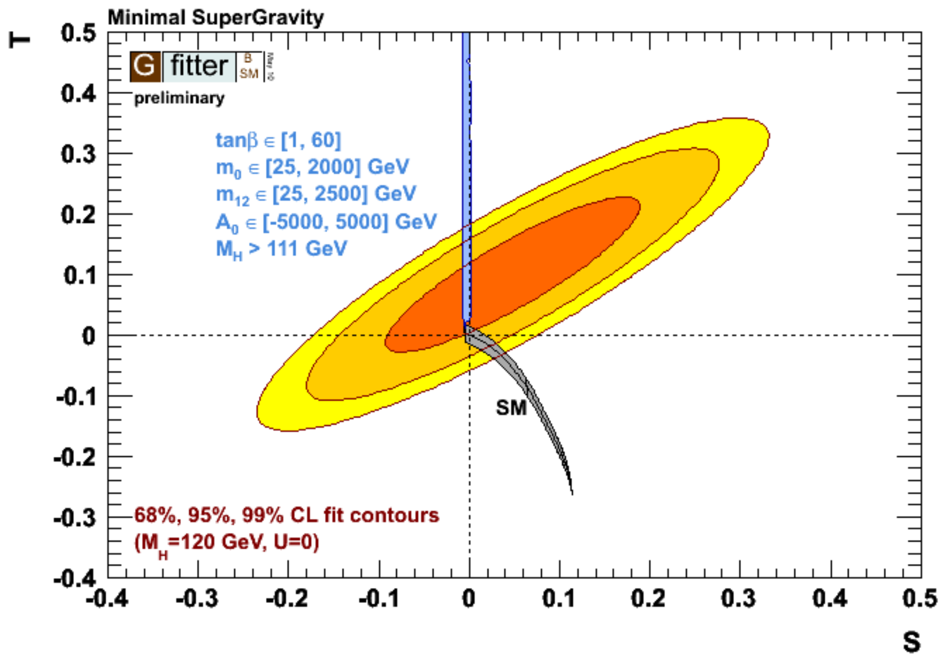
[G. Weiglein: arXiv:hep-ph/9712226v1]
[S. Heinemeyer, W. Hollik, G. Weiglein: arXiv:hep-ph/0412214v1]

mSUGRA: highly constrained SUSY breaking mechanism at GUT scale, determined by 5 parameters:

$m_{1/2}$, m_0	– fermion/scalar masses at GUT scale
$\tan\beta$	– ratio of two Higgs vev's
A_0	– trilinear coupling of Higgs
$\mathrm{sgn}(\mu)$	– sign of Higgsino mass term

- Oblique corrections dominated by weak isospin violation in: $m_{\tilde{b}_1}$, $m_{\tilde{t}_1}$, and $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$
- By construction of the oblique parameters → T parameter has dominant contribution

Fits use external code interfaced to Gfitter: FeynHiggs, MicrOMEGAs, SuperIso, SOFTSUSY



Fourth Fermion Generation

Introduce new lepton and quark states

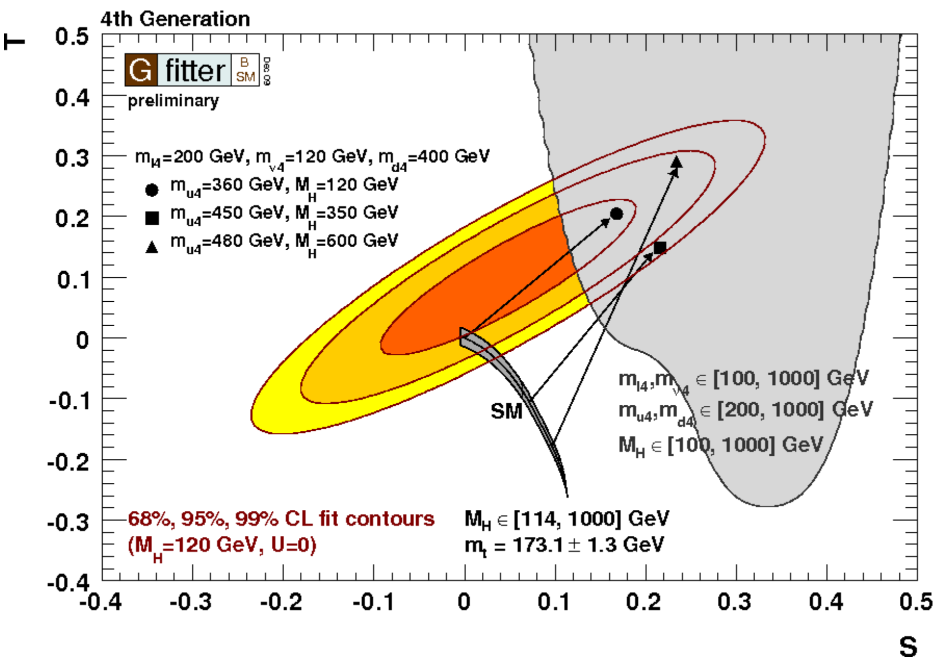
Free parameters: m_{u_4}, m_{d_4}, m_{e_4}, m_{ν_4}

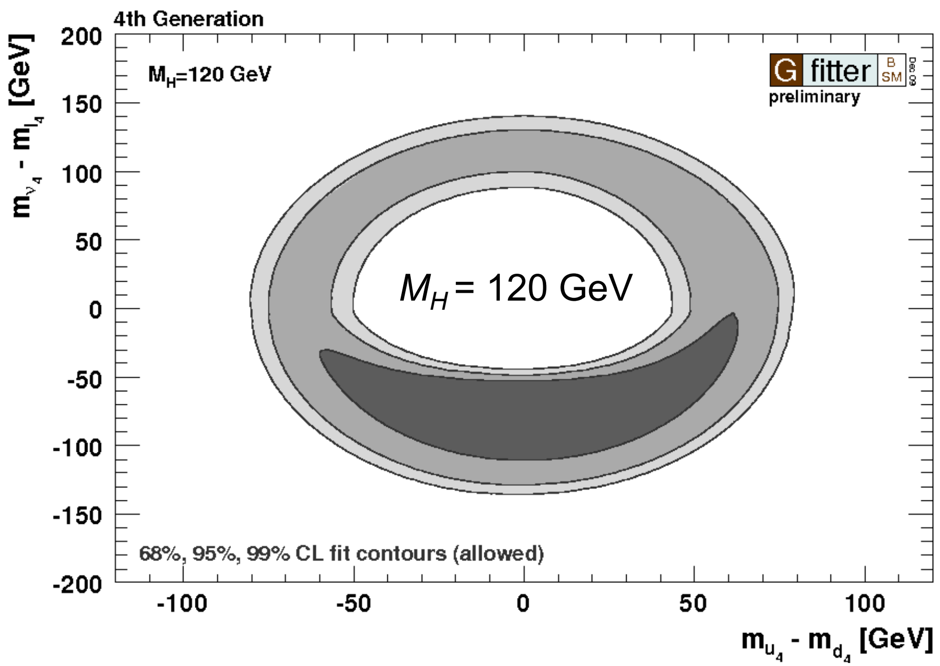
- Assume: no mixing of extra fermions

- Shift $\Delta S \approx 0.21$ from heavy generation
- Sensitive to mass difference between up- and down-type fields (not to absolute mass scale)

Results:

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





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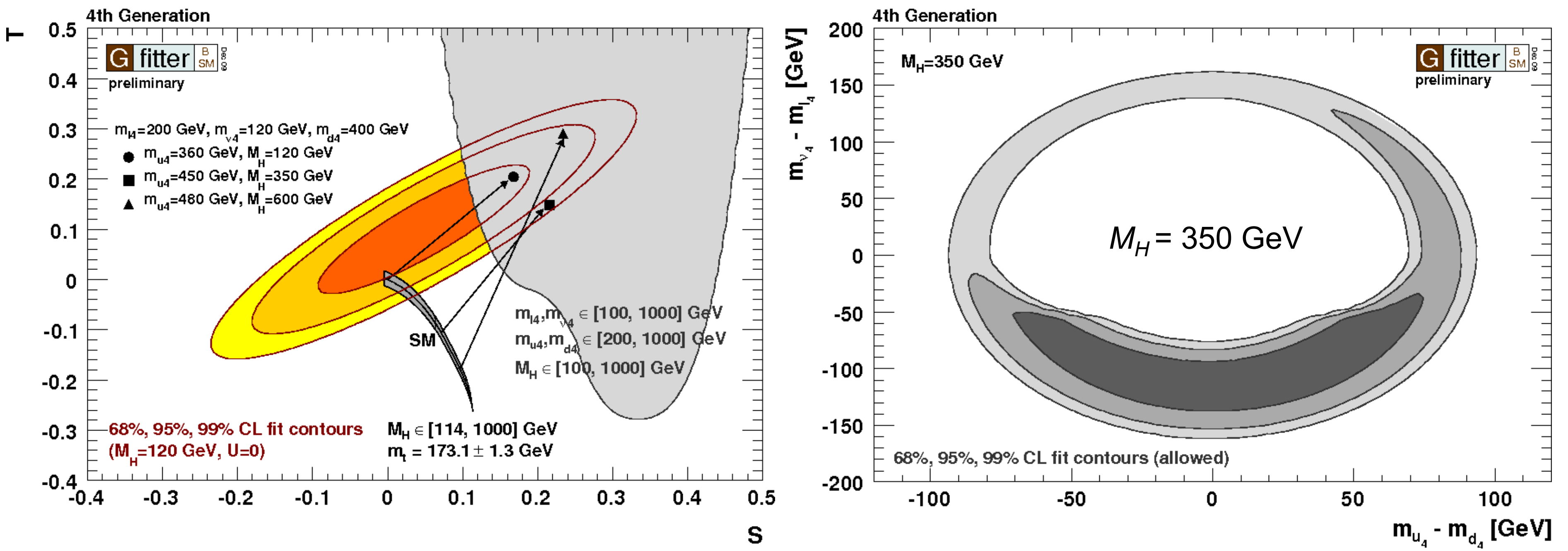

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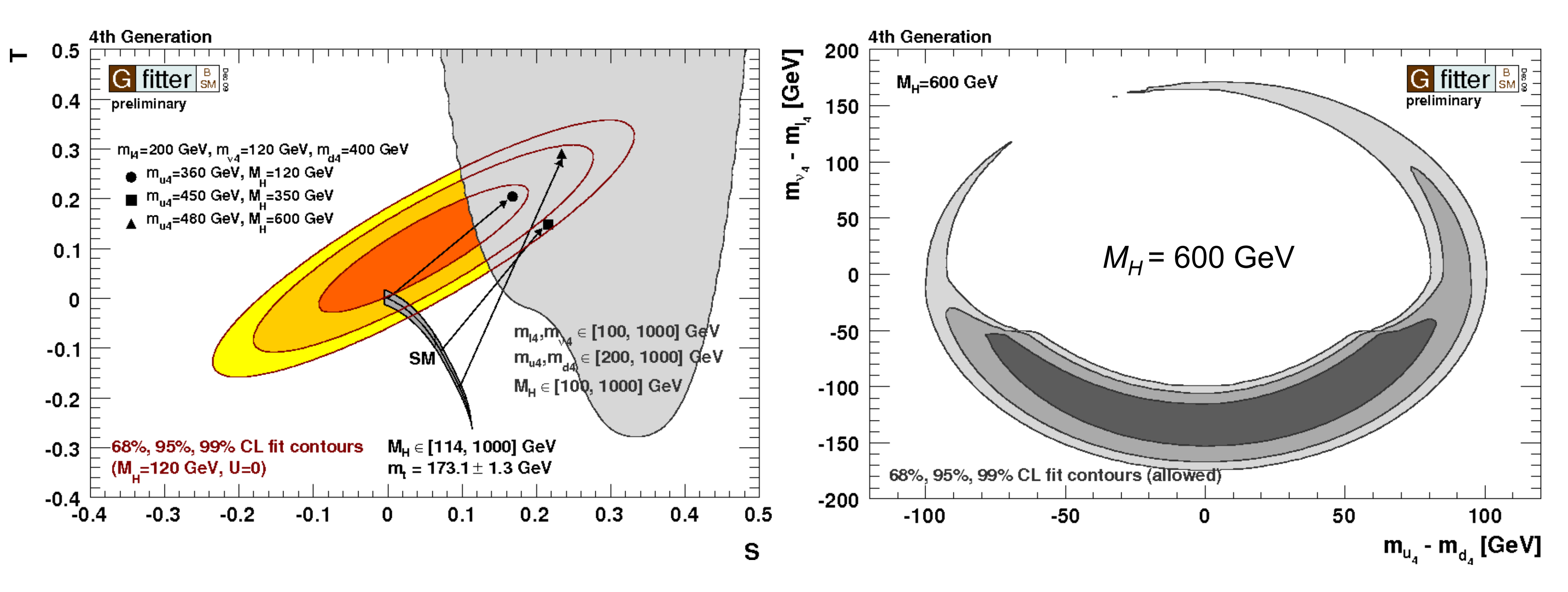


[Appelquist et al., Phys. Rev. D67, 055002 (2003)]
[Gogoladze et al., Phys. Rev. D74, 093012 (2006)]

Universal Extra Dimensions (UED)

All SM particles can propagate into ED

Compactification → KK excitations

Conserved KK parity (LKK is DM candidate)

Model parameters:

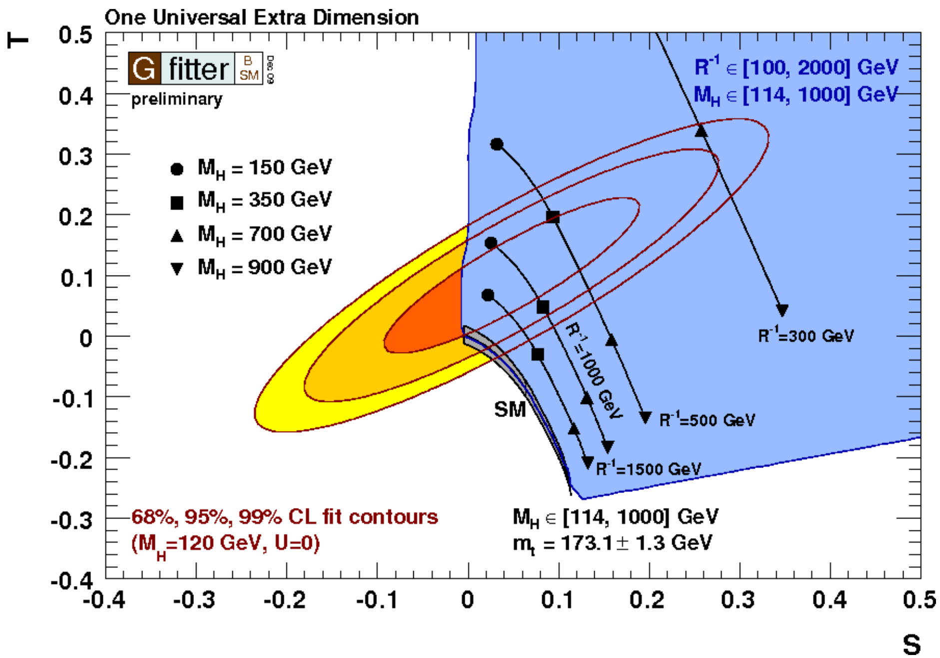
- d_{ED}: number of ED (fixed to d_{ED}=1)
- R^{-1}: compactification scale ($m_{KK} \sim n/R$)

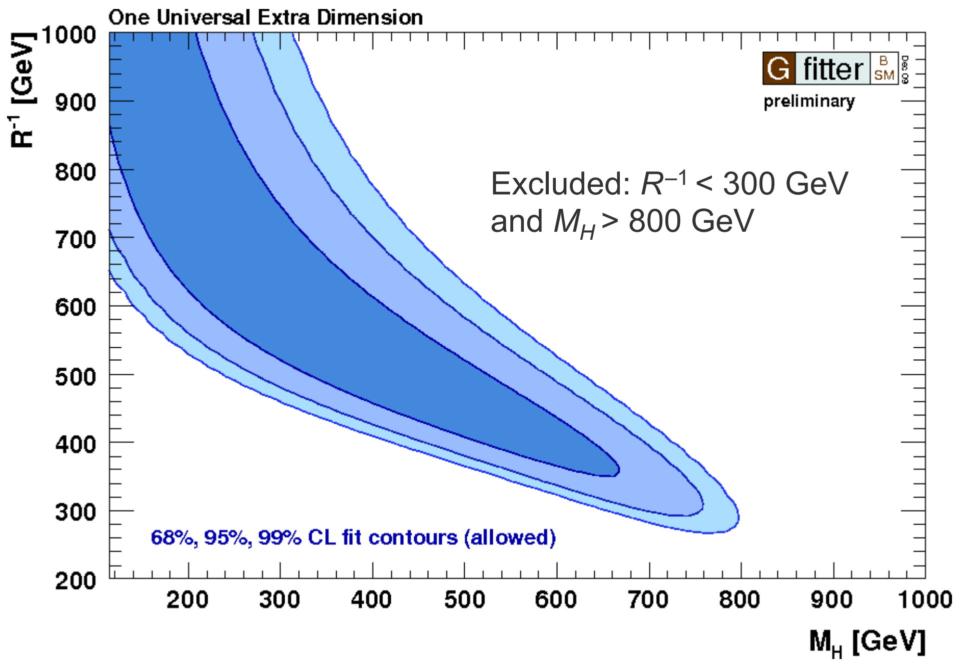
Contribution to oblique parameters:

- From KK-top/bottom and KK-Higgs loops

Results:

- Large R^{-1}: UED approaches SM (exp.)
- Small R^{-1}: large M_H required





Warped Extra Dimensions (Randall-Sundrum)

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

RS model characterized by one warped ED, confined by two three-branes

- One brane contains SM particles
- Extension: SM particles also in bulk

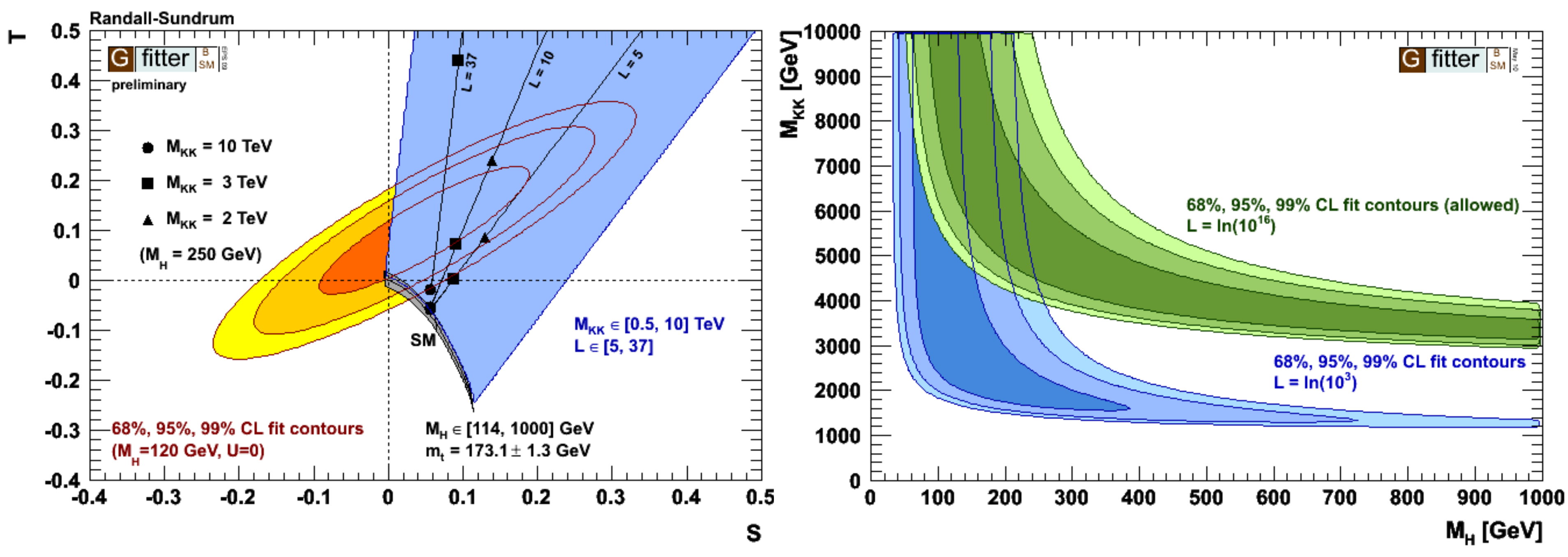
SM particles accompanied by towers of heavy KK modes.

Model parameters

- *L*: inverse warp factor
- M_{KK}: KK mass scale

Results:

- Large values of *T* (linear in *L*)
- Large *L* requires large M_{KK} (and small M_H)



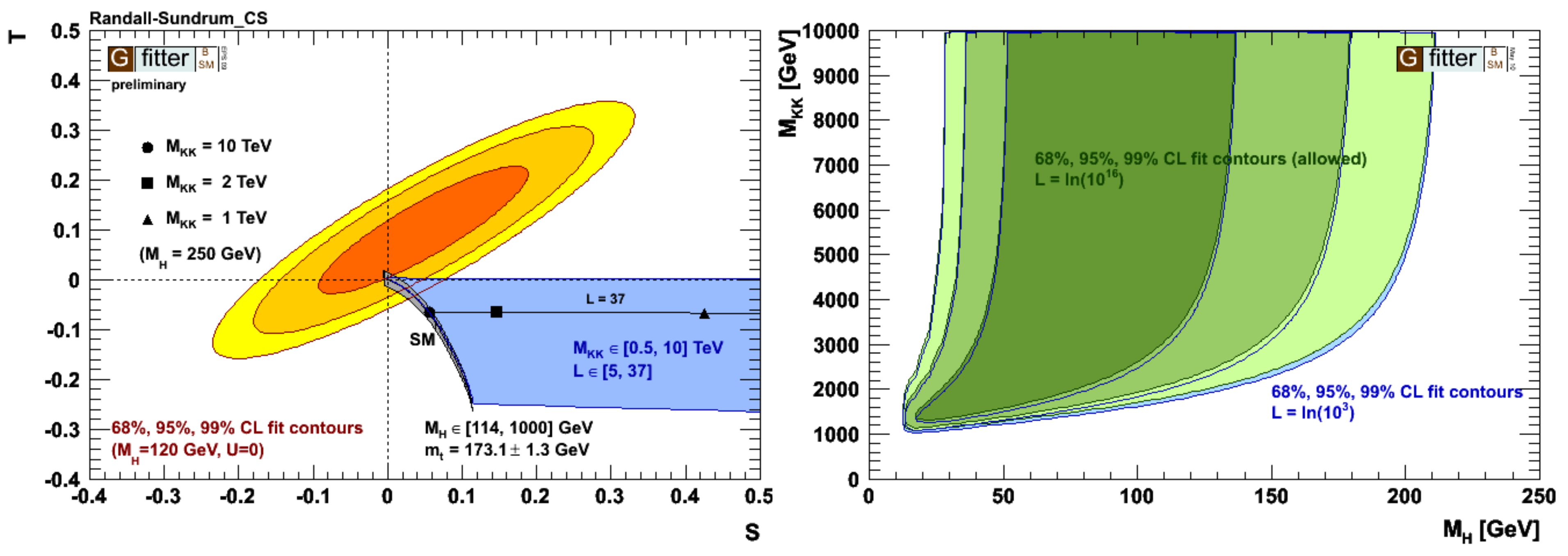
Warped Extra Dimensions w/ Custodial Symmetry

Goal: avoid large *T* values

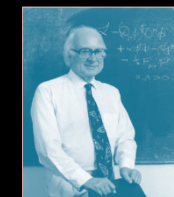
→ Introduce so-called **custodial isospin gauge symmetry** in the bulk

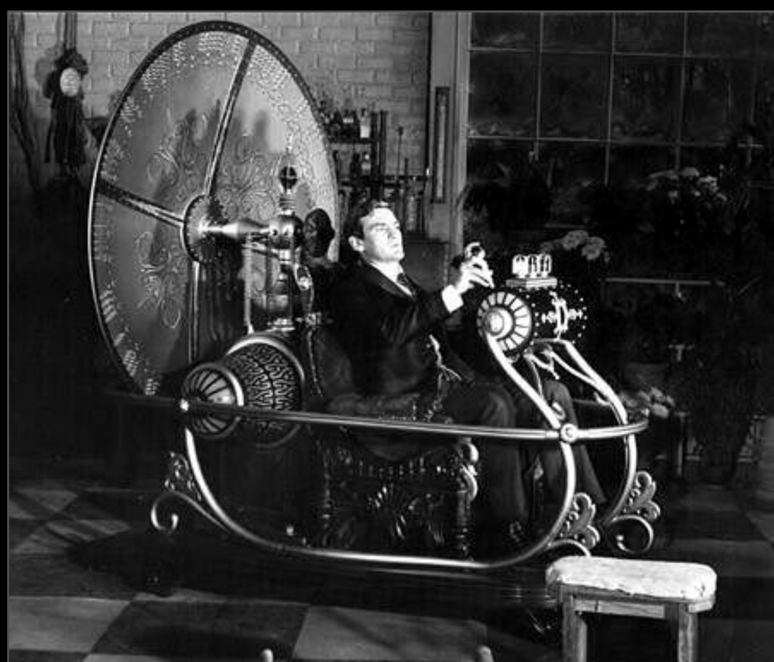
- Extend hypercharge group to $SU(2)_R \times U(1)_X$
- Bulk group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$
- Broken to $SU(3)_C \times SU(2)_L \times U(1)_Y$ on UV brane
- IR brane $SU(2)_R$ symmetric
- Right-handed fermionic fields are doublets

Results: only small M_H allowed



What the Future Brings … (for the EW Fit)





What happens with the EW fit if we build new exciting accelerators…

Prospects for LHC, ILC and ILC with Giga-Z

New colliders (LHC/ILC) will increase precision in electroweak observables

- Improvement of the predictive power of the fit
- Higgs discovery → testing goodness-of-fit → sensitivity to new physics

Expected improvement from LHC (10 fb^{-1}):

- δM_W: 25 MeV → 15 MeV *(at least)*
- δm_t: 1.2 GeV → 1.0 GeV

Expected improvement from ILC:

- From threshold scan δm_t = 50 MeV, translates to 100–200 MeV on the running mass

Expected improvement from GigaZ:

- From *WW* threshold scan: δM_W = 6 MeV
- From A_{LR}: $\delta\sin^2\theta^l_{\text{eff}}$: $17\cdot10^{-5}$ → $1.3\cdot10^{-5}$
- δR_l^0: $2.5\cdot10^{-2}$ → $0.4\cdot10^{-2}$

Improved determination of $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$ will become necessary

- Needs improvement in hadronic cross section data around *cc* resonance.
- Expected uncertainty of $7\cdot10^{-5}$ (today $22\cdot10^{-5}$) if relative cross-section precision below J/Ψ at 1% [Jegerlehner, hep-ph/0105283]
- Experiments with better acceptances and control of systematics needed
- Promising: ISR analyses at *B* and Φ factories; new data from BES-III

Prospects for LHC, ILC and ILC with Giga-Z

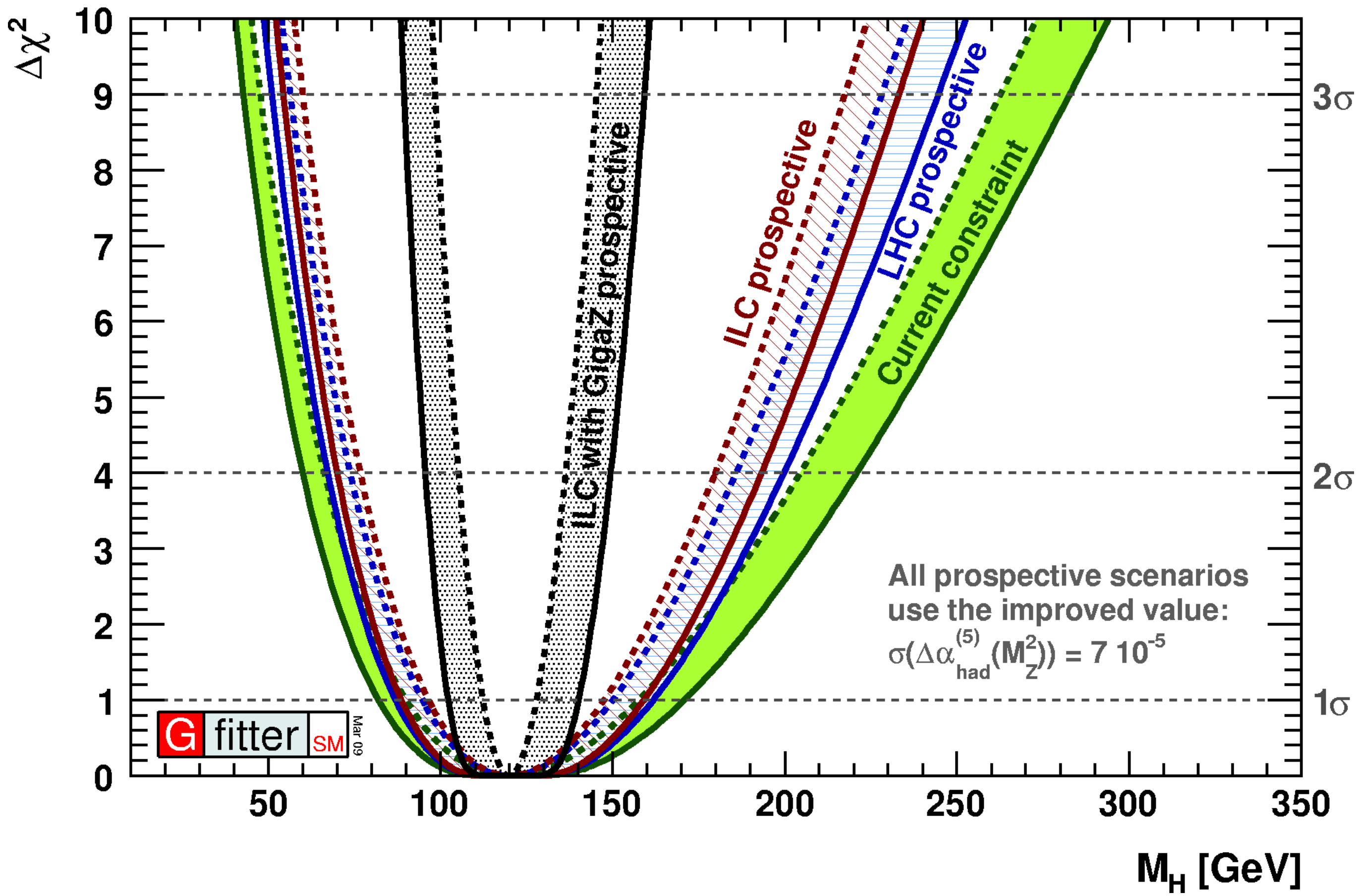
Fit inputs and results under various conditions

Quantity	Expected uncertainty: Present	LHC	ILC	GigaZ (ILC)
M_W [MeV]	23	15	15	6
m_t [GeV]	1.3	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]	${}^{+54}_{-40}$ $\left({}^{+51}_{-38}\right)$ $\left[{}^{+38}_{-30}\right]$	${}^{+45}_{-35}$ $\left({}^{+42}_{-33}\right)$ $\left[{}^{+30}_{-25}\right]$	${}^{+42}_{-33}$ $\left({}^{+39}_{-31}\right)$ $\left[{}^{+28}_{-23}\right]$	${}^{+26}_{-23}$ $\left({}^{+20}_{-18}\right)$ $\left[{}^{+8}_{-8}\right]$
$\alpha_S(M_Z^2)$ $[10^{-4}]$	28	28	28	6

Input from: [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]

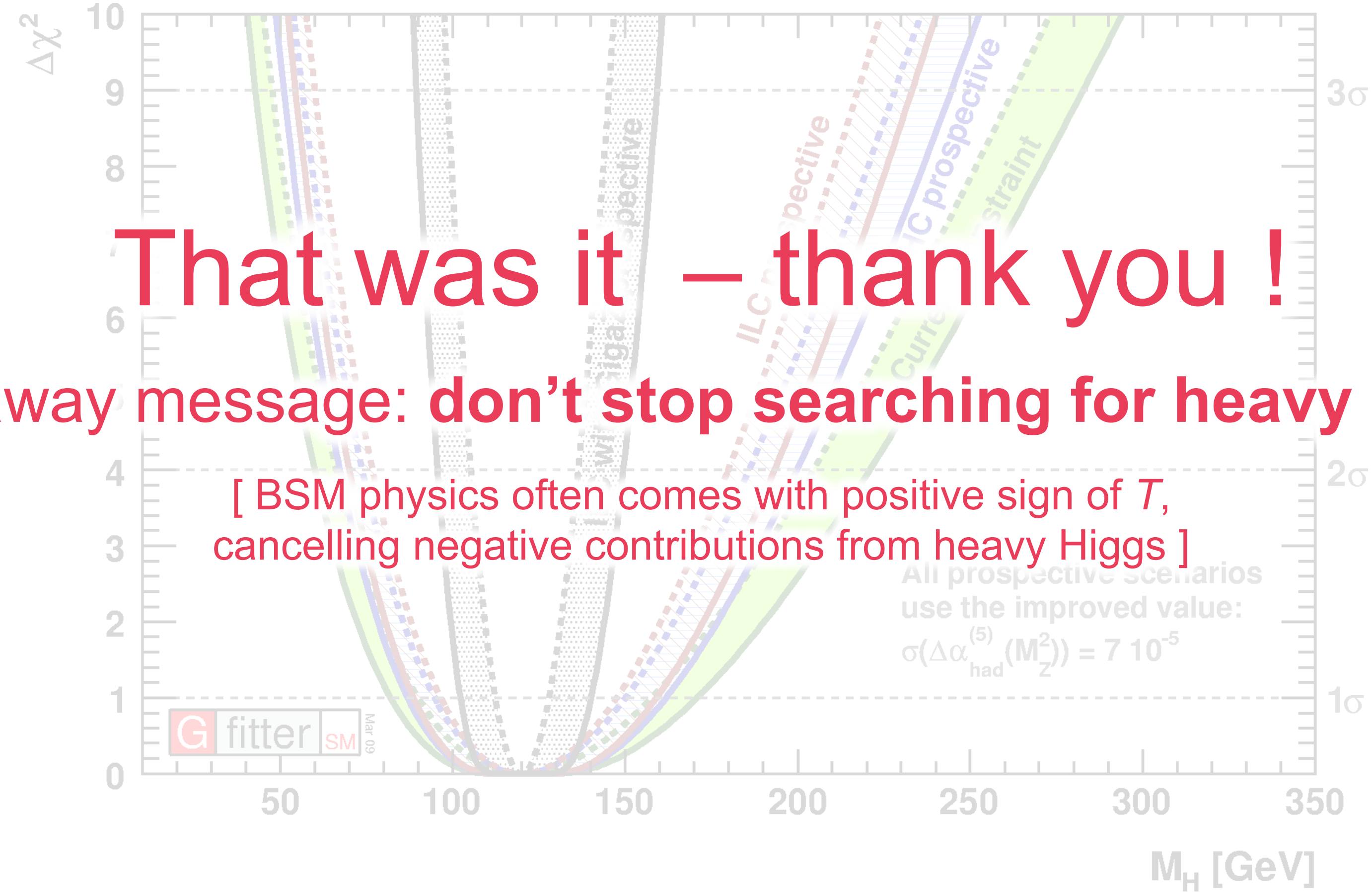
Prospects for LHC, ILC and ILC with Giga-Z

Results on M_H, including (solid) and excluding (dotted) theoretical errors



Prospects for LHC, ILC and ILC with Giga-Z

Results on M_H, including (solid) and excluding (dotted) theoretical errors

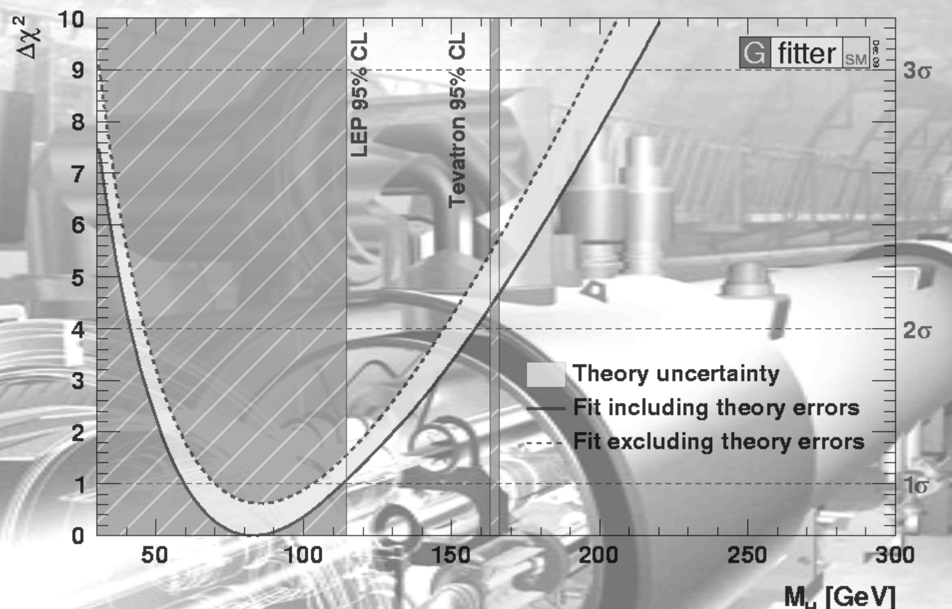


That was it – thank you !

Take away message: **don't stop searching for heavy Higgs !**

[BSM physics often comes with positive sign of *T*, cancelling negative contributions from heavy Higgs]

Additional slides



Oblique Parameters and Corrections

Definitions of S,T,U,V,W,X :

[STU parameters suffice when $(q/M)^2$ small, so that linear approximation is accurate]

[Burgess et al., PLB 326, 276 (1994), PRD 49, 6115 (1994)]

$$\frac{\alpha S}{4s_W^2c_W^2} = \left[\frac{\delta\Pi_{ZZ}(M_Z^2)-\delta\Pi_{ZZ}(0)}{M_Z^2}\right] - \frac{\left(c_W^2 - s_W^2\right)}{s_W c_W}\delta\Pi'_{Z\gamma}(0) - \delta\Pi'_{\gamma\gamma}(0)\ ,$$

$$\alpha T = \frac{\delta\Pi_{WW}(0)}{M_W^2} - \frac{\delta\Pi_{ZZ}(0)}{M_Z^2}\ ,$$

$$\frac{\alpha U}{4s_W^2} = \left[\frac{\delta\Pi_{WW}(M_W^2)-\delta\Pi_{WW}(0)}{M_W^2}\right] - c_W^2\left[\frac{\delta\Pi_{ZZ}(M_Z^2)-\delta\Pi_{ZZ}(0)}{M_Z^2}\right] - s_W^2\delta\Pi'_{\gamma\gamma}(0) - 2s_W c_W\delta\Pi'_{Z\gamma}(0)\ ,$$

$$\alpha V = \delta\Pi'_{ZZ}(M_Z^2) - \left[\frac{\delta\Pi_{ZZ}(M_Z^2)-\delta\Pi_{ZZ}(0)}{M_Z^2}\right]\ ,$$

$$\alpha W = \delta\Pi'_{WW}(M_W^2) - \left[\frac{\delta\Pi_{WW}(M_W^2)-\delta\Pi_{WW}(0)}{M_W^2}\right]\ ,$$

$$\alpha X = -s_W c_W\left[\frac{\delta\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - \delta\Pi'_{Z\gamma}(0)\right]\ .$$

Oblique Parameters and Corrections

Dependence of electroweak observables on *S*,*T*,*U*,*V*,*W*,*X*.

[The numerical values are based on $\alpha^{-1}(M_Z)$ = 128 and $\sin^2\theta_W$=0.23]

[Burgess et al., PLB 326, 276 (1994), PRD 49, 6115 (1994)]

$$\Gamma_Z = (\Gamma_Z)_{\rm SM} - 0.00961S + 0.0263T + 0.0194V - 0.0207X \text{ [GeV]}$$
$$\Gamma_{bb} = (\Gamma_{bb})_{\rm SM} - 0.00171S + 0.00416T + 0.00295V - 0.00369X \text{ [GeV]}$$
$$\Gamma_{\ell^+\ell^-} = (\Gamma_{\ell^+\ell^-})_{\rm SM} - 0.000192S + 0.000790T + 0.000653V - 0.000416X \text{ [GeV]}$$
$$\Gamma_{\rm had} = (\Gamma_{\rm had})_{\rm SM} - 0.00901S + 0.0200T + 0.0136V - 0.0195X \text{ [GeV]}$$
$$A_{\rm FB(\mu)} = (A_{\rm FB(\mu)})_{\rm SM} - 0.00677S + 0.00479T - 0.0146X$$
$$A_{\rm pol(\tau)} = (A_{\rm pol(\tau)})_{\rm SM} - 0.0284S + 0.0201T - 0.0613X$$
$$A_{e(P\tau)} = (A_{e(P\tau)})_{\rm SM} - 0.0284S + 0.0201T - 0.0613X$$
$$A_{\rm FB(b)} = (A_{\rm FB(b)})_{\rm SM} - 0.0188S + 0.0131T - 0.0406X$$
$$A_{\rm FB(c)} = (A_{\rm FB(c)})_{\rm SM} - 0.0147S + 0.0104T - 0.03175X$$
$$A_{\rm LR} = (A_{\rm LR})_{\rm SM} - 0.0284S + 0.0201T - 0.0613X$$
$$M_W^2 = (M_W^2)_{\rm SM}\,(1 - 0.00723S + 0.0111T + 0.00849U)$$
$$\Gamma_W = (\Gamma_W)_{\rm SM}\,(1 - 0.00723S - 0.00333T + 0.00849U + 0.00781W)$$
$$g_L^2 = (g_L^2)_{\rm SM} - 0.00269S + 0.00663T$$
$$g_R^2 = (g_R^2)_{\rm SM} + 0.000937S - 0.000192T$$
$$g^e_{V,(\nu e\to\nu e)} = (g_V^e)_{\rm SM} + 0.00723S - 0.00541T$$
$$g^e_{A,(\nu e\to\nu e)} = (g_A^e)_{\rm SM} - 0.00395T$$
$$Q_W({}^{133}_{55}\text{Cs}) = Q_W(\text{Cs})_{\rm SM} - 0.795S - 0.0116T$$