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on behalf of the Gfitter group (*)

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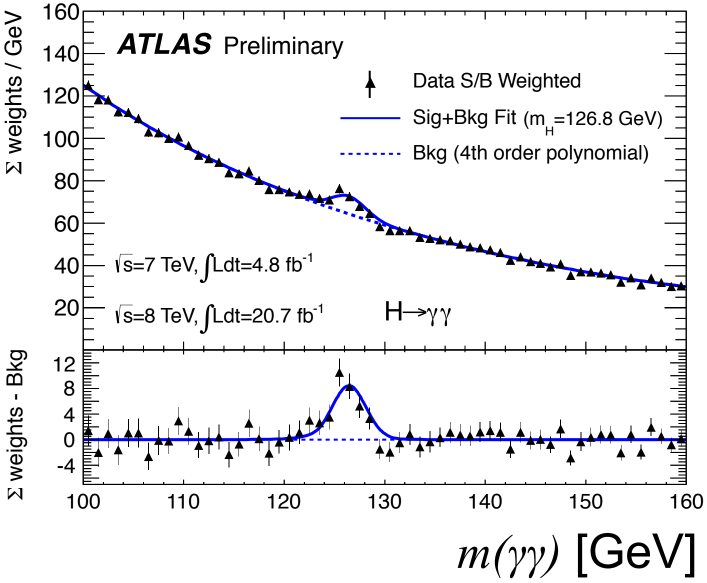
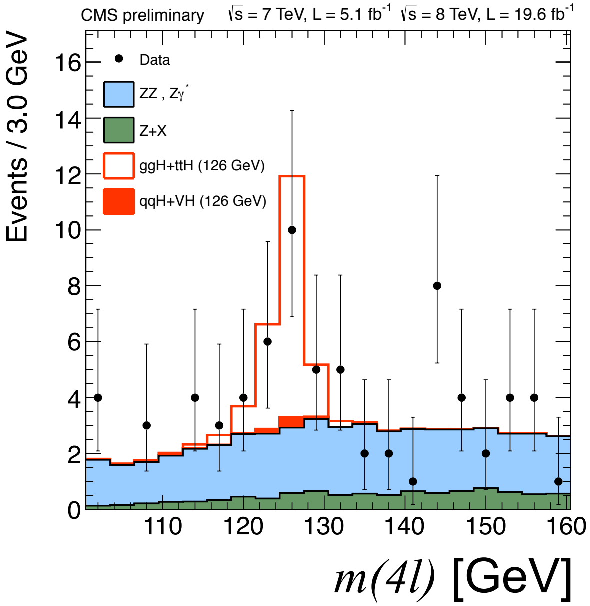
http://cern.ch/Gfitter

EPJC 72, 2205 (2012), arXiv:1209.2716

The ElectroWeak fit of Standard Model after the Discovery of the Higgs-like boson





(*) M. Baak, J. Haller, A. Höcker, R. Kogler, K. Mönig, M. Schott, J. Stelzer

Outline

G fitter

This presentation:

- Introduction to Gfitter
- Introduction to the electroweak fit of the Standard Model
- Inputs to the electroweak fit
- Fit results
- Future Prospects of ILC
- Conclusion & Outlook

The Gfitter Project – Introduction

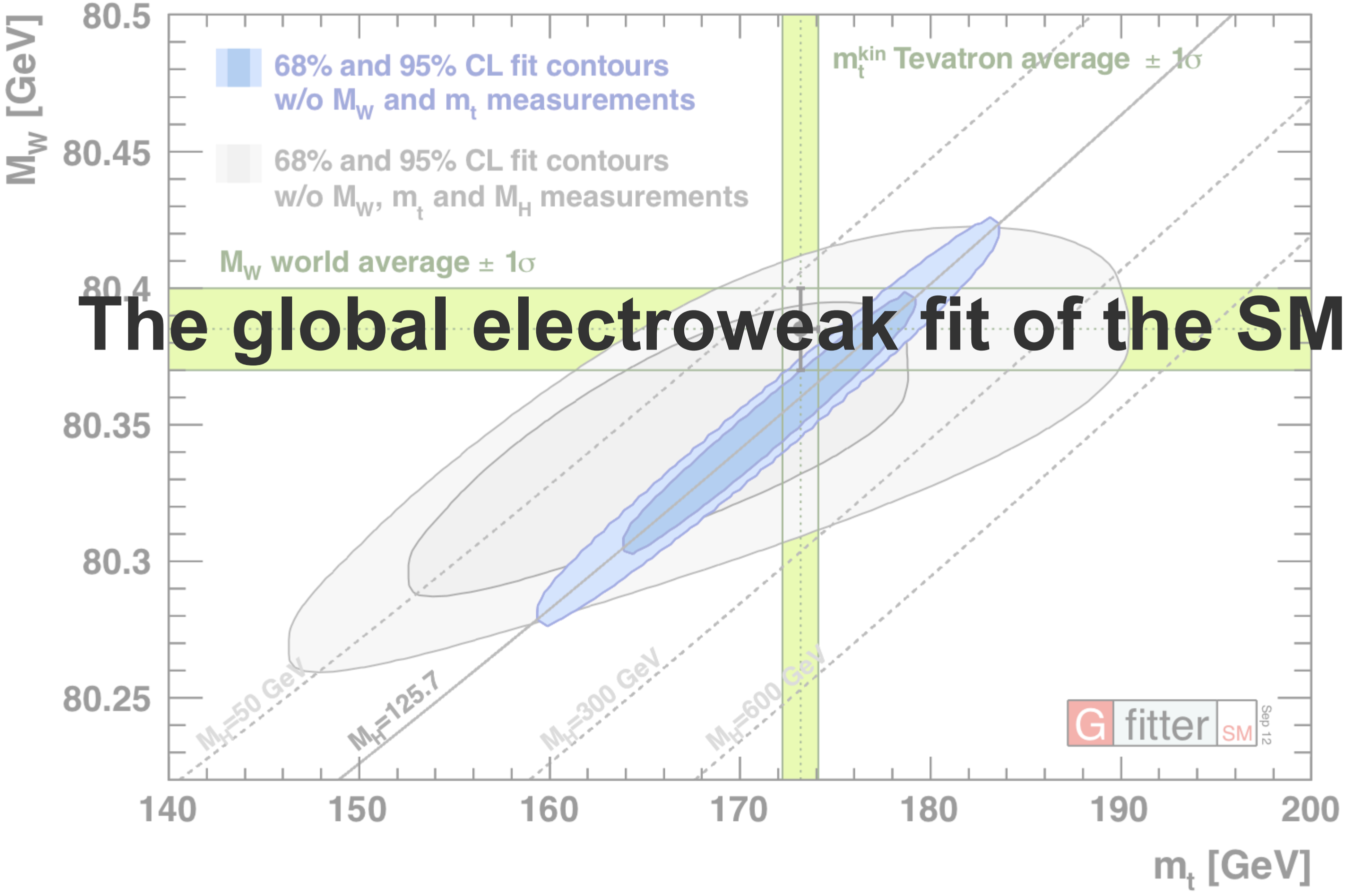
G fitter

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, etc.
  - 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 “plug-in” physics libraries: SM, 2HDM, multiple BSM model, ...

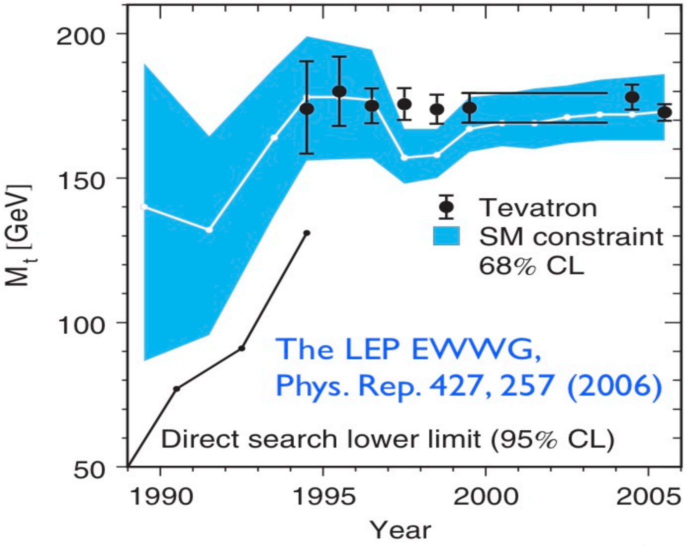
- Our publications and new results available at: www.cern.ch/Gfitter



The global electroweak fit of the SM

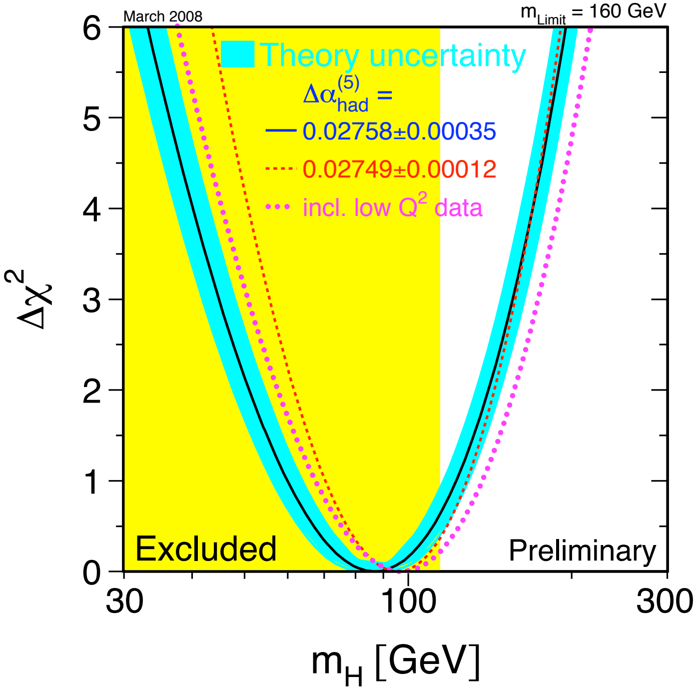
Global EW fits: a long history

- Huge amount of pioneering work by many!
  - Needed to understand importance of loop corrections
    - Observables (now) known at least at two-loop order, sometimes more.
  - High-precision Standard Model (SM) predictions and measurements required
    - First from LEP/SLC, then Tevatron, now LHC.



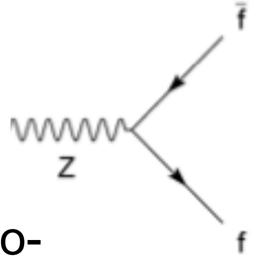
- EW fits performed by many groups in past
  - D. Bardinet al. (ZFITTER), G. Passarinoet al. (TOPAZ0), LEP EW WG (M. Grünewald, K. Mönig et al.), J. Erler (GAPP), …
  - Important results obtained!

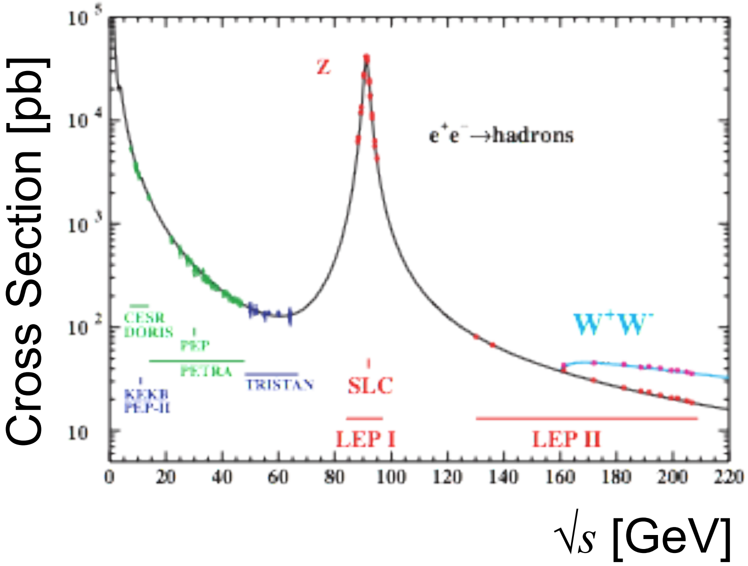
- (Global SM fits also used at lower energies [CKM-matrix], and many groups pursuing global beyond-SM fits.)



The predictive power of the SM

- As the Z boson couples to all fermions, it is ideal to measure & study both the electroweak and strong interactions.
- Tree level relations for Z→f$\bar{f}$
  - $$i\bar{f}\gamma^{\mu}\left(g_{V,f}-g_{A,f}\gamma_5\right)fZ_{\mu}$$
  - Unification connects the electro-magnetic and weak couplings





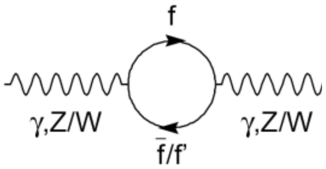
- The impact of radiative corrections
  - Absorbed into EW form factors: ρ, κ, Δr
  - Effective couplings at the Z-pole
  - Quadraticly dependent on m_t, *logarithmic* dependence on M_H

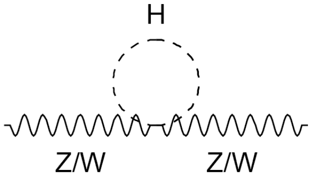
$$g_{V,f}=\sqrt{\rho_Z^f}\left(I_3^f-2Q^f\sin^2\theta_{\text{eff}}^f\right)$$

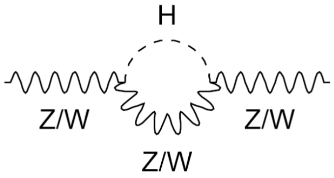
$$g_{A,f}=\sqrt{\rho_Z^f}I_3^f$$

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

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

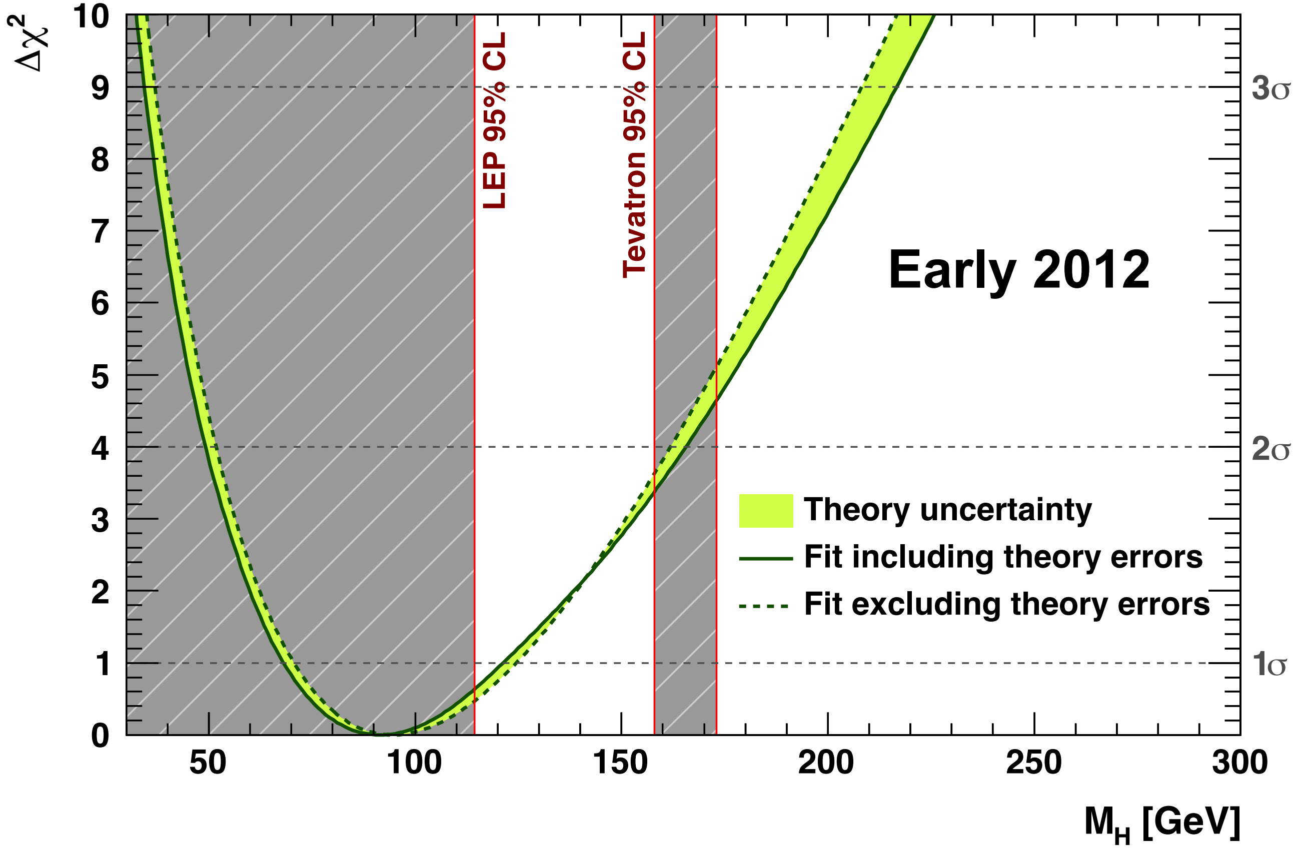






Hunt for the Higgs

Gfitter group, EPJC 72, 2003 (2012)

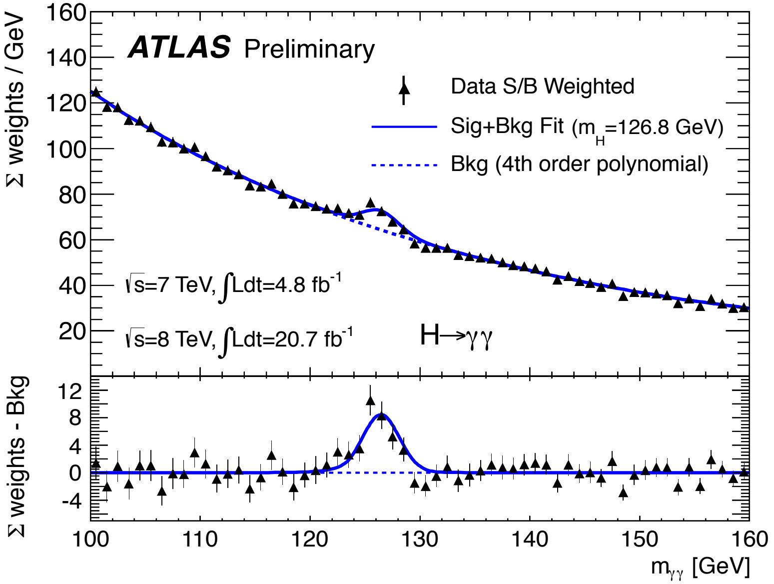


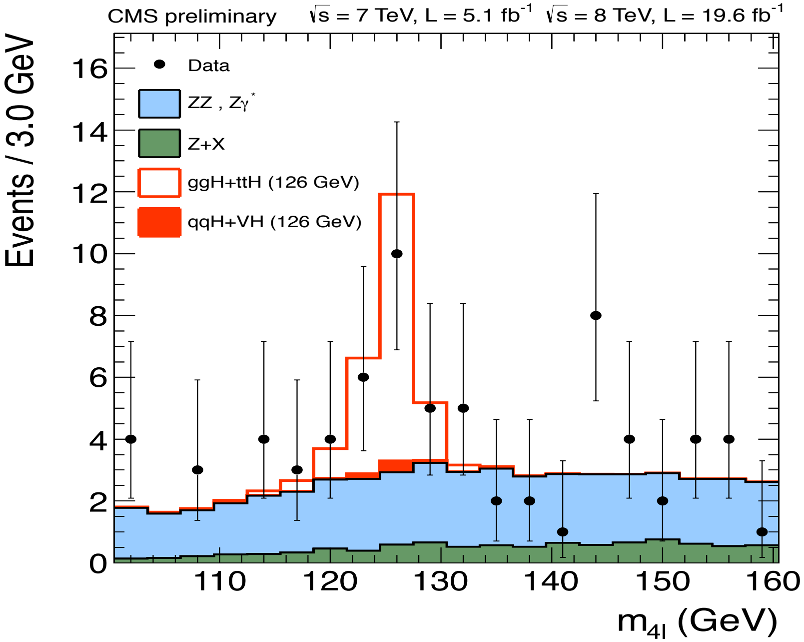
- M_H was last missing input parameter of the electroweak fit
- Indirect determination from EW fit (2012): $M_H = 96^{+31}_{-24}$ GeV
- (Direct Higgs limits of course also available in the EW fit.)

The SM fit with Gfitter, including the Higgs

- Discovery of Higgs-like boson at LHC
  - Cross section, branching ratios, spin, parity sofar compatible with SM Higgs boson.
  - This talk: assume boson is SM Higgs.
  - Use in EW fit: $M_H = 125.7 \pm 0.4$ GeV
    - ATLAS: $M_H = 126.0 \pm 0.4 \pm 0.4$ GeV
    - CMS: $M_H = 125.3 \pm 0.4 \pm 0.5$ GeV

    [arXiv:1207.7214, arXiv:1207.7235]
  - Change in average between fully uncorrelated and fully correlated systematic uncertainties is minor: δM_H : 0.4 → 0.5 GeV





- *Unique situation: for first time SM is fully over-constrained → Test its self-consistency!*
  - *The focus of this talk …*

Measurements at the Z-pole (1/2)

- Total cross-section
  - Express in terms of partial decay width of initial and final width:

$$\boxed{\sigma^Z_{f\bar{f}} = \sigma^0_{f\bar{f}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} \frac{1}{R_{\mathrm{QED}}} \quad \text{with} \quad \sigma^0_{f\bar{f}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}}$$

Corrected for QED radiation

  - Full width: $\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\mathrm{had}} + \Gamma_{\mathrm{inv}}$
  - (Correlated set of measurements.)

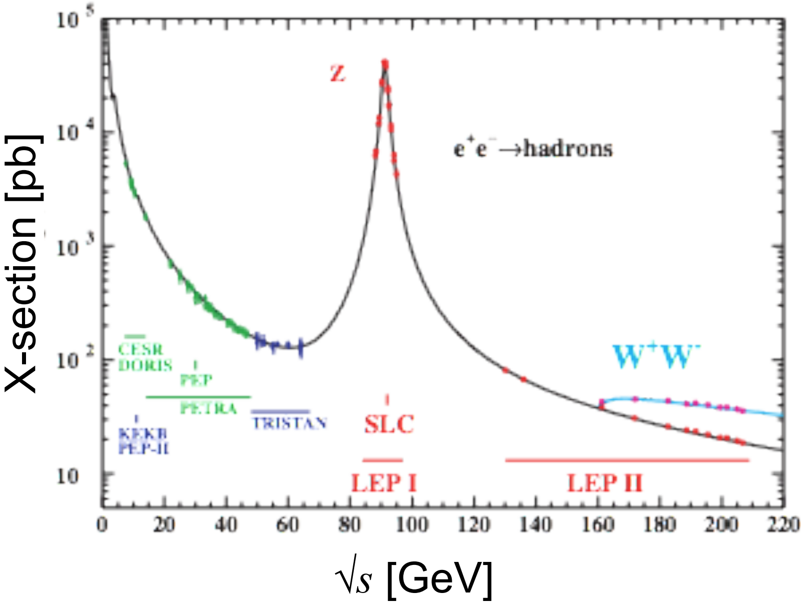
- Set of input (width) parameters to EW fit:
  - Z mass and width: $\boxed{M_Z}$, $\boxed{\Gamma_Z}$
  - Hadronic pole cross section:

$$\boxed{\sigma^0_{\mathrm{had}}} = 12\pi/M_Z^2 \cdot \Gamma_{ee}\Gamma_{\mathrm{had}}/\Gamma_Z^2$$

  - Three leptonic ratios (lepton univ.):

$$\boxed{R^0_\ell} = R^0_e = \Gamma_{\mathrm{had}}/\Gamma_{ee} \; (= R^0_\mu = R^0_\tau)$$

  - Hadronic width ratios: $\boxed{R^0_b}$, $\boxed{R^0_c}$



Measurements at the Z-pole (2/2)

Definition of Asymmetry

- Distinguish vector and axial-vector couplings of the Z

$$A_f = \frac{g_{L,f}^2 - g_{R,f}^2}{g_{L,f}^2 + g_{R,f}^2} = \frac{2 g_{V,f}\, g_{A,f}}{g_{V,f}^2 + g_{A,f}^2}$$

- Directly related to $\sin^2 \theta_{\text{eff}}^{f\bar{f}} = \frac{1}{4Q_f}\left(1 + \mathcal{R}e\left(\frac{g_{V,f}}{g_{A,f}}\right)\right)$

Observables

- In case of no beam polarisation (LEP) use final state angular distribution to define *forward/backward asymmetry*

$$A_{FB}^f = \frac{N_F^f - N_B^f}{N_F^f + N_B^f} \qquad A_{FB}^{0,f} = \frac{3}{4} A_e A_f$$

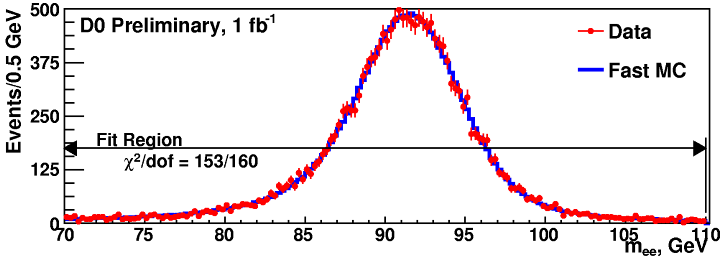
- Polarised beams (SLC), define *left/right asymmetry*

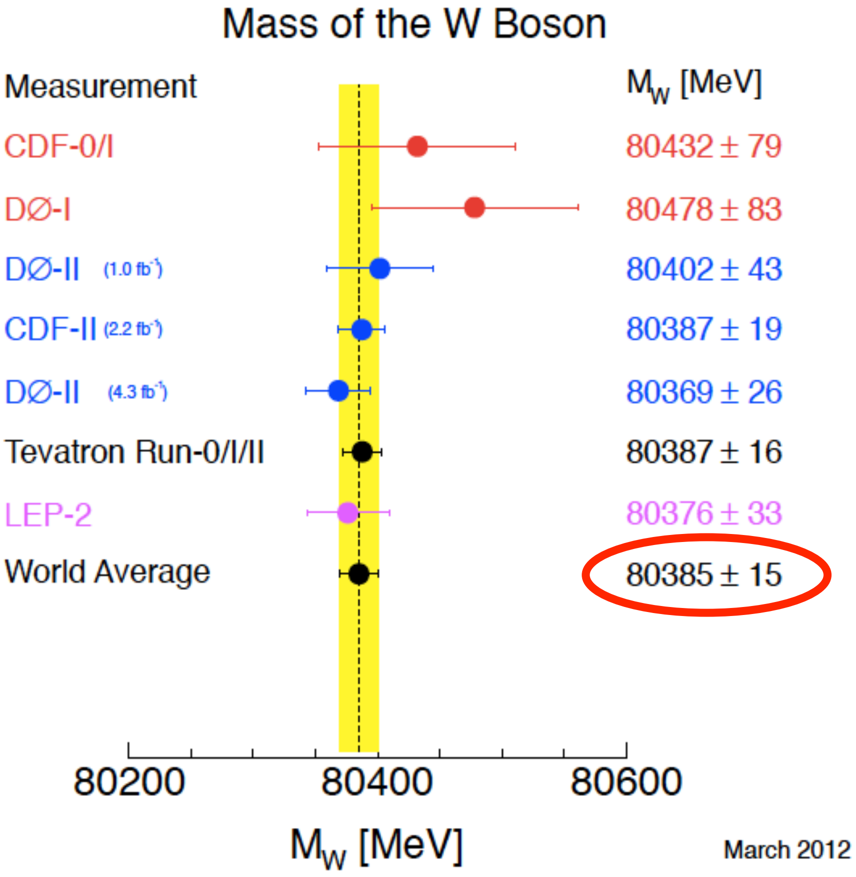
$$A_{LR}^f = \frac{N_L^f - N_R^f}{N_L^f + N_R^f} \frac{1}{\langle |P|_e \rangle} \qquad A_{LR}^0 = A_e$$

- Measurements: $\boxed{A_{FB}^{0,\ell},}$ $\boxed{A_{FB}^{0,c},}$ $\boxed{A_{FB}^{0,b}}$ $\boxed{A_\ell,}$ $\boxed{A_c,}$ $\boxed{A_b}$

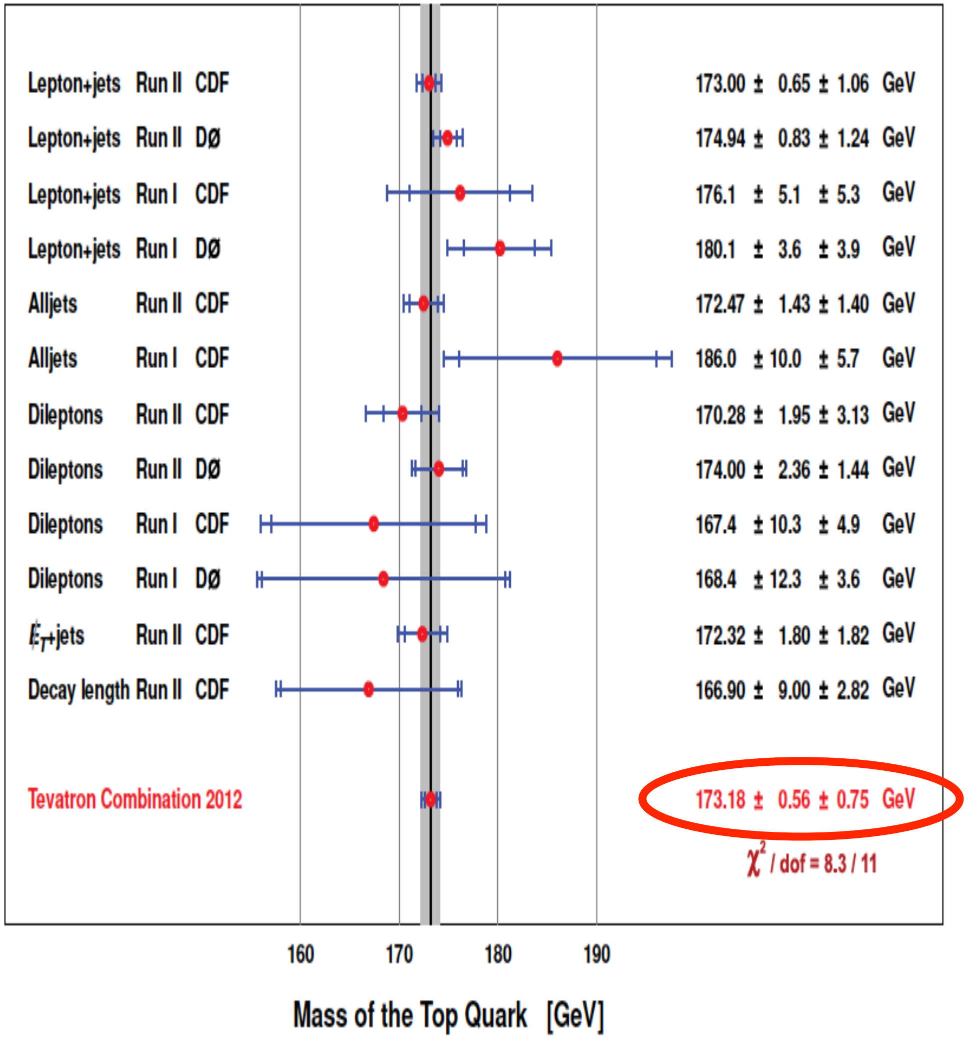
2012 averages for M_W and m_{top}

Latest Tevatron result from: arXiv:1204.0042





Tevatron result from: arXiv:1207.1069



Used here: m_t = 173.18 ± 0.94 GeV
Moriond'13: m_t = 173.20 ± 0.87 GeV

The electromagnetic coupling

- The EW fit requires precise knowledge of $\alpha(M_Z)$ – better than 1% level
  - Enters various places: hadr. radiator functions, predictions of M_W and $\sin^2\theta^f_{eff}$
- Conventionally parametrized as ($\alpha(0)$ = fine structure constant) :

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)}$$

- Evolution with renormalization scale:

$$\Delta\alpha(s) = \Delta\alpha_{\mathrm{lep}}(s) + \Delta\alpha^{(5)}_{\mathrm{had}}(s) + \Delta\alpha_{\mathrm{top}}(s)$$

- Leptonic term known up to three loops (for $q^2 \gg m_l$)
- Top quark contribution known up to 2 loops, *small: $-0.7\mathrm{x}10^{-4}$*

[M. Steinhauser,
PLB 429, 158 (1998)]

- Hadronic contribution (from the 5 light quarks) is difficult to calculate, cannot be obtained from pQCD alone.
  - Analysis of low-energy e^+e^- data
  - Usage of pQCD if lack of data

$$\boxed{\Delta\alpha^{(5)}_{had}(M_Z) = (274.9 \pm 1.0)\cdot 10^{-4}}$$

- Similar analysis to evaluation of hadronic contribution to $(g-2)_\mu$

[M. Davier et al., Eur. Phys. J. C71, 1515 (2011)]

Theoretical input

- In EW fit with Gfitter we use state-of-the-art calculations:
  - M_W Mass of the W boson [M. Awramik et al., Phys. Rev. D69, 053006 (2004)]
  - $\sin^2\theta^f_{\text{eff}}$ Effective weak mixing angle [M. Awramik et al., JHEP 11, 048 (2006), M. Awramik et al., Nucl.Phys.B813:174-187 (2009)]
    - Full two-loop + leading beyond-two-loop form factor corrections
  - Γ_{had} QCD Adler functions at N^3LO [P. A. Baikov et al., PRL108, 222003 (2012)]
    - N^3LO prediction of the hadronic cross section
  - R_b Partial width of Z→bb [Freitas et al., JHEP08, 050 (2012)] ⟵ **New! full 2-loop calc.**

- Two nuisance parameters in EW fit for theoretical uncertainties:
  - *δM_W (4 MeV), $\delta\sin^2\theta^l_{\text{eff}}$ ($4.7\text{x}10^{-5}$)*

- Radiative corrections are important!
  - E.g. consider tree-level EW unification relation:
    - This predicts: $M_W = (79.964 \pm 0.005)$ GeV
    - Experiment: $M_W = (80.385 \pm 0.015)$ GeV

$$M_W^2\Big|_{\text{tree-level}} = \frac{M_Z^2}{2}\cdot\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$

- Without loop corrections: 27σ discrepancy!

Electroweak fit – Experimental inputs

- Latest experimental inputs:
  - Z-pole observables: from LEP / SLC
    [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - M_W and Γ_W from LEP/Tevatron
    [arXiv:1204.0042]
  - m_{top} : average from Tevatron
    [arXiv:1207.1069]
  - m_c, m_b world averages (PDG)
    [PDG, J. Phys. G33,1 (2006)]
  - $\Delta\alpha_{had}^{(5)}(M_Z^2)$ including α_S dependency
    [Davier et al., EPJC 71, 1515 (2011)]
  - M_H from LHC
    [arXiv:1207.7214, arXiv:1207.7235]

- 7+2 free fit parameters:
  - M_Z, M_H, $\alpha_S(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_t, $\overline{m}_c$, $\overline{m}_b$
  - 2 theory nuisance parameters
    - *δM_W (4 MeV), $\delta\sin^2\theta^l_{eff}$ (4.7×10^{-5})*

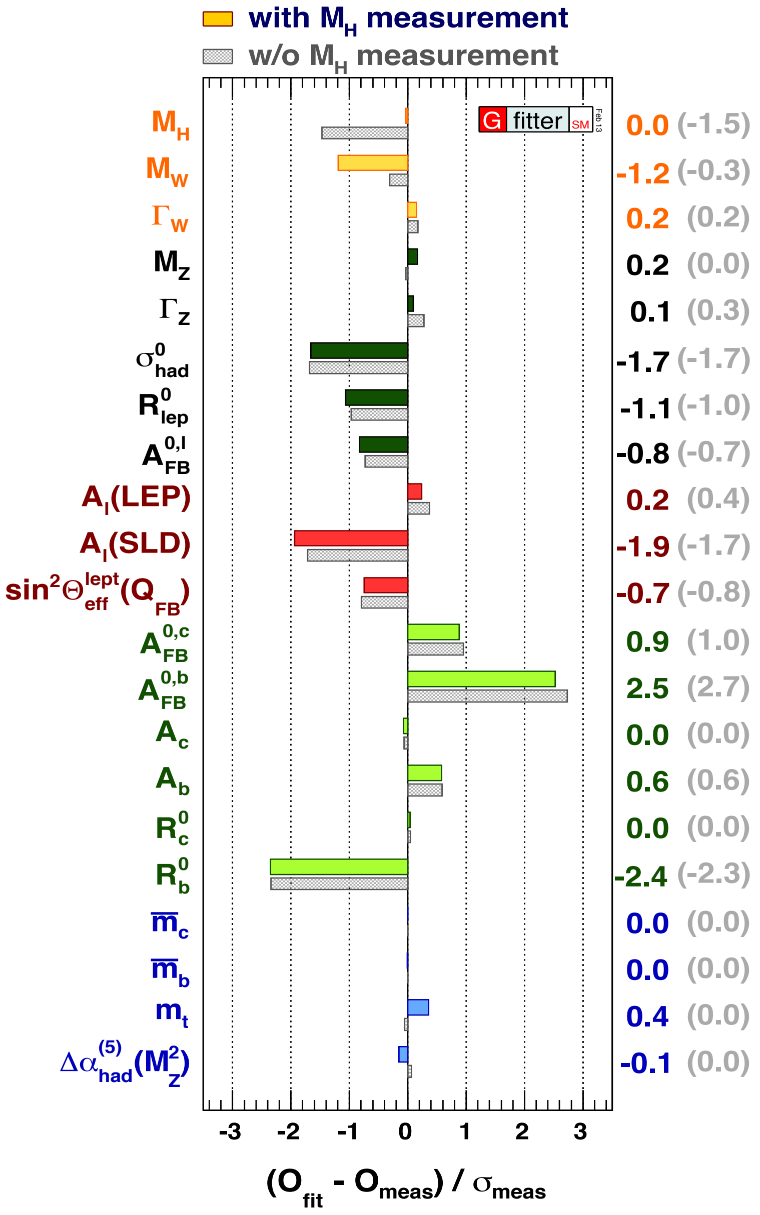
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LHC
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	
R^0_c	0.1721 ± 0.0030	
R^0_b	0.21629 ± 0.00066	
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.18 ± 0.94	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\bigtriangledown)}$	2757 ± 10	

Electroweak Fit – SM Fit Results

- From the Gfitter Group, EPJC 72, 2205 (2012)
- Left: full fit incl. M_H
- Middle: fit not incl. M_H
- Right: fit incl M_H, not the row

Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	94^{+25}_{-22}	94^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0116
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01627 ± 0.0002	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	0.1477 ± 0.0009	$0.1468 \pm 0.0005^{(\dagger)}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23148^{+0.00011}_{-0.00007}$	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6680^{+0.00025}_{-0.00038}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00004}_{-0.00007}$	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	0.0740 ± 0.0005	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	0.1036 ± 0.0007	0.1034 ± 0.0004
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21474 ± 0.00003	0.21475 ± 0.00003	0.21473 ± 0.00003
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\bigtriangledown)}$	2757 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-1.4	4.7	–

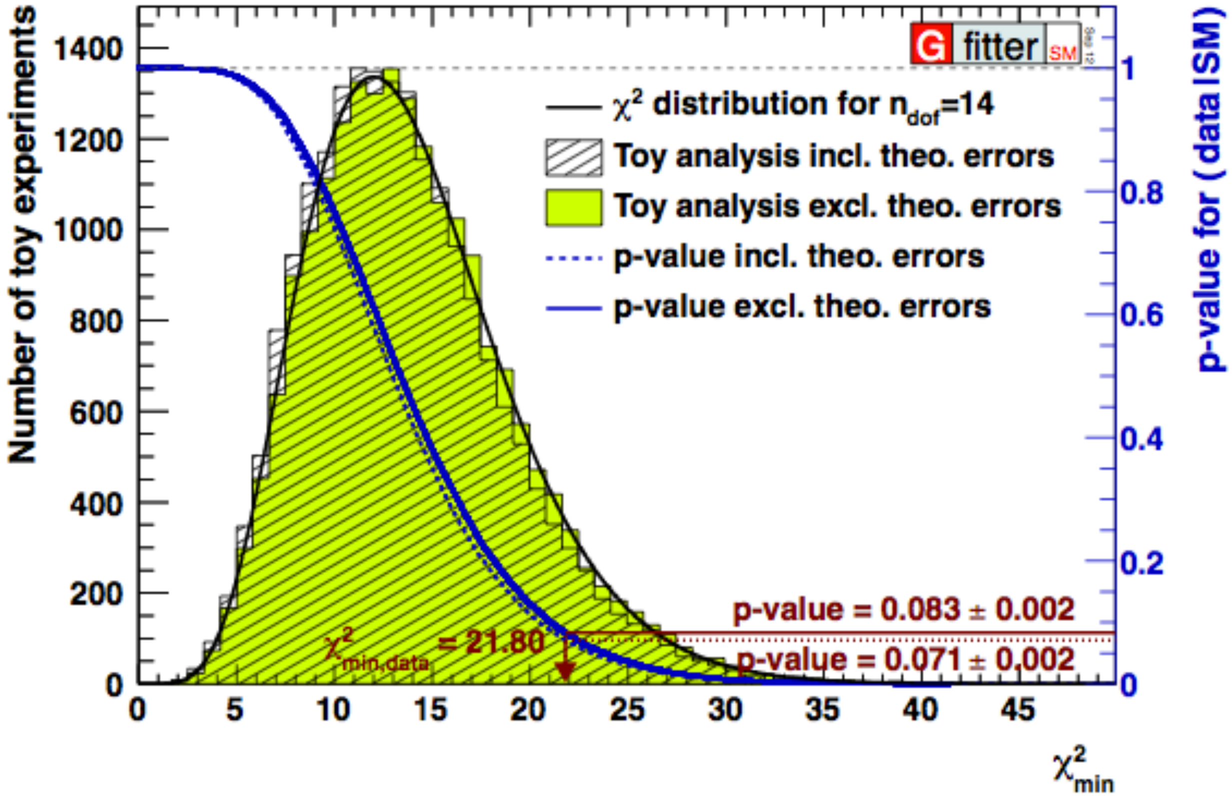
Electroweak Fit – SM Fit Results



Plot inspired by Eberhardt et al. [arXiv:1209.1101]

- No individual value exceeds 3σ
- Small pulls for M_H, M_Z, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, $\overline{m}_c$, $\overline{m}_b$ indicate that input accuracies exceed fit requirements
- Largest deviations in b-sector: $A^{0,b}_{FB}$ and R^0_b with 2.5σ and -2.4σ
  - → largest contribution to χ^2
- R^0_b using one-loop calculation -0.8σ
  - R^0_b has only little dependence on M_H
- Most affected when including M_H : M_W prediction:
  - Shift in predicted M_W value of 13 MeV.

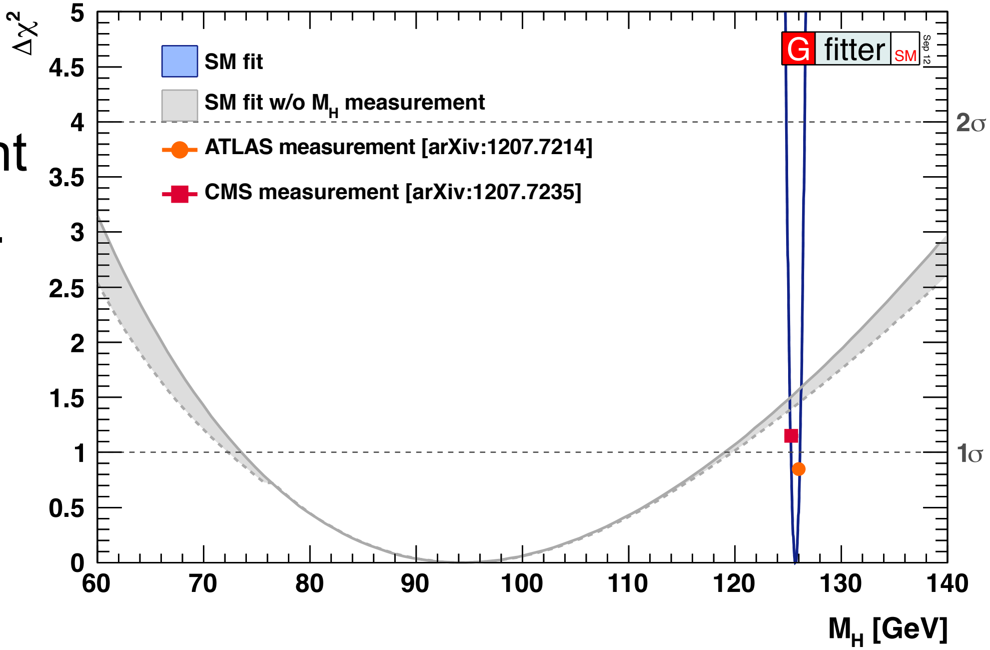
Goodness of Fit



- Toy analysis: p-value for wrongly rejecting the SM = $0.07^{+0.01\ \text{(theo)}}$
  - p-value is equivalent to 1.8σ.
  - Evaluated with 20k pseudo experiments – follows χ^2 with 14 d.o.f.
  - For comparison: χ^2_{min}= 21.8 → Prob(χ^2_{min}, 14) = 8 %
- Large value of χ^2_{min} *not* due to inclusion of M_H measurement.
  - Without M_H measurement: χ^2_{min}= 20.3 → Prob(χ^2_{min}, 13) = 9%

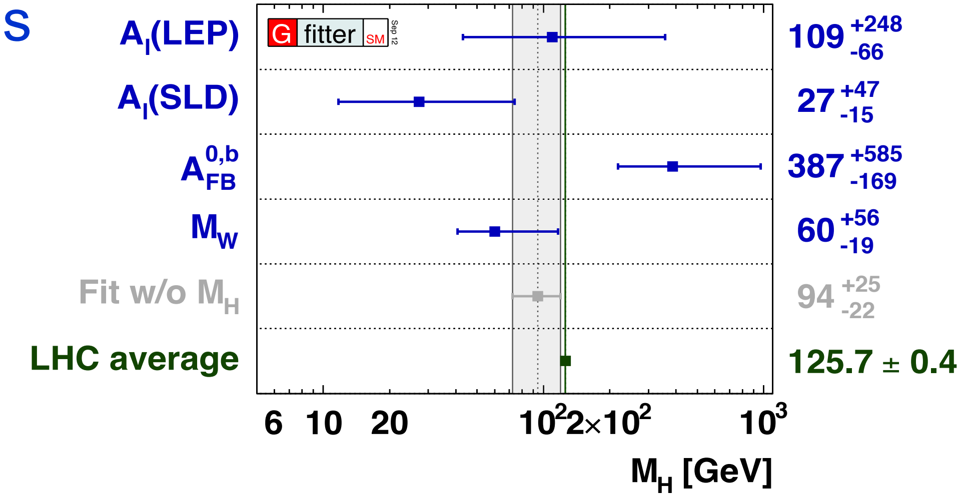
Higgs results of the EW fit

- Scan of $\Delta\chi^2$ profile versus M_H
  - Grey band: fit w/o M_H measurement
  - Blue line: full SM fit, with M_H meas.
  - Fit w/o M_H measurement gives: $M_H = 94^{+25}_{-22}$ GeV
  - Consistent at 1.3σ with LHC measurement.



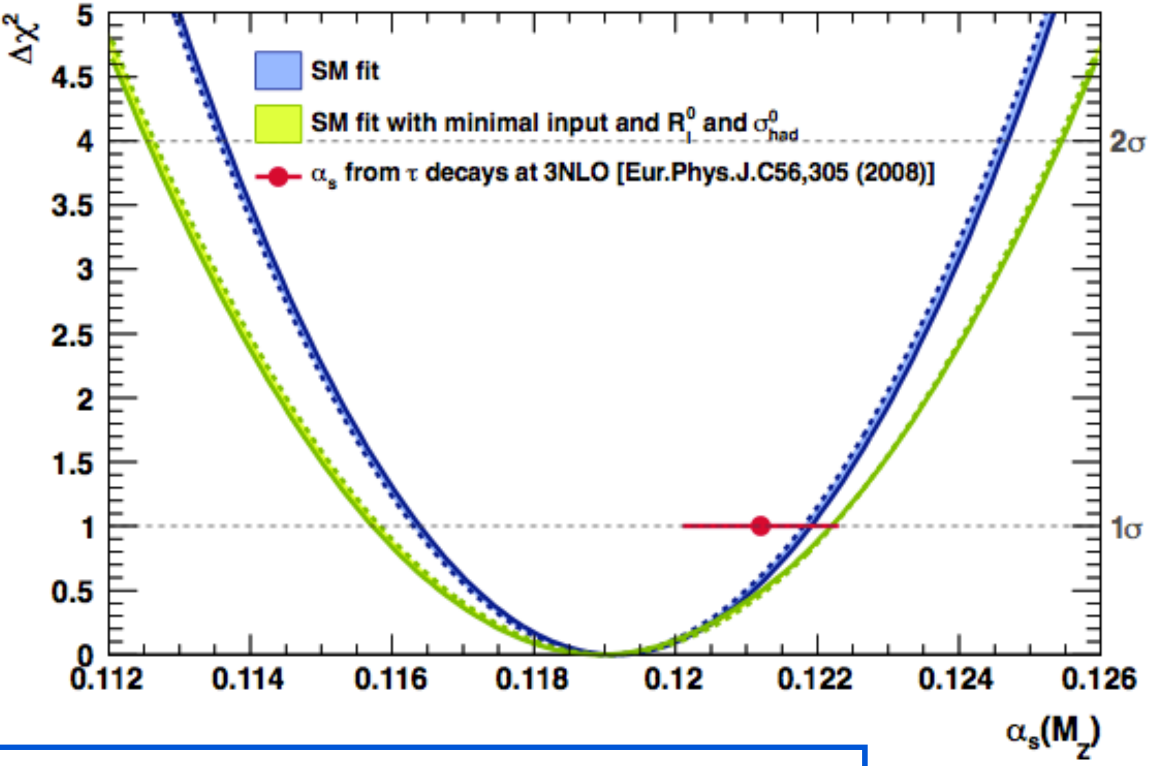
- Bottom plot: impact of other most sensitive Higgs observables
  - Determination of M_H removing all sensitive observables except the given one.
  - Known tension (2.5σ) between A_l(SLD), $A^{0,b}_{FB}$, and M_W clearly visible.

fit below only includes the given observable



Prediction for $\alpha_s(M_Z)$ from Z→hadrons

- Scan of $\Delta\chi^2$ versus α_s
  - Also shown: SM fit with minimal inputs: M_Z, G_F, $\Delta\alpha_{had}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, M_H, and fermion masses
- Determination of α_s at N^3LO.
  - Most sensitive through total hadronic cross-section σ^0_{had} and partial leptonic width R^0_l



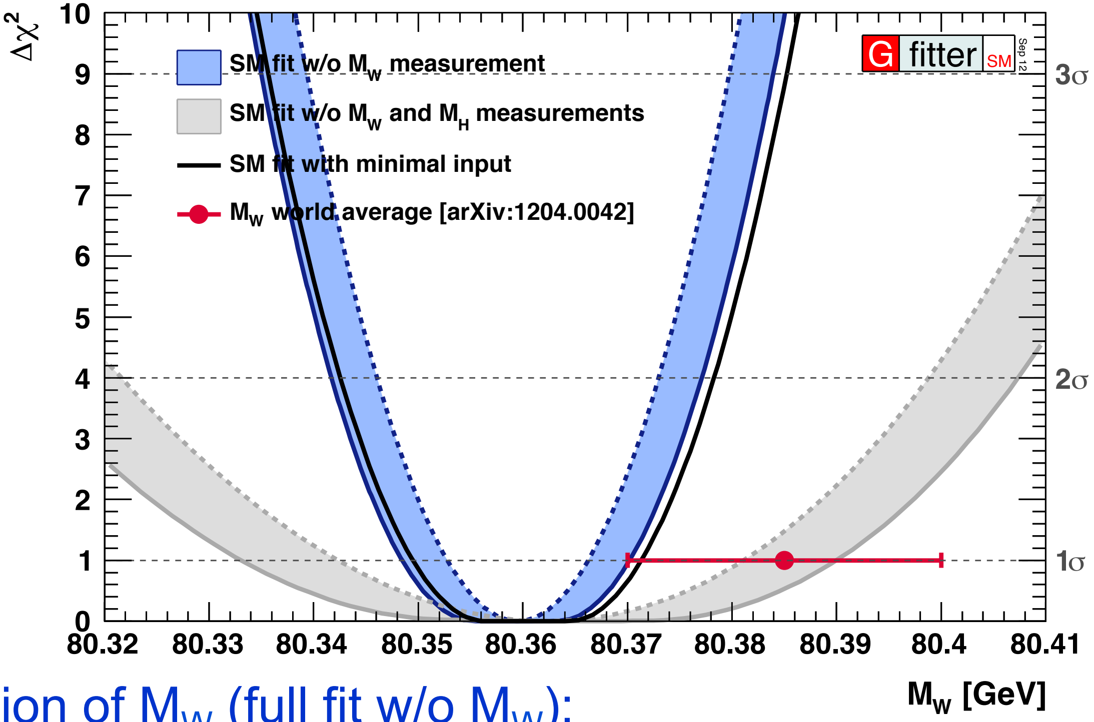
$$\alpha_s(M_Z) = 0.1191 \pm 0.0028\,(\text{exp.}) \pm 0.0001\,(\text{theo.})$$

- Theory uncertainty at per-mille level (obtained by scale variation of Γ_{had}).

- *In good agreement with value from τ decays, also at N^3LO.*
  - (Improvements in precision only expected with ILC/GigaZ. See later.)

Indirect determination of W mass

- Scan of $\Delta\chi^2$ profile versus M_W
  - Also shown: SM fit with minimal inputs: M_Z, G_F, $\Delta\alpha_{had}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, M_H, and fermion masses
  - Good consistency between total fit and SM w/ minimal inputs



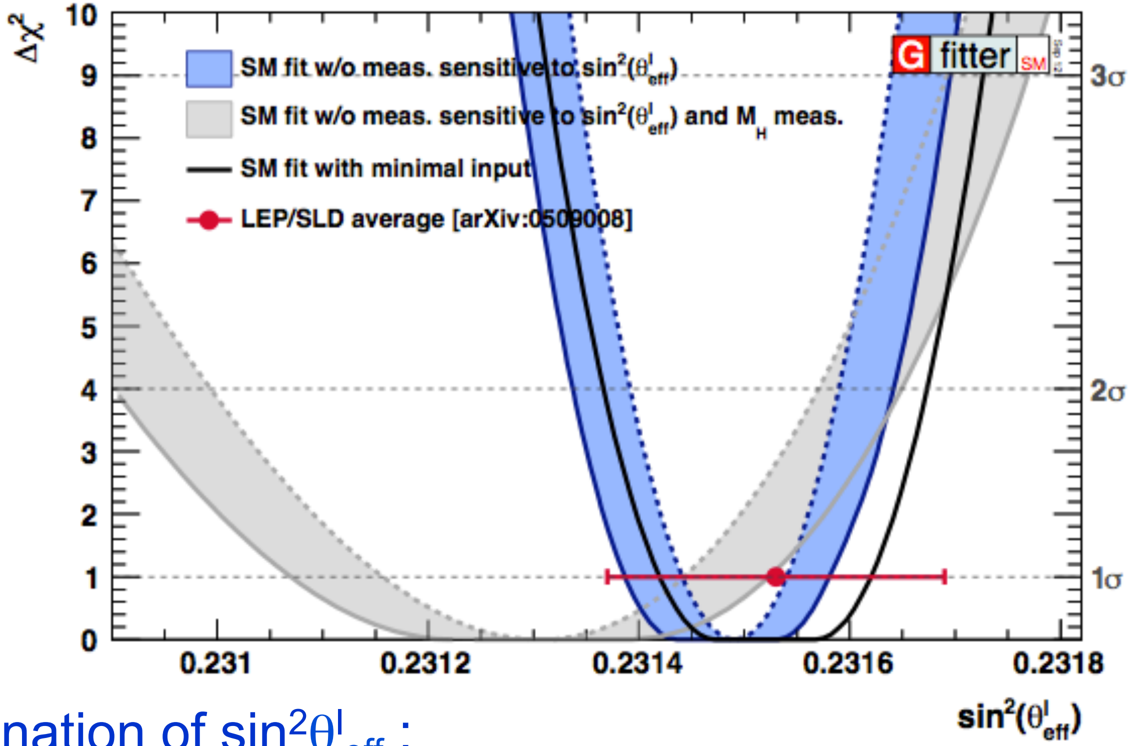
- M_H measurement allows for precise constraint on M_W
  - Agreement at 1.4σ
- Fit result for indirect determination of M_W (full fit w/o M_W):

$$\begin{aligned} M_W &= 80.3593 \pm \boxed{0.0056_{m_t}} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\ &\qquad \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm \boxed{0.0040_{\rm theo}} \\ &= 80.359 \pm 0.011_{\rm tot}\ , \end{aligned}$$

- More precise estimate of M_W than the direct measurements!
  - Uncertainty on world average measurement: 15 MeV

Indirect effective weak mixing angle

- Right: scan of $\Delta\chi^2$ profile versus $\sin^2\theta^l_{eff}$
  - All sensitive measurements removed from the SM fit.
  - Also shown: SM fit with minimal inputs



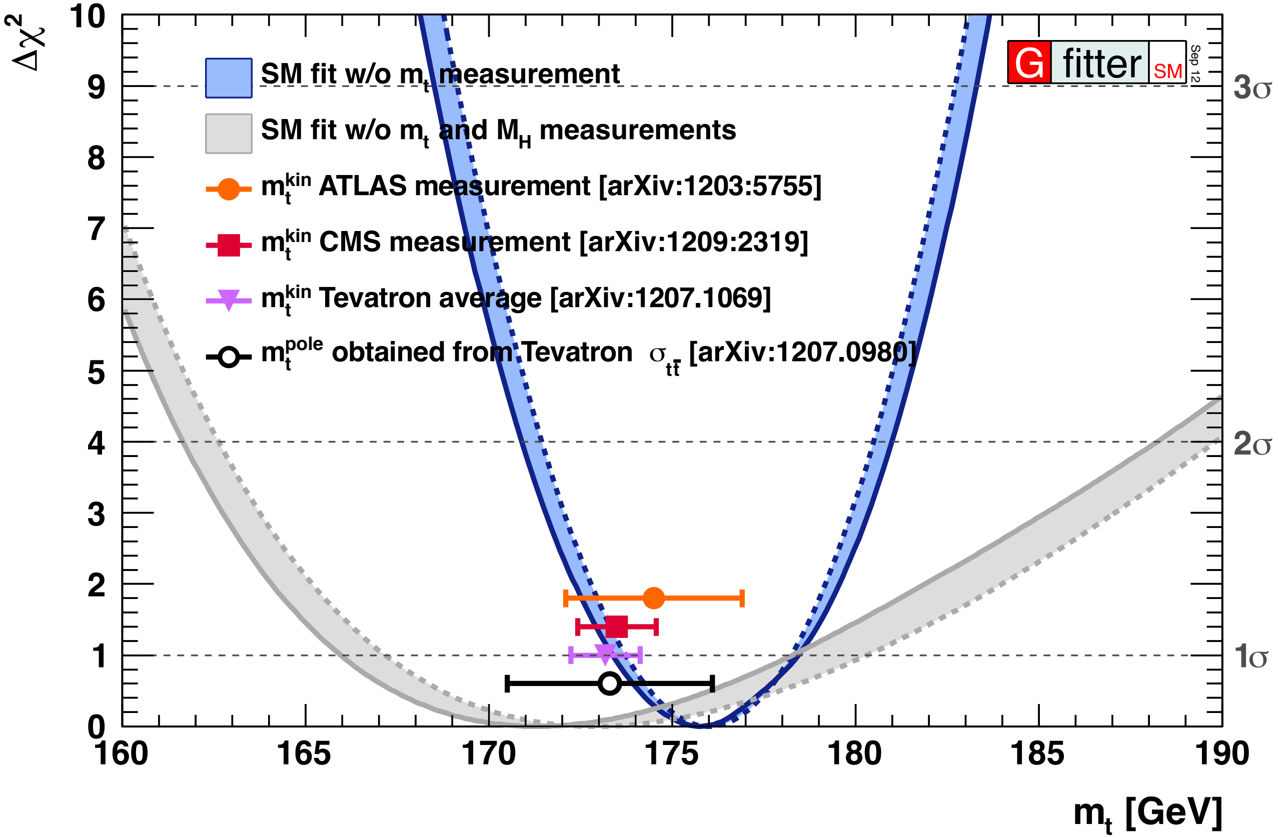
- M_H measurement allows for very precise constraint on $\sin^2\theta^l_{eff}$

- Fit result for indirect determination of $\sin^2\theta^l_{eff}$:

$$\begin{aligned}\sin^2\theta^\ell_{\rm eff} &= 0.231496 \pm \boxed{0.000030_{m_t}} \pm 0.000015_{M_Z} \pm \boxed{0.000035_{\Delta\alpha_{\rm had}}}\\ &\quad \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm \boxed{0.000047_{\rm theo}}\ ,\\ &= 0.23150 \pm 0.00010_{\rm tot}\ ,\end{aligned}$$

- More precise than direct determination (from LEP/SLD) !
  - Uncertainty on LEP/SLD average: $1.6\text{x}10^{-4}$

Indirect determination of top mass

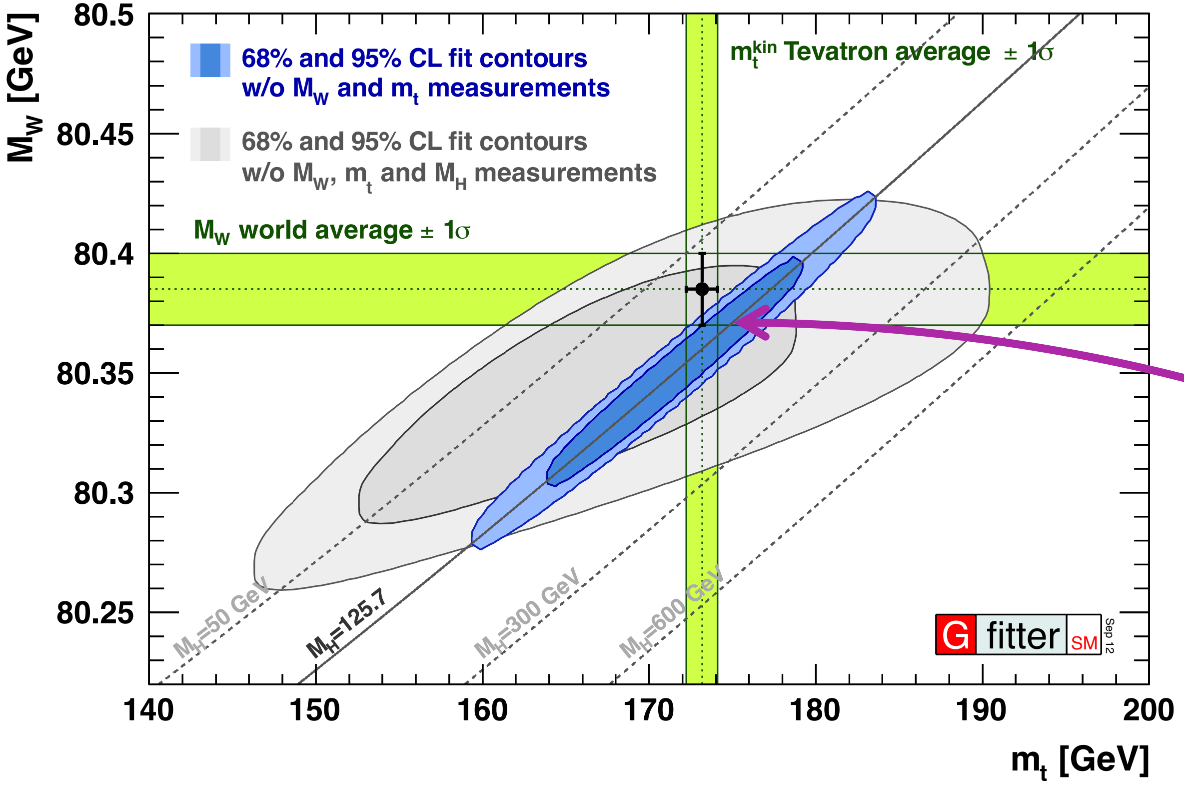


- Shown: scan of $\Delta\chi^2$ profile versus m_t (without m_t measurement)
  - M_H measurement allows for significant better constraint of m_t
  - Indirect determination consistent with direct measurements
    - Remember: fully obtained from loop corrections!

- Indirect result: $m_t = 175.8^{+2.7}_{-2.4}$ GeV (Tevatron w.a.: 173.2 ± 0.9 GeV)

State of the SM: W versus top mass

- Scan of M_W vs m_t, with the direct measurements excluded from the fit.
- Results from Higgs measurement significantly reduces allowed indirect parameter space → corners the SM!

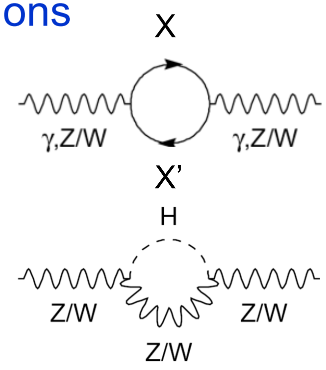


- Observed agreement demonstrates impressive consistency of the SM!

Constraints on Oblique Corrections

G fitter B SM

- At low energies, BSM physics appears dominantly through vacuum polarization corrections
  - Aka, “oblique corrections”
- Oblique corrections reabsorbed into electroweak form factors
  - $\Delta\rho$, $\Delta\kappa$, Δr parameters, appearing in: M_W^2, $\sin^2\theta_{eff}$, G_F, α, etc.
- Electroweak fit sensitive to BSM physics through oblique corrections
  - Similar to 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 results for S, T, U

- S,T,U obtained from fit to the EW observables
- SM: M_H = 126 GeV, m_t = 173 GeV
  - This defines (S,T,U) = (0,0,0)
- SM: S, T depend logarithmically on M_H
- Fit result:

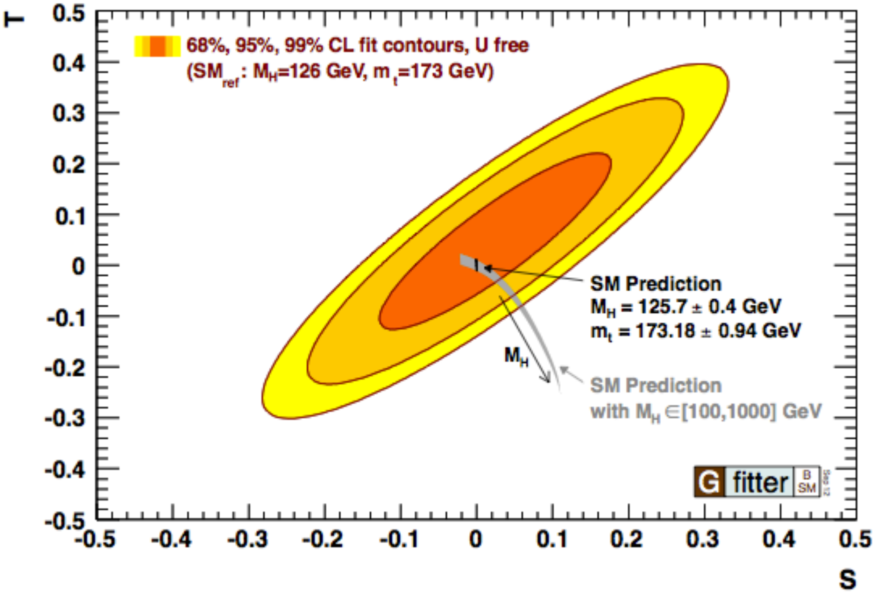
$S = 0.03 \pm 0.10$

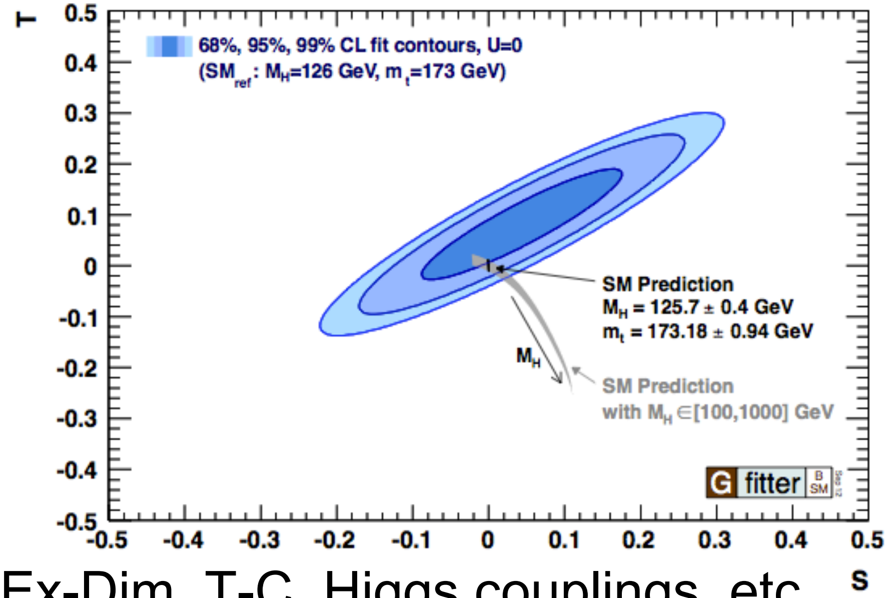
$T = 0.05 \pm 0.12$

$U = 0.03 \pm 0.10$

	S	*T*	*U*
S	1	+0.89	-0.54
T		1	-0.83
U			1

- Stronger constraints from fit with U=0.
- Also available for Z→bb correction.
- No indication for new physics.
- Can now use this to constrain 4th gen, Ex-Dim, T-C, Higgs couplings, etc.





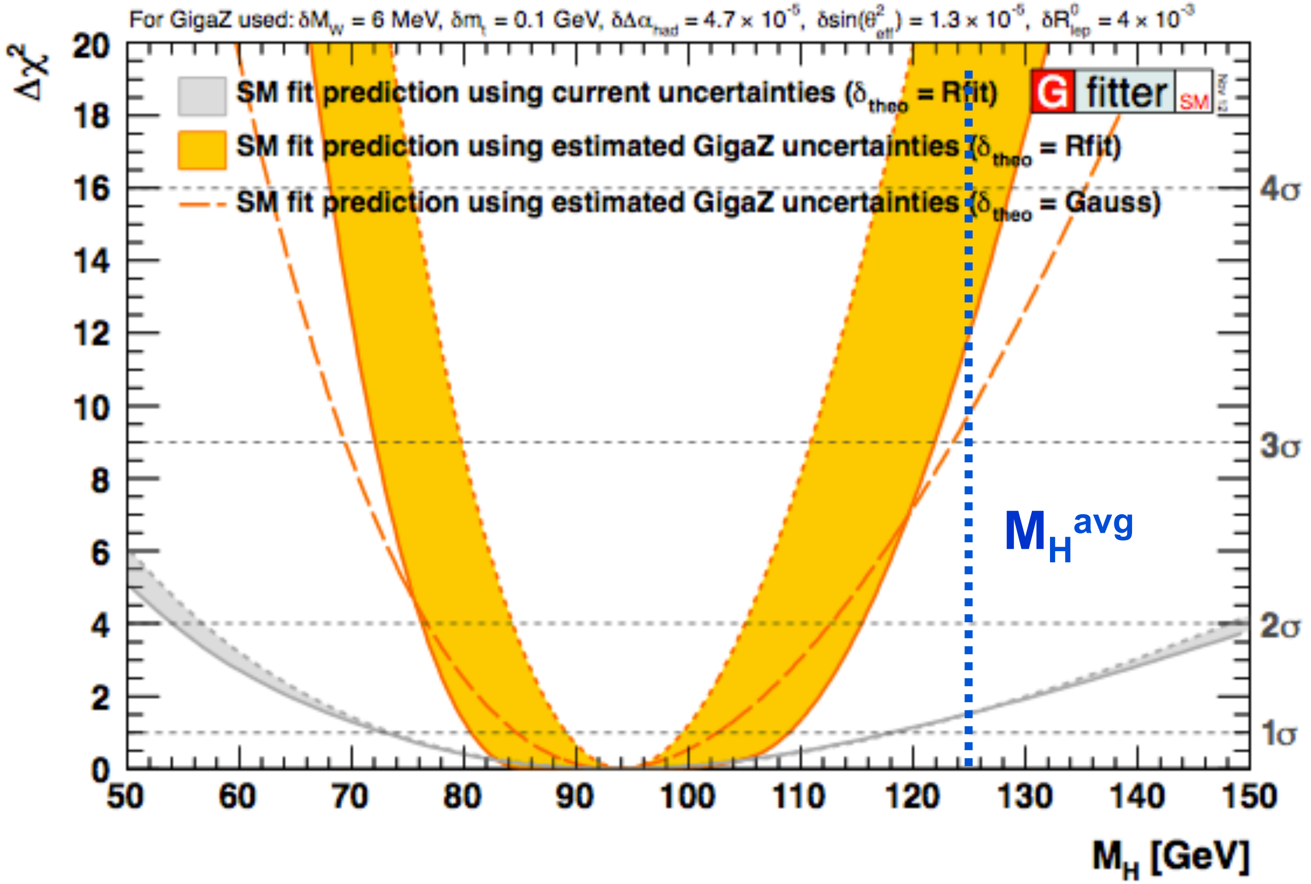
ILC Prospects for the Standard Model fit

Prospects for ILC with Giga Z

- Future Linear Collider could improve precision of EW observables tremendously.
  - *WW threshold, to obtain M_W*
    - from threshold scan: δM_W : 15 → 6 MeV
  - *ttbar threshold, to obtain m_t*
    - obtain m_t indirectly from production cross section: δm_t : 0.9 → 0.1 GeV
  - *Z pole measurements*
    - High statistics: 10^9 Z decays: $\delta R^0_{lep} : 2.5 \cdot 10^{-2} \rightarrow 4 \cdot 10^{-3}$
    - With polarized beams, uncertainty on $\delta A^{0,f}_{LR}$: $10^{-3} \rightarrow 10^{-4}$, which translates to $\delta \sin^2\theta^l_{eff} : 1.6 \cdot 10^{-4} \rightarrow 1.3 \cdot 10^{-5}$

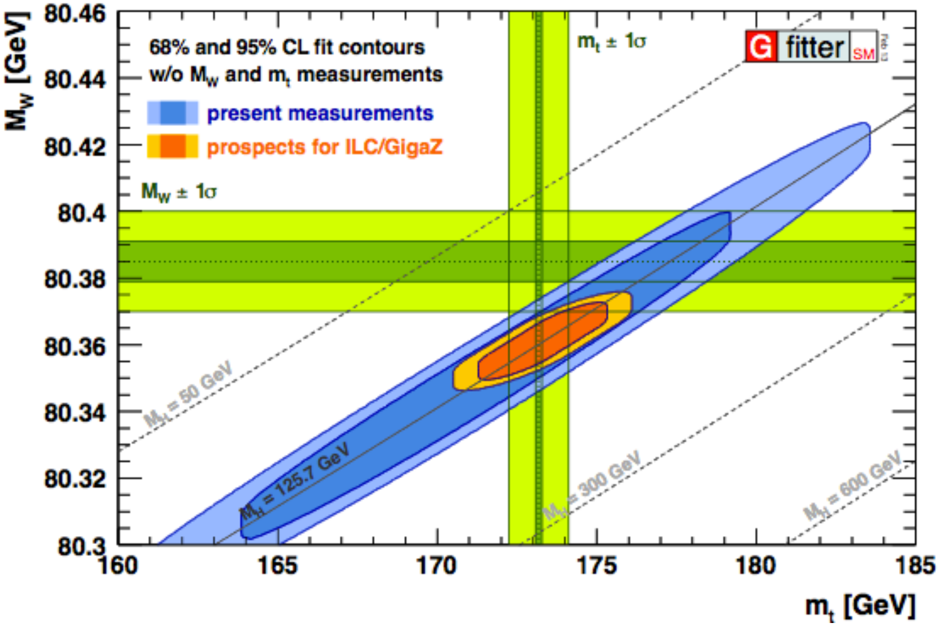
- Low-energy data results to improve $\Delta\alpha_{had}$:
  - ISR-based (BABAR) and KLOE-II, BESIII e^+e^- cross-section measurements, in particular around cc resonance …
  - … plus: improved α_s, improvements in theory: $\Delta\alpha_{had}$: $10^{-4} \rightarrow 5 \cdot 10^{-5}$

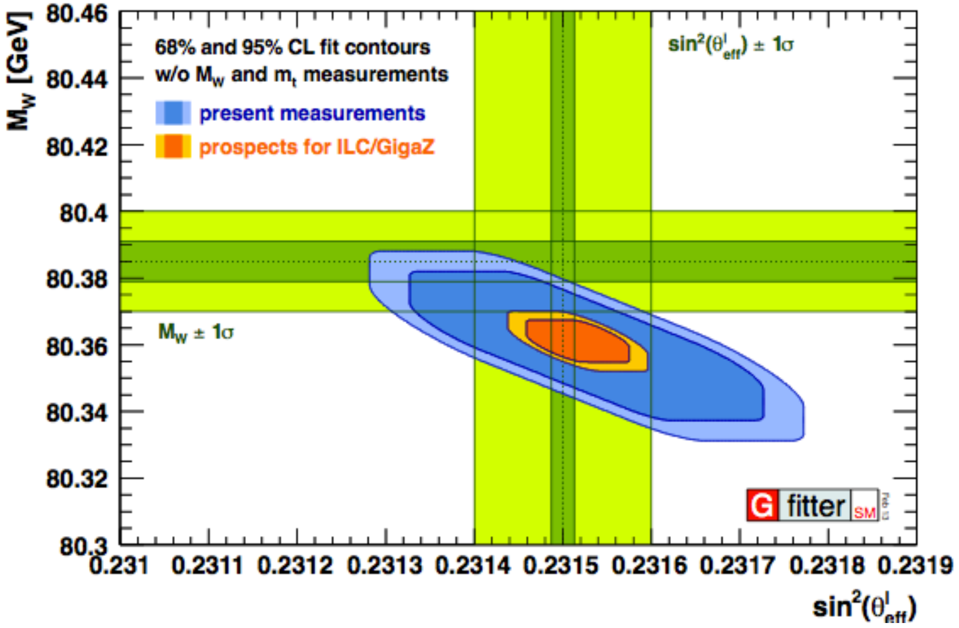
Prospects for ILC with Giga Z



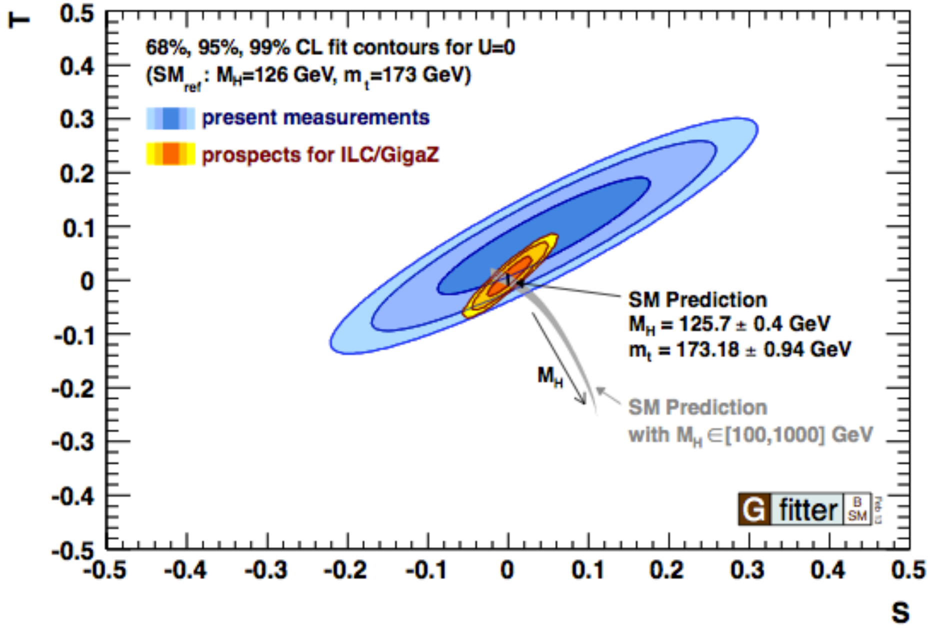
- Logarithmic dependency on M_H → cannot compete with direct M_H meas.
- Indirect prediction M_H dominated by theory uncertainties.
  - No theory uncertainty: $M_H = 94.2^{+5.3}_{-5.0}$ GeV
  - R-fit scheme: $M_H = 92.3^{+16.6}_{-11.6}$ GeV

Prospects for ILC with Giga Z





🟩 current precision
🟩 prospects for direct ILC measurements



- *Assuming also 50% of today's theoretical uncertainties*
  - Implies three-loop EW calculations!
- Huge reduction of uncertainty on indirect determinations
- Also strong constraints on S, T, U

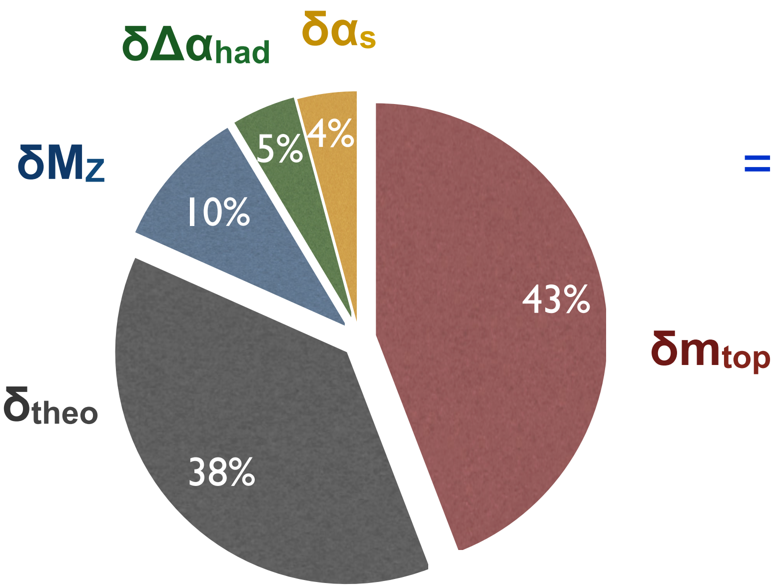
Summary

- Including M_H measurement, for first time SM is fully over-constrained!
  - M_H consistent at 1.3σ with indirect prediction from EW fit.
- p-Value of global electroweak fit of SM: 7% (pseudo-experiments)
  - Would be great to revisit $Z \rightarrow b\bar{b}$, both theoretically and experimentally
- Knowledge of M_H dramatically improves SM prediction of key observables
  - M_W (28→11 MeV), $\sin^2\theta^l_{eff}$ ($2.3\times10^{-5} \rightarrow 1.0\times10^{-5}$), m_t (6.2→2.5 GeV)
- Improved accuracies set benchmark for new direct measurements!

Outlook

- Paradigm shift for EW fit: from Higgs mass prediction to … consistency tests of the Standard Model:

- δM_W (indirect) = = 11 MeV
  - Large contributions to δM_W (and $\delta\sin^2\theta^l_{eff}$) from top and unknown higher-order EW corrections.



- δM_W (direct) = 15 MeV

- What's next for Gfitter:
combine Higgs couplings in the EW fit. To be continued …

- Latest results always available at: http://cern.ch/Gfitter
  - Results of this presentation: EPJC 72, 2205 (2012)

Backup

G fitter

A Generic Fitter Project for HEP Model Testing

Backup

New R^0_b calculation

[A. Freitas et al., JHEP 1208, 050 (2012)]

- The branching ratio R^0_b: partial decay width of Z→bb to Z→qq
- Freitas et al: full 2-loop calculation of Z→bb
- Contribution of same terms as in the calculation of $\sin^2\theta^{bb}_{eff}$
  → cross-check of two results found good agreement
- Two-loop corrections comparable to experimental uncertainty (6.6×10^{-4})

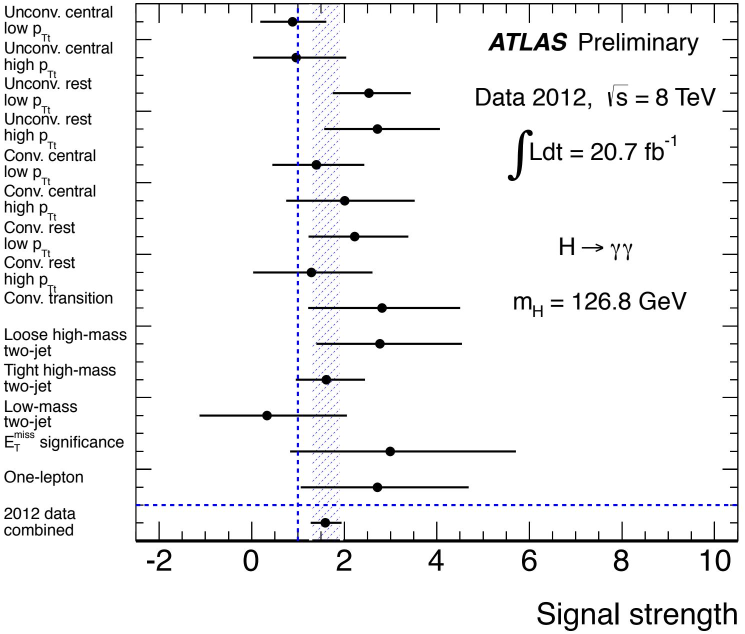
	1-loop EW and QCD correction to FSR	2-loop EW correction	2-loop EW and 2+3-loop QCD correction to FSR	1+2-loop QCD correction to gauge boson self-energies
M_H [GeV]	$\mathcal{O}(\alpha) + \mathrm{FSR}_{1-\mathrm{loop}}$ $[10^{-3}]$	$\mathcal{O}(\alpha^2_{\mathrm{ferm}})$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\mathrm{ferm}}) + \mathrm{FSR}_{>1-\mathrm{loop}}$ $[10^{-4}]$	$\mathcal{O}(\alpha\alpha_s, \alpha\alpha_s^2)$ $[10^{-4}]$
100	−3.632	−6.569	−9.333	−0.404
200	−3.651	−6.573	−9.332	−0.404
400	−3.675	−6.581	−9.331	−0.404

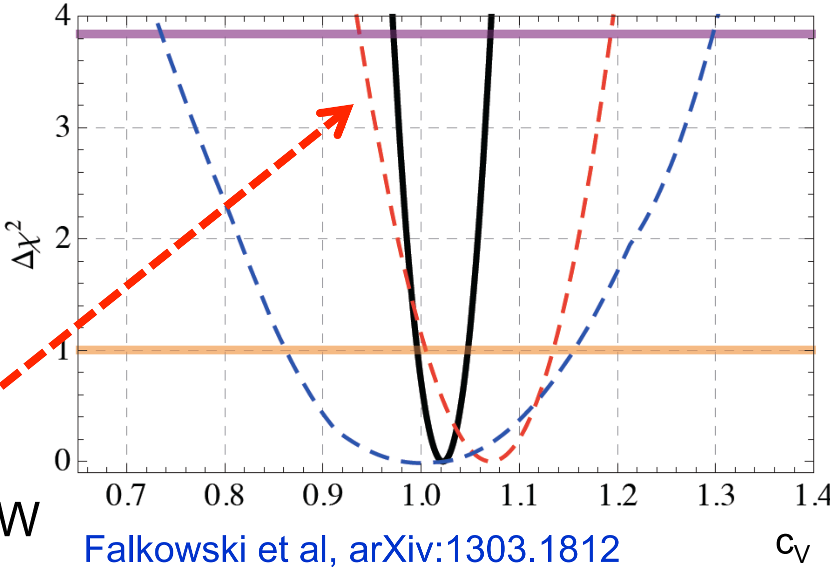
Higgs couplings in the EW fit

- In latest ATLAS H→γγ, 2.3σ deviation seen from SM μ (≡1.0)
- Interpret.: H→VV couplings scaled with c_V

From: Falkowski et al, arXiv:1303.1812

- Modified Higgs couplings can be constrained by EW fit through extended STU formalism.
- Result of c_V driven by limit on T parameter.
  - Tree-level relation: $\rho_0 = \dfrac{M_{W_0}^2}{M_{Z_0}^2 c_W^2} = 1 + \alpha T$
  - $$\alpha T \approx \frac{3g_Y^2}{32\pi^2}\left(c_V^2 - 1\right)\log(\Lambda/m_Z)$$
  - Reminder: T = 0.05 ± 0.12 (Gfitter)
- EW-fit Falkowski et al: $c_V \simeq 1.08 \pm 0.07$
  - Blue dashed: c_V from μ's, black: comb. w/ EW





Falkowski et al, arXiv:1303.1812

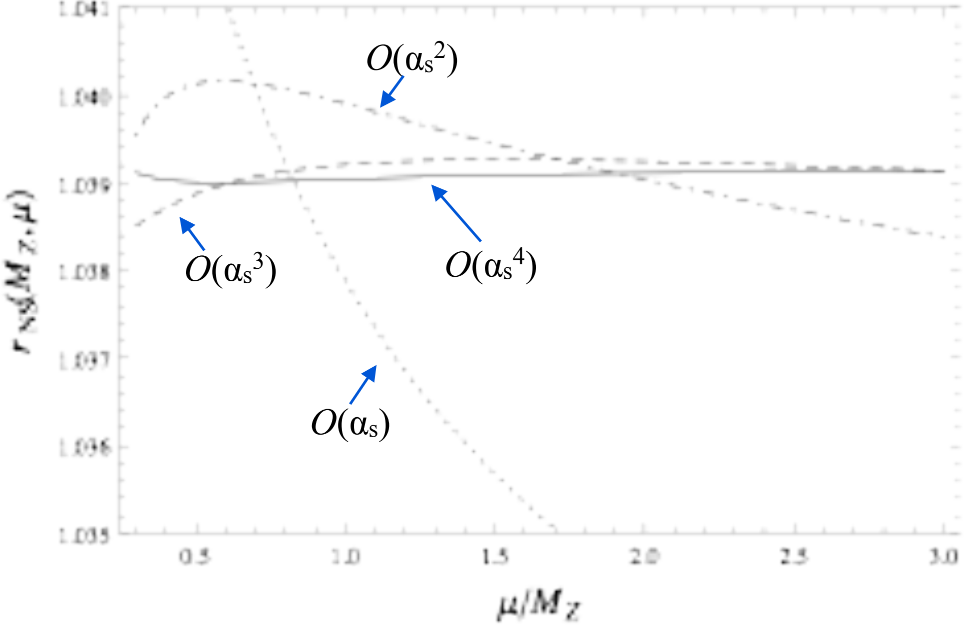
Radiator Functions

- Partial widths are defined inclusively: contain both QCD and QED contributions.
- Corrections expressed as so-called radiator functions $R_{A,f}$ and $R_{V,f}$

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

[D. Bardin, G. Passarino, “The Standard Model in the Making”, Clarendon Press (1999)]

- High sensitivity to the strong coupling α_s
- Recently, full four-loop calculation of QCD Adler function became available (N^3LO)
- Much-reduced scale dependence!
- Theoretical uncertainty of 0.1 MeV, compared with experimental uncertainty of 2.0 MeV.

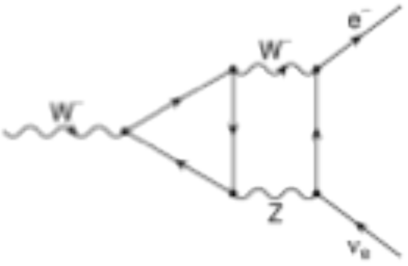


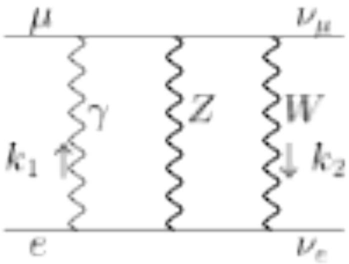
[P. Baikov et al., Phys. Rev. Lett. 108, 222003 (2012)]
[P. Baikov et al Phys. Rev. Lett. 104, 132004 (2010)]

Calculation of M_W

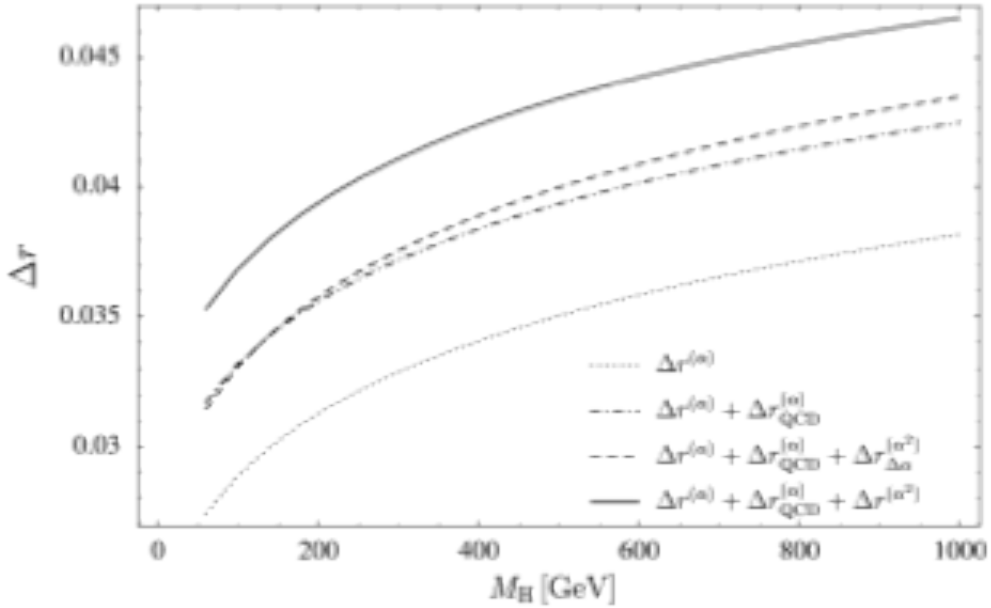
- Full EW one- and two-loop calculation of fermionic and bosonic contributions.
- One- and two-loop QCD corrections and leading terms of higher order corrections.
- Results for Δr include terms of order $O(\alpha)$, $O(\alpha\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^2_{ferm})$, $O(\alpha^2_{bos})$, $O(\alpha^2\alpha_s m_t^4)$, $O(\alpha^3 m_t^6)$
- Uncertainty estimate:
  - Missing terms of order $O(\alpha^2\alpha_s)$: about 3 MeV (from $O(\alpha^2\alpha_s m_t^4)$)
  - Electroweak three-loop correction $O(\alpha^3)$: < 2 MeV
  - Three-loop QCD corrections $O(\alpha\alpha_s^3)$: < 2 MeV
- Total: $\delta M_W \approx 4$ MeV

[M Awramik et al., Phys. Rev. D69, 053006 (2004)]
[M Awramik et al., Phys. Rev. Lett. 89, 241801 (2002)]





[A Freitas et al., Phys. Lett. B495, 338 (2000)]



Calculation of $\sin^2(\theta^l_{eff})$

[M Awramik et al, Phys. Rev. Lett. 93, 201805 (2004)]
[M Awramik et al., JHEP 11, 048 (2006)]

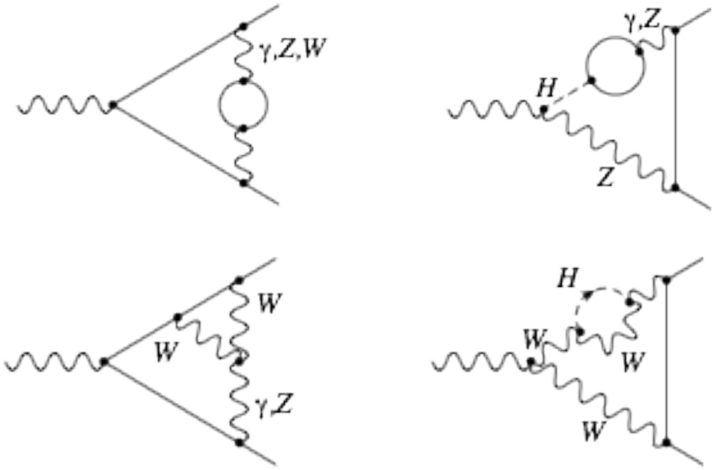
- Effective mixing angle:

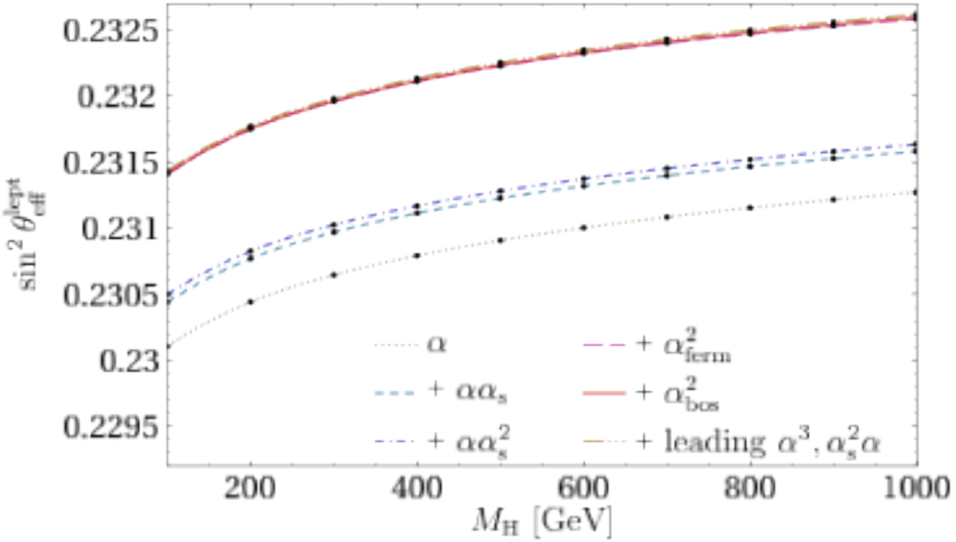
$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = \left(1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2\right)(1+\Delta\kappa)$$

- Two-loop EW and QCD correction to $\Delta\kappa$ known, leading terms of higher order QCD corrections.

- Fermionic two-loop correction about 10^{-3}, whereas bosonic one 10^{-5}.

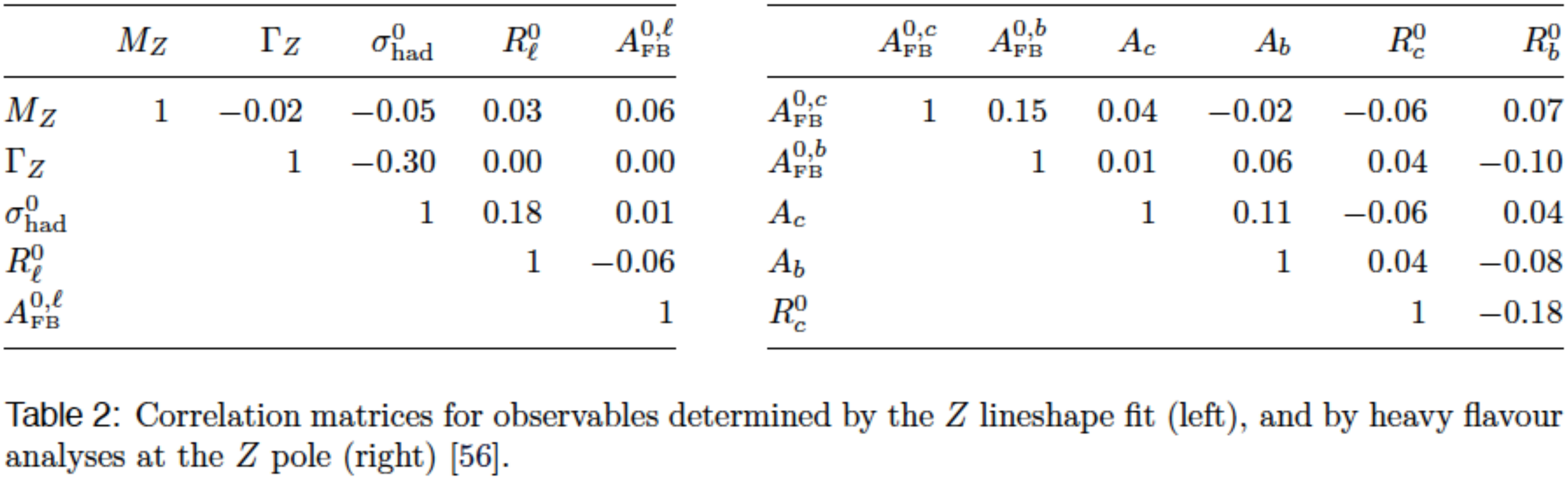
- Uncertainty estimate obtained with different methods, geometric progression, leading to total: $\delta\sin^2(\theta^l_{eff}) = 4.7\text{x}10^{-5}$





Input correlations of the EW fit

- Input correlation coefficients between Z pole measurements



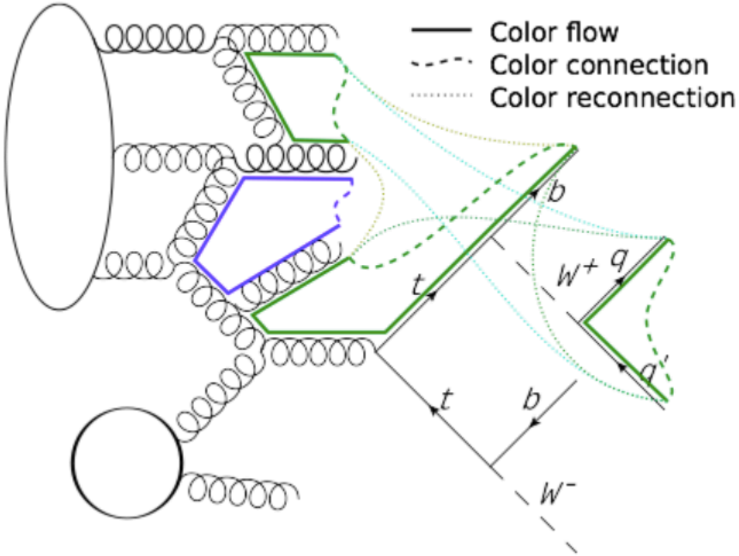
	M_Z	Γ_Z	σ^0_{had}	R^0_ℓ	$A^{0,\ell}_{\text{FB}}$
M_Z	1	-0.02	-0.05	0.03	0.06
Γ_Z		1	-0.30	0.00	0.00
σ^0_{had}			1	0.18	0.01
R^0_ℓ				1	-0.06
$A^{0,\ell}_{\text{FB}}$					1

	$A^{0,c}_{\text{FB}}$	$A^{0,b}_{\text{FB}}$	A_c	A_b	R^0_c	R^0_b
$A^{0,c}_{\text{FB}}$	1	0.15	0.04	-0.02	-0.06	0.07
$A^{0,b}_{\text{FB}}$		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

Table 2: Correlation matrices for observables determined by the Z lineshape fit (left), and by heavy flavour analyses at the Z pole (right) [56].

Top mass dependence on Event Kinematics

- Difficult to define a pole mass for heavy, unstable and colored particle.
- The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_t) \sim 1$ GeV
  - Single top decays before hadronizing. To have colorless final states, additional quarks needed.
    - Non-perturb. color-reconnection effects in fragmentation.
    - Ambiguities in top mass definition
- Result: $m_t^{exp} \not\equiv m_t^{pole}$, and event-dependent.



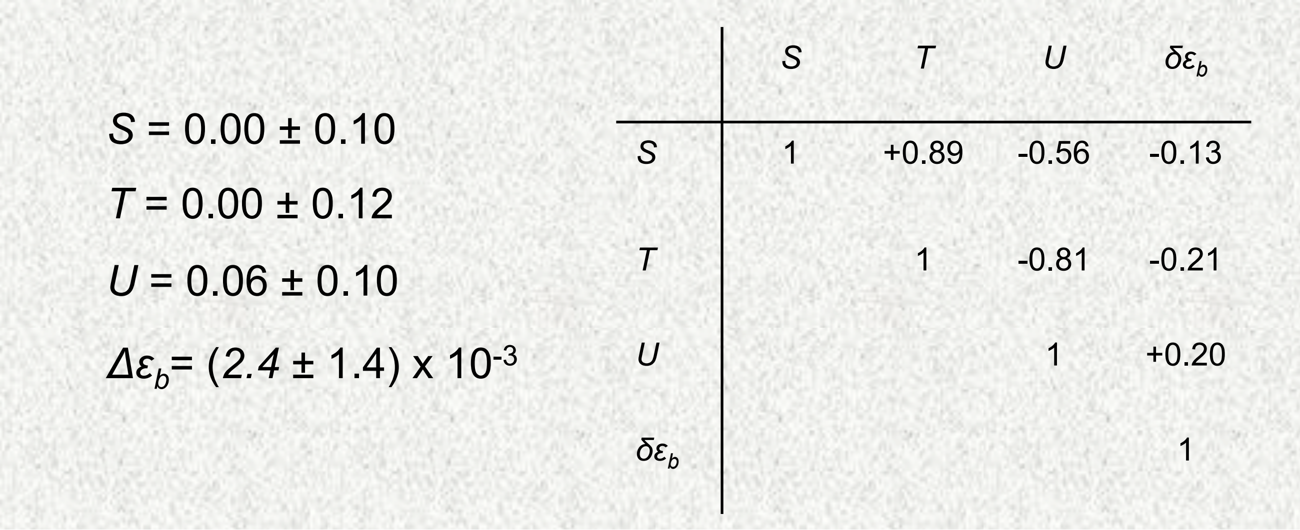
- With additional theo. uncertainty of 0.5 GeV on m_t:
  - $M_H = 90^{+34}_{-21}$ GeV, $M_W = 80.359 \pm 0.013$ GeV, $\sin^2\theta^l_{eff} = 0.23148 \pm 0.00010$.
  - Only small deterioration in precision.

Extended STU results

- Several extended STU parametrizations available
  - Here: STU + $\delta\varepsilon_b$, latter parameter describing Z→bb vertex

- SM: $M_H = 125.7$ GeV, $m_t = 173.2$ GeV
  - This defines (S,T,U) = (0,0,0)
- S, T depend logarithmically on M_H

- Fit result:



$S = 0.00 \pm 0.10$

$T = 0.00 \pm 0.12$

$U = 0.06 \pm 0.10$

$\Delta\varepsilon_b = (2.4 \pm 1.4) \times 10^{-3}$

	S	T	U	$\delta\varepsilon_b$
S	1	+0.89	-0.56	-0.13
T		1	-0.81	-0.21
U			1	+0.20
$\delta\varepsilon_b$				1

- (Stronger constraints from fit with U=0.)

Prospects for LHC, ILC and ILC with Giga-Z

- Assumed experimental improvements for prospective study:
  - LHC: M_W, m_{top}
  - ILC: M_W, m_{top}
  - Giga-Z: M_W, m_{top}, $\sin^2\theta^l_{eff}$, R_{lep}
  - ISR-based (BABAR) and BESIII, KLOE-II cross-section measurements, should improve $\Delta\alpha_{had}(M_Z)$

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)
$M_H(=120\text{ GeV})$ [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]