Roman Kogler (Uni Hamburg),
on behalf of the Gfitter group (*)

Hamburg Workshop on Higgs Physics, DESY
Thursday October 23rd, 2014

G fitter

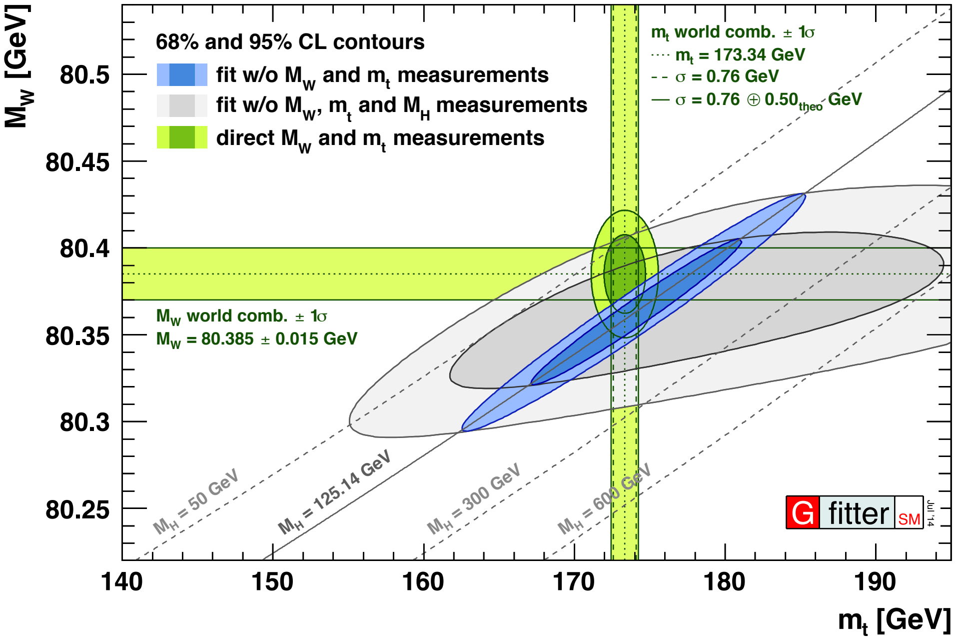
http://cern.ch/Gfitter

EPJC 74, 3046 (2014), arXiv:1407.3792

The global electroweak fit at NNLO
Prospects for LHC and ILC

Outline:

- ✓ What's new in the Electroweak Fit
- ✓ Prospects for LHC and ILC

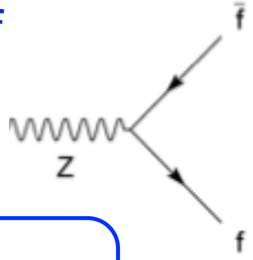


Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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

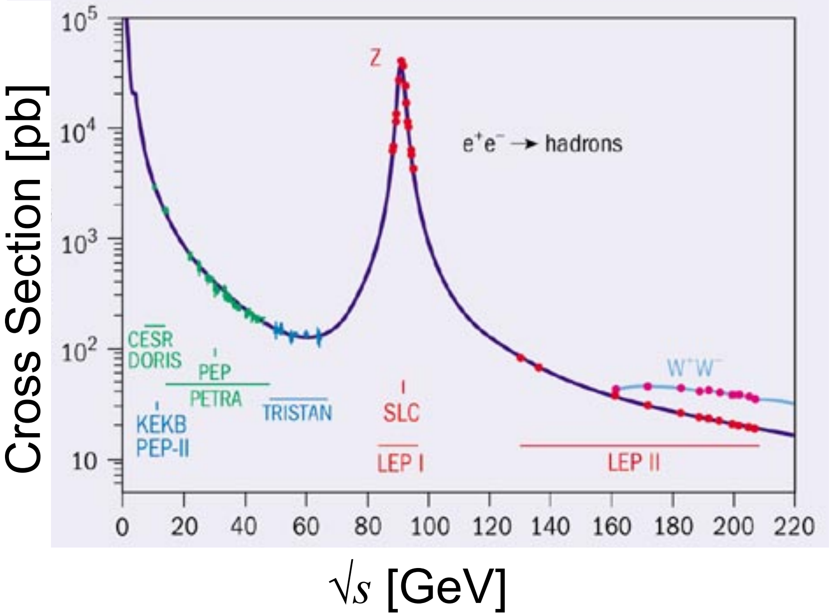
The predictive power of the SM

- 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$\bar{f}$
  - $i\bar{f}\gamma^{\mu}\left(g_{V,f} - g_{A,f}\gamma_5\right) f Z_{\mu}$



- Prediction EWSB at tree-level:

$$\boxed{\frac{M_W^2}{M_Z^2 \cos\theta_W^2} = 1}$$



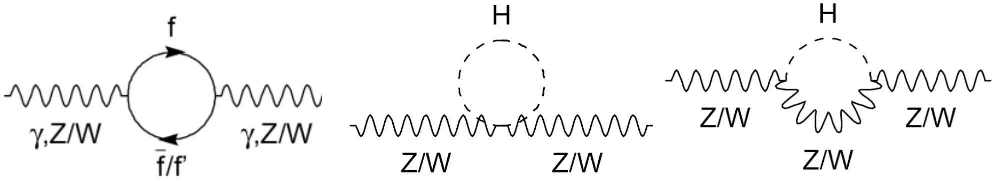
- The impact of loop corrections
  - Absorbed into EW form factors: ρ, κ, Δr
  - Effective couplings at the Z-pole
  - Quadraticly dependent on m_t, *logarithmic* dependence on M_H

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

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

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

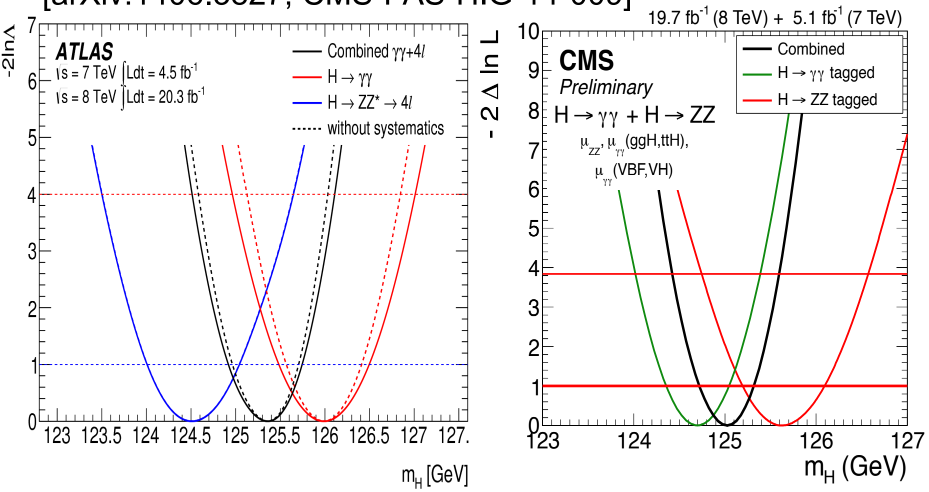
$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$



The SM fit with Gfitter, including the Higgs

- Discovery of Higgs-like boson by LHC
  - Cross section x branching ratios, spin, parity, compatible with SM Higgs boson
  - This talk: assume boson is SM Higgs.
  - Use in EW fit: $M_H = 125.14 \pm 0.24$ GeV
  - Change between fully uncorrelated and fully correlated systematic uncertainties is minor: δM_H : 0.24 → 0.32 GeV

[arXiv:1406.3827, CMS-PAS-HIG-14-009]



- *EW observables precisely predicted at loop level → test consistency of SM!*

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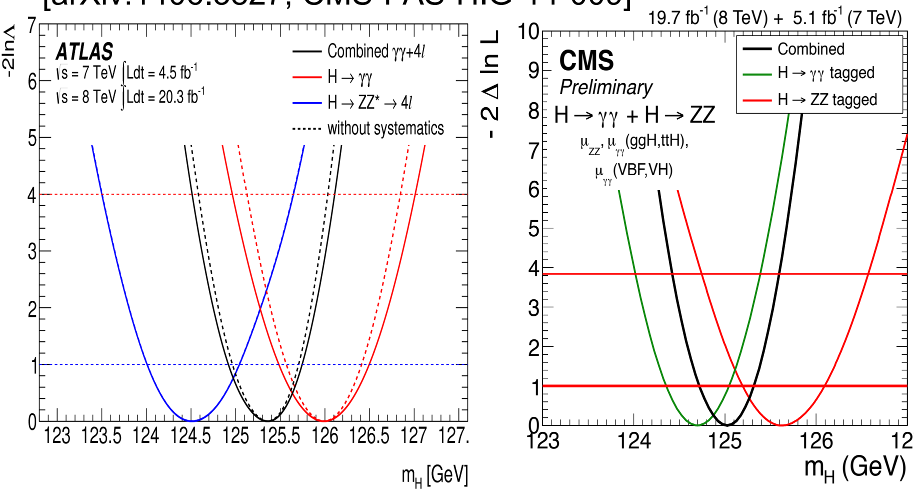


- *EW observables precisely predicted at loop level → test consistency of SM!*
- *New: all EWPOs$^{(*)}$ now calculated at 2-loop level or better!*
  - $\sin^2\theta^f_{\mathrm{eff}}$ Effective weak mixing angle [M. Awramik et al., JHEP 11, 048 (2006), M. Awramik et al., Nucl.Phys.B813:174-187 (2009)]
  - M_W Mass of the W boson [M. Awramik et al., Phys. Rev. D69, 053006 (2004)]
    - Full two-loop + leading beyond-two-loop + 4-loop QCD correction ← **New!** [Kuhn et al., hep-hp/0504055,0605201,0606232]
  - Γ_{had} QCD Radiator functions at N^{3}LO [P. A. Baikov et al., PRL108, 222003 (2012)]
    - N^{3}LO prediction of the hadronic cross section
  - Γ_i Partial Z decay widths and BRs at NNLO ← **New!** [A. Freitas, JHEP04, 070 (2014)]

full fermionic 2-loop calc.

Uncertainties from unknown H.O. terms

Most important observables:

Observable	Exp. error	Theo. error
M_W	15 MeV	4 MeV
$\sin^2\theta^l_{\text{eff}}$	$1.6 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$
Γ_Z	2.3 MeV	0.5 MeV
$\sigma^0_{\text{had}} = \sigma[e^+e^- \to Z \to \text{had.}]$	37 pb	6 pb
$R^0_b = \Gamma[Z \to b\bar{b}]/\Gamma[Z \to \text{had.}]$	$6.6 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$
m_t	0.76 GeV	$\leq O(1)$ GeV

Theory uncertainties accounted for in EW fit
(w/ Gauss constraints):

New in EW fit

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

Newly included:

- Full fermionic 2-loop corrections of partial Z decay widths (A. Freitas)
  - *6 corresponding nuisance parameters. ($\delta\Gamma_Z$ = 0.5 MeV)*
- Γ_{had} QCD Adler functions at N^{3}LO
  - *2 nuisance parameters.*
- Top quark mass: conversion from measurement to MS-bar mass
  - *Agnostic value used here: $\delta_{theo}\, m_t$ = **0.5 GeV**.* *(more later)*

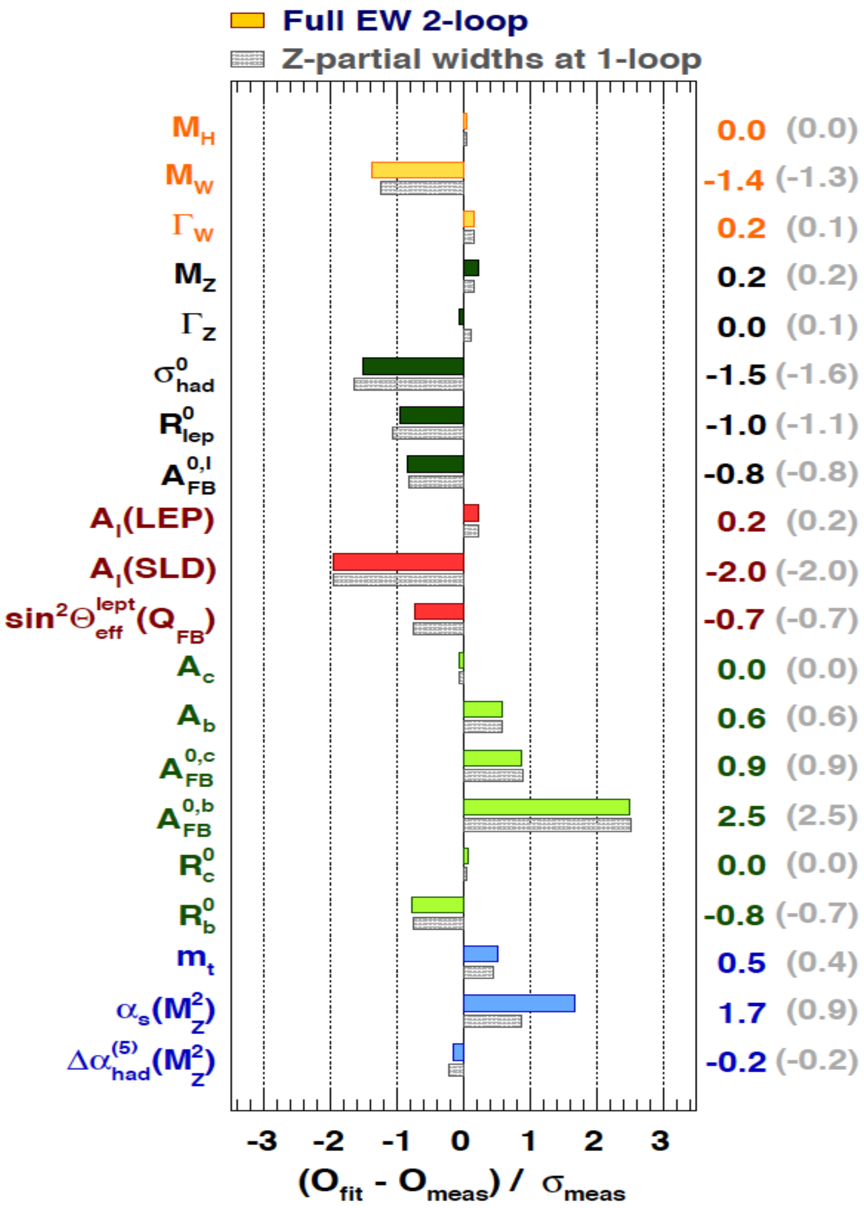
Electroweak Fit – Experimental inputs

- **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, arXiv:1302.3415]
  - m_{top} latest avg from Tevatron+LHC
    [arXiv:1403.4427]
  - 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:1406.3827, CMS-PAS-HIG-14-009]

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

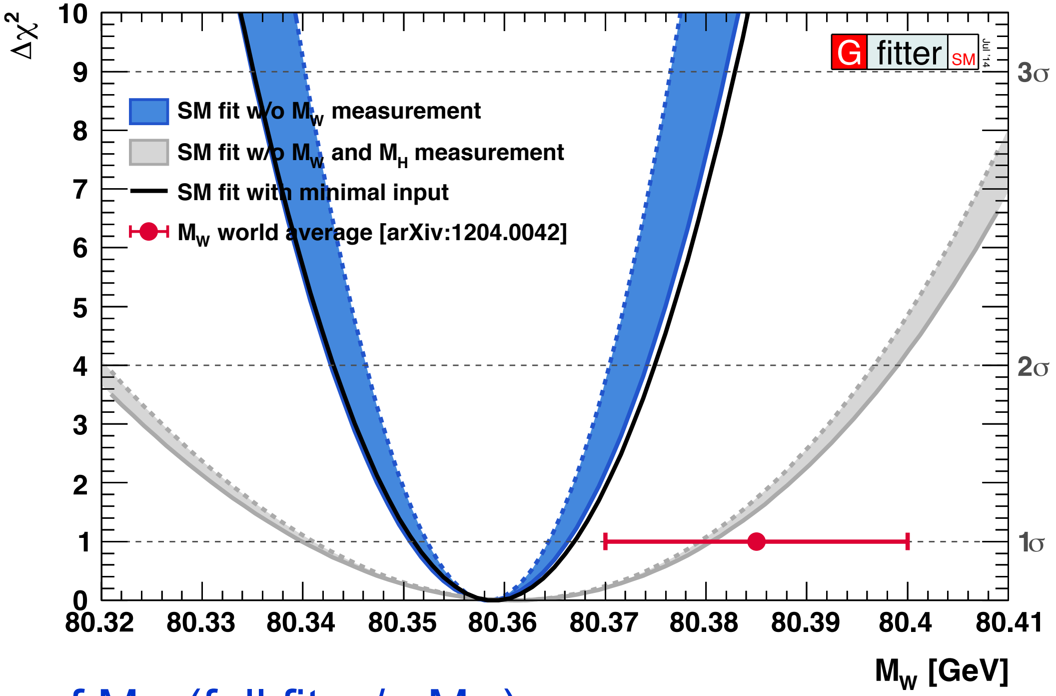
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	
Γ_Z [GeV]	2.4952 ± 0.0023	
σ^0_{had} [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLC
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012	
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	LEP
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]	173.34 ± 0.76	Tevatron
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)^{(\dagger\triangle)}$	2757 ± 10	+ LHC

Electroweak Fit – SM Fit Results



- No individual value exceeds 3σ
- Largest deviations in b-sector: $A^{0,b}_{FB}$ with 2.5σ
  - → largest contribution to χ^2
- 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
- Goodness of fit – p-value:
  - χ^2_{min}= 17.8 → Prob(χ^2_{min}, 14) = 21%
  - Pseudo experiments: 21 ± 2 (theo) %
- Small changes from switching between 1 and 2-loop calc. for partial Z widths and small M_W correction.
  - χ^2_{min}(1-loop Z width) = 18.0
  - χ^2_{min}(no M_W correction) = 17.4
  - χ^2_{min}(no extra theory errors) = 18.2

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):

$$M_W = 80.3584 \pm \boxed{0.0046_{m_t}} \pm \boxed{0.0030_{\delta_\text{theo} m_t}} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_\text{had}} \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm \boxed{0.0040_{\delta_\text{theo} M_W}} \ \text{GeV}\,,$$

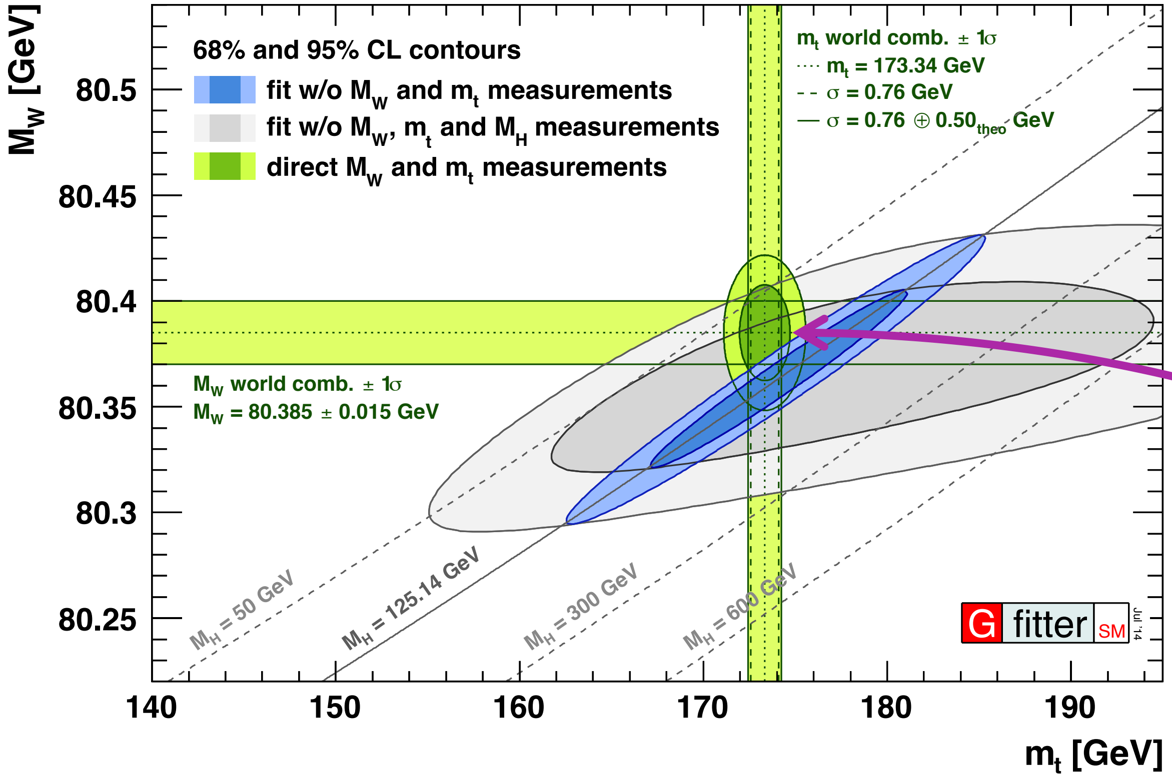
$$= 80.358 \pm 0.008_\text{tot} \ \text{GeV}\,.$$

Obtained with simple error propagation

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

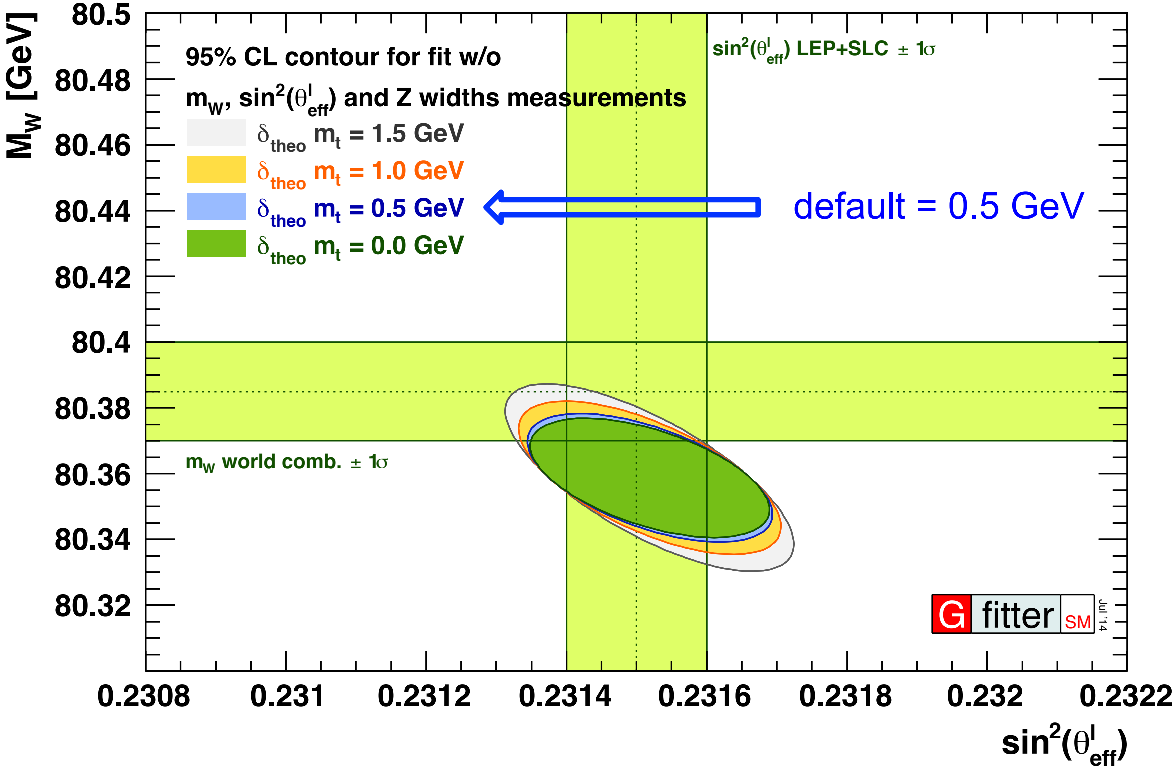
State of the SM: W versus top mass

- 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!

Theoretical uncertainty on m_{top}



- *δ_{theo} m_t : unc. on conversion of measured top mass to MS-bar mass*
  - Sources: ambiguity top mass definition, fragmentation process, pole→MS conv.
  - Predictions for δ_{theo} m_t : *between 0.25 – 0.9 GeV or greater*.
    [Moch etal, aX:1405.4781, Mangano: TOP'12, Buckley etal, aX:1101.2599, Juste etal: aX:1310.0799]
  - δ_{theo} m_t varied here between 0 and 1.5 GeV, in steps of 0.5 GeV.
- *Better assessment of δ_{theo} m_t of relevance for the EW fit.*

Two prospects scenarios: LHC, ILC/GigaZ

Prospects of EW fit tested for two scenarios:

1. LHC Phase-1 = *before HL upgrade*
2. ILC **with GigaZ** (*)

(*) GigaZ:

- Operation of ILC at lower energies like Z-pole or WW threshold.
  - Allows to perform precision measurements of EW sector of the SM.
- At Z-pole, several billion Z's can be studied within ~1-2 months.
  - Physics of LEP1 and SLC can be revisited with few days of data.

In following studies:
central values of input measurements adjusted to M_H = 125 GeV.

- *(Except where indicated.)*

Prospects of EW fit for: ILC with Giga Z

Future Linear Collider can improve precision of EWPO's tremendously.

- *WW threshold scan + kinematic reconstruction, to obtain M_W*
  - From threshold scan: δM_W : 15 → 5 MeV
- *ttbar threshold scan, to obtain m_t*
  - Obtain m_t indirectly from production cross section: δm_t : 0.8 → 0.1 GeV
    - Dominated by conversion from threshold to MSbar mass.
- *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 $\delta \sin^2\theta^l_{eff} : 1.6 \cdot 10^{-4} \rightarrow 1.3 \cdot 10^{-5}$
- *H→ZZ and H→WW couplings*: measured at 1% precision.

ILC prospects: from ILC TDR (Vol-2).

Prospects of EW fit for: LHC Phase-1

LHC Phase-1 (300/fb)

- *W mass measurement* : δM_W : 15 → 8 MeV
- *Final top mass measurement m_t* : δm_t : 0.8 → 0.6 GeV
- *H→ZZ and H→WW couplings*: measured at 3% precision.

LHC prospects: possibly optimistic scenario, but not impossible.

Prospects of EW fit

LHC Phase-1 (300/fb)

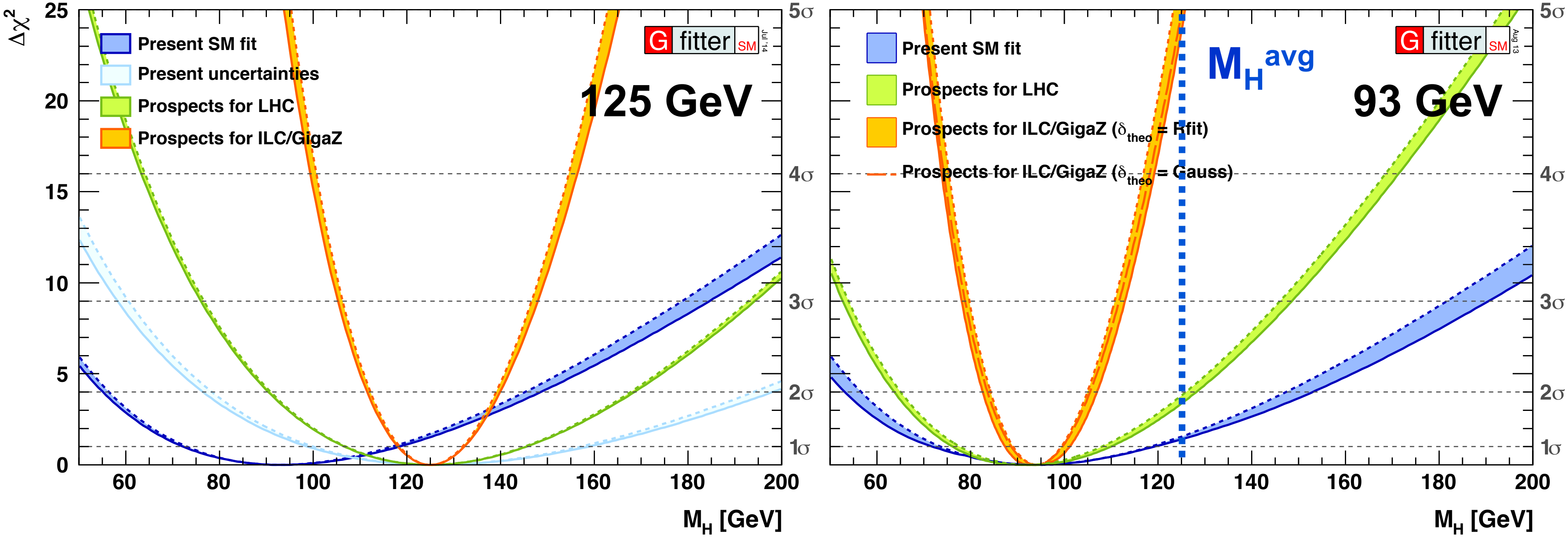
- *W mass measurement* : δM_W : 15 → 8 MeV
- *Final top mass measurement m_t* : δm_t : 0.8 → 0.6 GeV
- *H→ZZ and H→WW couplings*: measured at 3% precision.

For both LHC and ILC:

- Low-energy data results to improve $\Delta\alpha_{had}$:
  - ISR-based (BABAR), KLOE-II, VEPP-2000 (at energy below cc resonance), and BESIII e^+e^- cross-section measurements (around cc resonance).
  - Plus: improved α_s (precision meas. and calculations): $\Delta\alpha_{had}$: $10^{-4} \rightarrow 5 \cdot 10^{-5}$

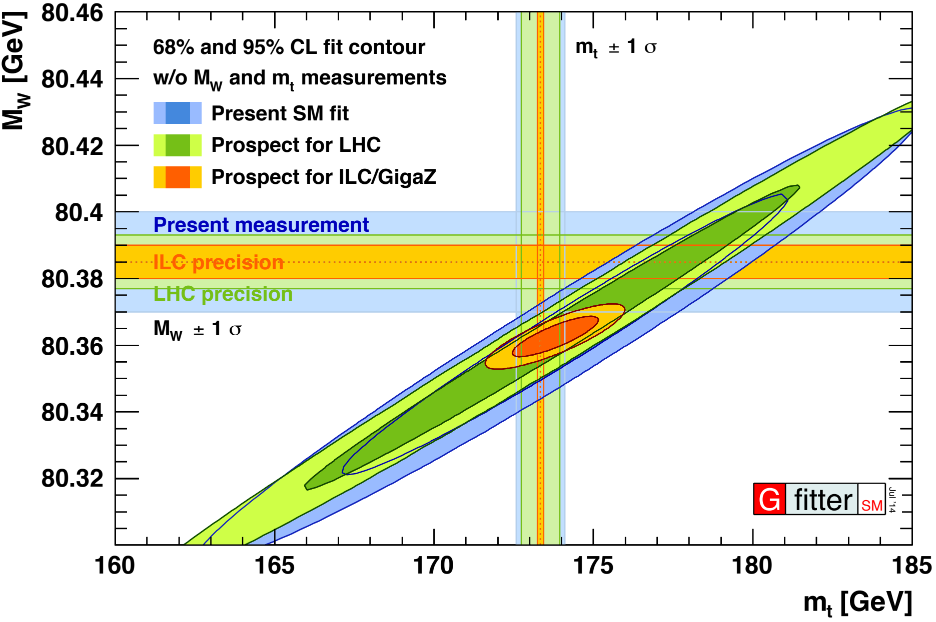
- Assuming ~25% of today's theoretical uncertainties on M_W and $\sin^2\theta^l_{eff}$
  - *Implies ambitions three-loop electroweak calculations!*
    - δM_W (4→1 MeV), $\delta\sin^2\theta^l_{eff}$ ($4.7\times10^{-5} \rightarrow 1\times10^{-5}$)   (from Snowmass report)
  - Partial Z decay widths at 3-loop level: factor 4 improvement
  - LHC: top quark mass theo uncertainty: 0.50 → 0.25 GeV

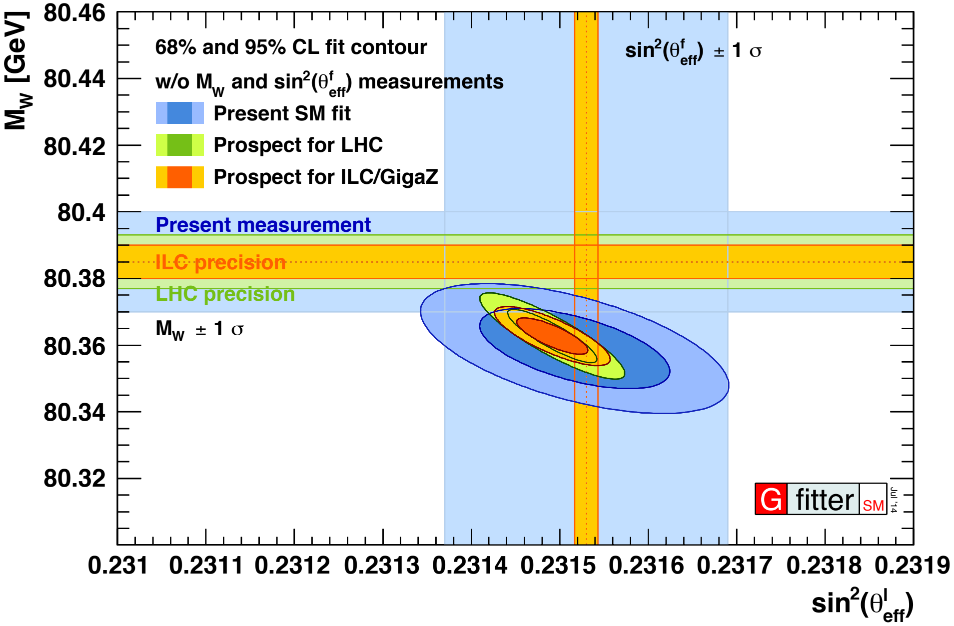
Prospects of EW fit



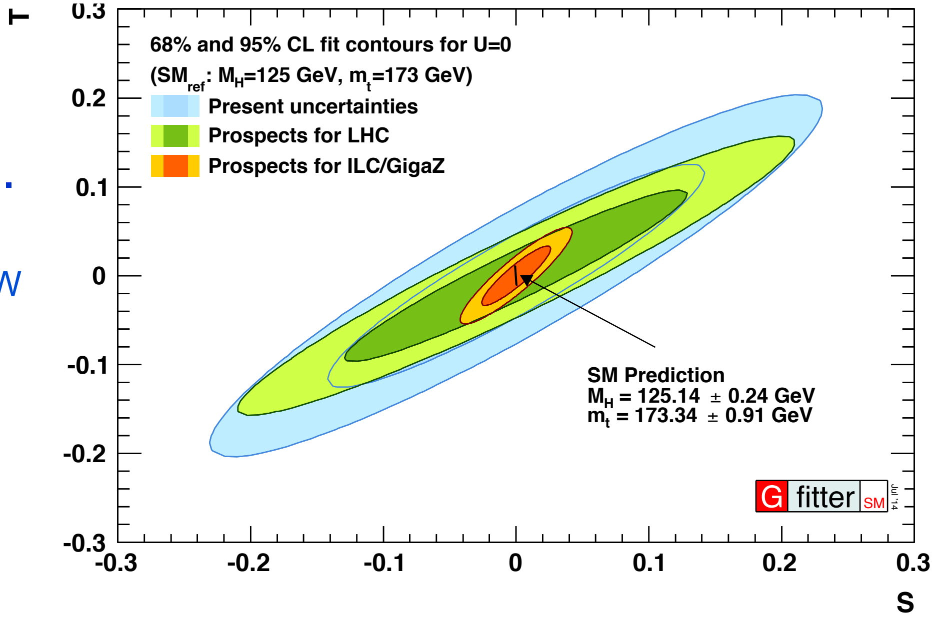
- Indirect prediction M_H dominated by experimental uncertainties.
  - Present: $\sigma(M_H) = {}^{+31}_{-26}$ (exp) ${}^{+10}_{-8}$ (theo) GeV
  - LHC: $\sigma(M_H) = {}^{+20}_{-18}$ (exp) ${}^{+3.9}_{-3.8}$ (theo) GeV
  - ILC: $\sigma(M_H) = {}^{+6.9}_{-6.6}$ (exp) ${}^{+2.5}_{-2.3}$ (theo) GeV
- Logarithmic dependency on M_H → *cannot compete with direct M_H meas.*
- If EWP-data central values unchanged, i.e. keep favoring low value of Higgs mass (93 GeV), ~5σ discrepancy with measured Higgs mass.

Prospects of EW fit



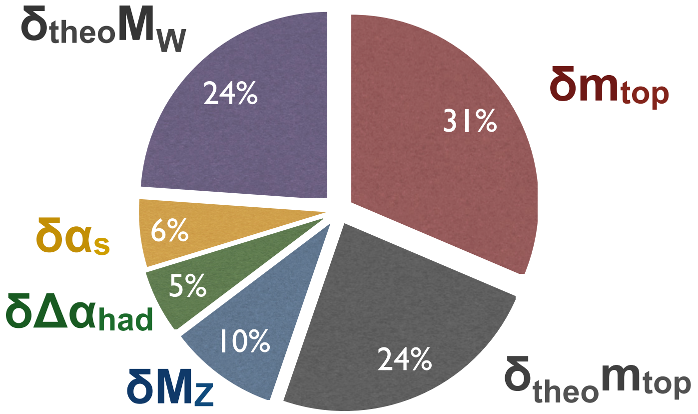


- Huge reduction of uncertainty on indirect determinations of m_t, m_W, $\sin^2\theta^l_{eff}$, STU, by a factor of 3 or more.
- Assuming central values of m_t and M_W do not change, (at ILC) a deviation between the SM prediction and the direct measurements would be prominently visible.



Conclusion and Today's prospects

- 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: 21% (pseudo-experiments)
- New: NNLO calculations and theory uncertainties for all relevant observables.
  - δ_{theo} m_t starting to become relevant.
- Knowledge of M_H dramatically improves SM prediction of key observables
  - M_W (20→8 MeV), $\sin^2\theta^l_{eff}$ ($1.1\times10^{-5} \rightarrow 0.7\times10^{-5}$), m_t (9.0→2.4 GeV)
- Improved accuracies set benchmark for new direct measurements!
- δM_W (indirect) = 8 MeV
  - Large contributions to δM_W from top and unknown higher-order EW corrections
- δM_W (direct) = 15 MeV
- Including new data electroweak fits remain very interesting in the next years!
- Latest results always available at: http://cern.ch/Gfitter



Thanks!

Backup

G fitter

A Generic Fitter Project for HEP Model Testing

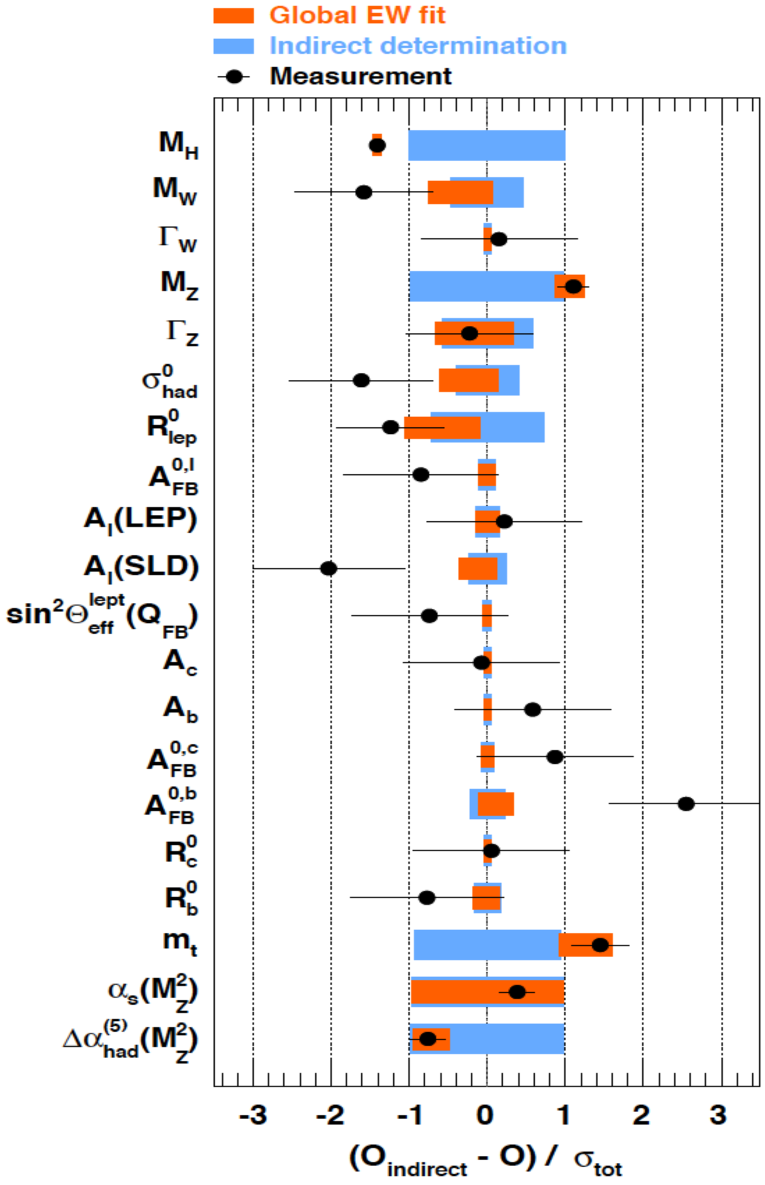
Backup

Electroweak Fit – SM Fit Results

- Results drawn as *pull values:* → deviations to the *indirect* determinations, divided by *total error*.
- Total error: *error of direct measurement plus error from indirect determination.*

- Black: direct measurement (data)
- Orange: full fit
- Light-blue: fit excluding input from the row

- *The prediction (light blue) is often more precise than the measurement!*



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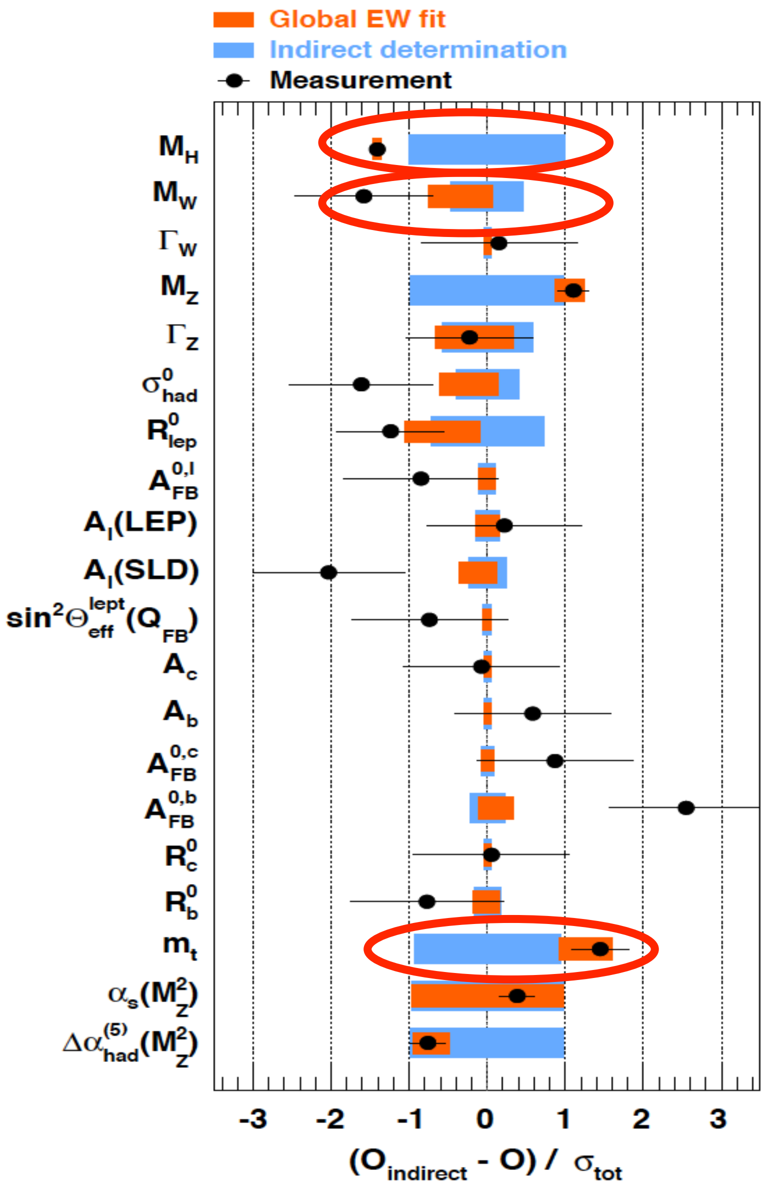
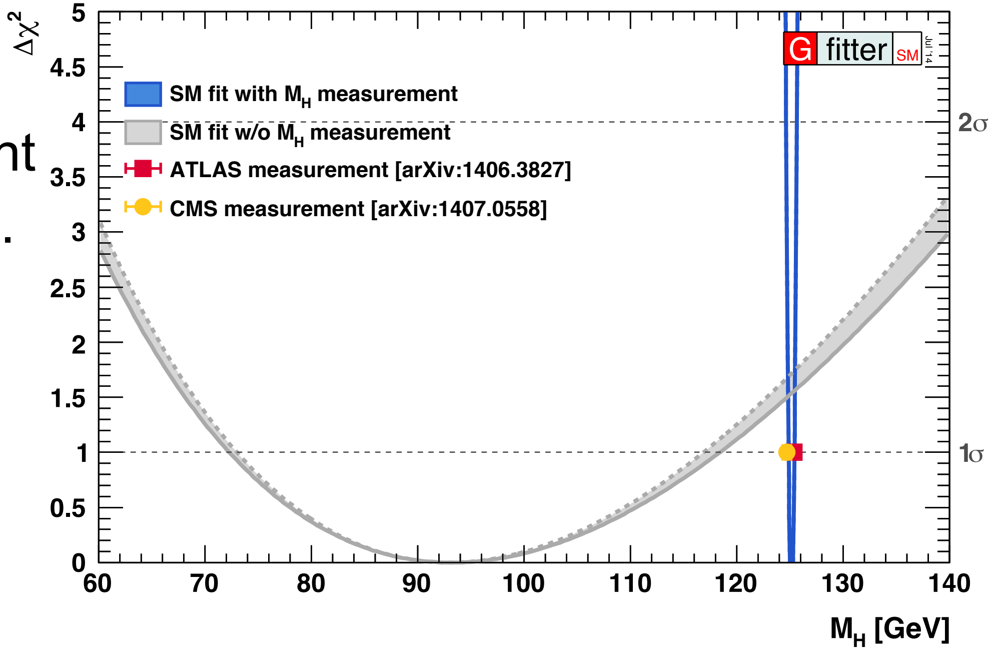


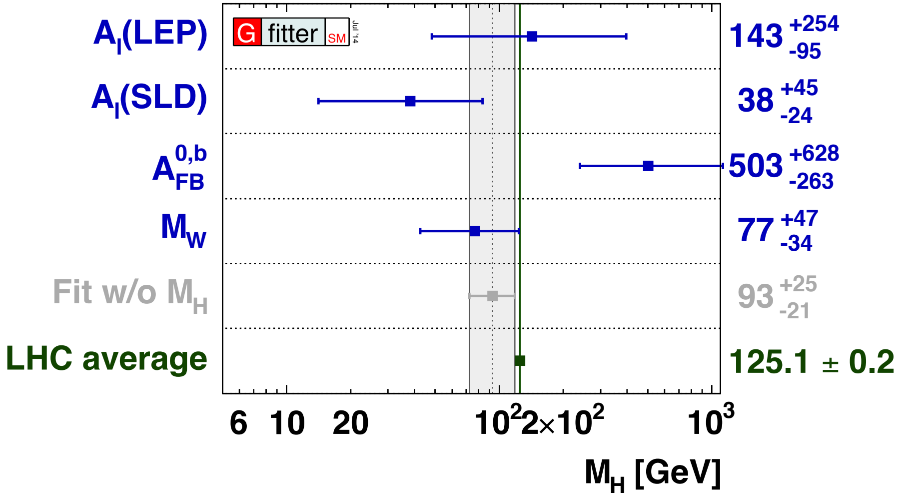
Higgs results of the EW fit

- 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: $M_H = 93^{+25}_{-21}$ GeV
  - Consistent at 1.3σ with LHC measurements.



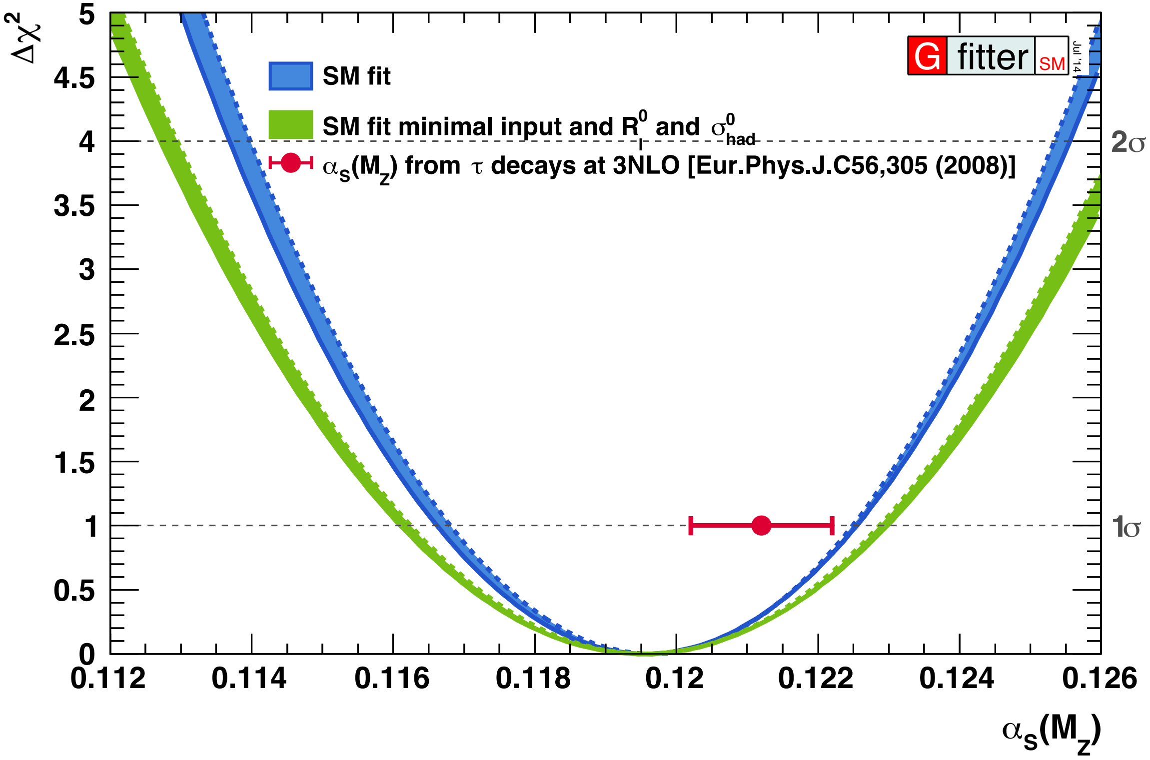
- Bottom plot: impact of other most sensitive Higgs observables
  - Determination of M_H removing all sensitive observables except the given one.
  - Known tension (2.5σ) between A_l(SLD), $A^{0,b}_{FB}$, and M_W clearly visible.

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 full N²LO and partial N³LO.
  - Most sensitive through total hadronic cross-section σ^0_{had} and partial leptonic width R^0_l



$$\alpha_s(M_Z^2) = 0.1196 \pm 0.0028_{\rm exp} \pm \boxed{0.0006_{\delta_{\rm theo}\mathcal{R}_{V,A}} \pm 0.0006_{\delta_{\rm theo}\Gamma_i} \pm 0.0002_{\delta_{\rm theo}\sigma^0_{\rm had}}}$$
$$= 0.1196 \pm 0.0030_{\rm tot}\,,$$

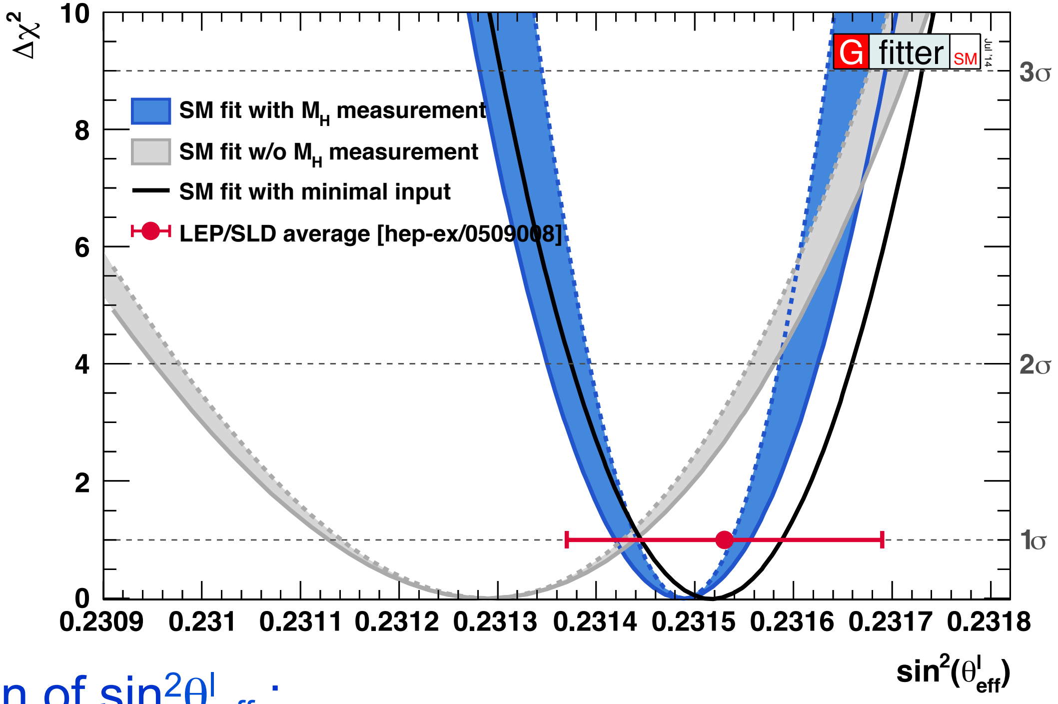
Most affected by new theory uncertainties

Before: δ_{theo} = 0.0001

- *In good agreement with value from τ decays, at N³LO, and with WA.*
  - (Improvements in precision only expected with ILC/GigaZ. See later.)

Indirect effective weak mixing angle

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



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

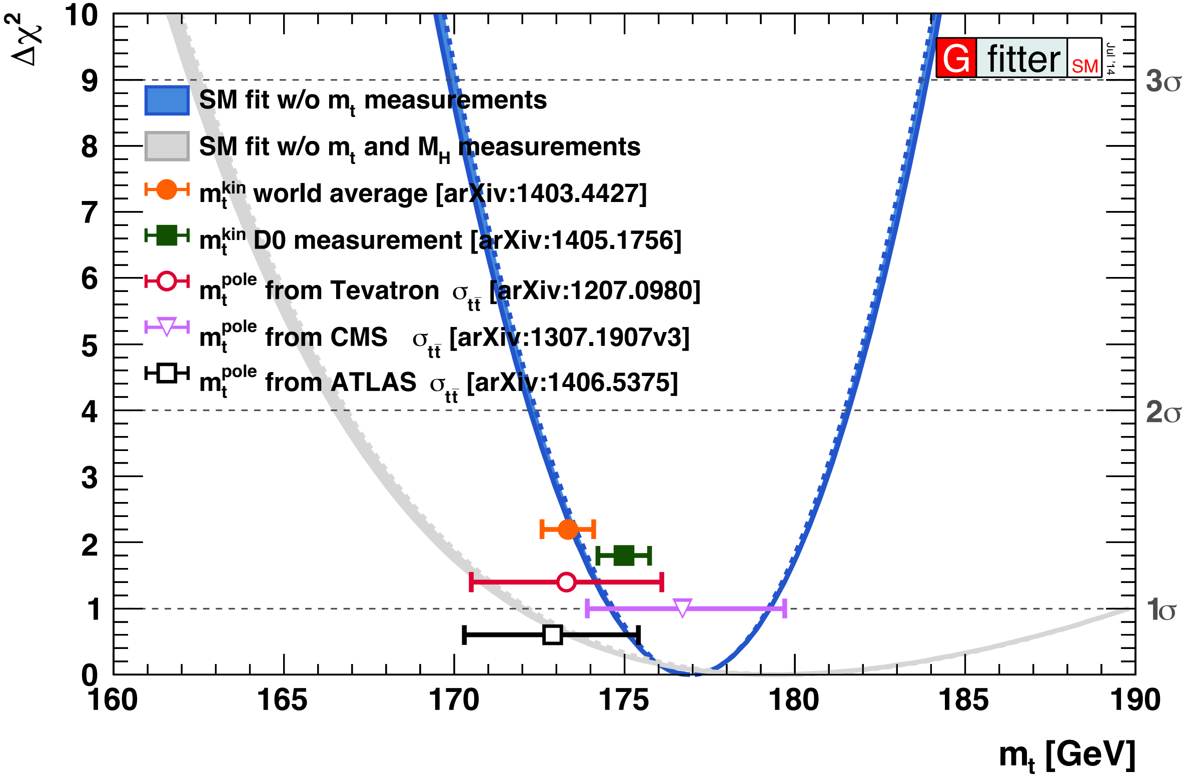
- Fit result for indirect determination of $\sin^2\theta^l_{\text{eff}}$:

$$\begin{aligned}\sin^2\theta^\ell_{\text{eff}} &= 0.231488 \pm \boxed{0.000024_{m_t}} \pm 0.000016_{\delta_{\text{theo}} m_t} \pm 0.000015_{M_Z} \pm \boxed{0.000035_{\Delta\alpha_{\text{had}}}} \\ &\quad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm \boxed{0.000047_{\delta_{\text{theo}} \sin^2\theta^f_{\text{eff}}}} , \\ &= 0.23149 \pm 0.00007_{\text{tot}} ,\end{aligned}$$

Obtained with simple error propagation

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

Indirect determination of top mass

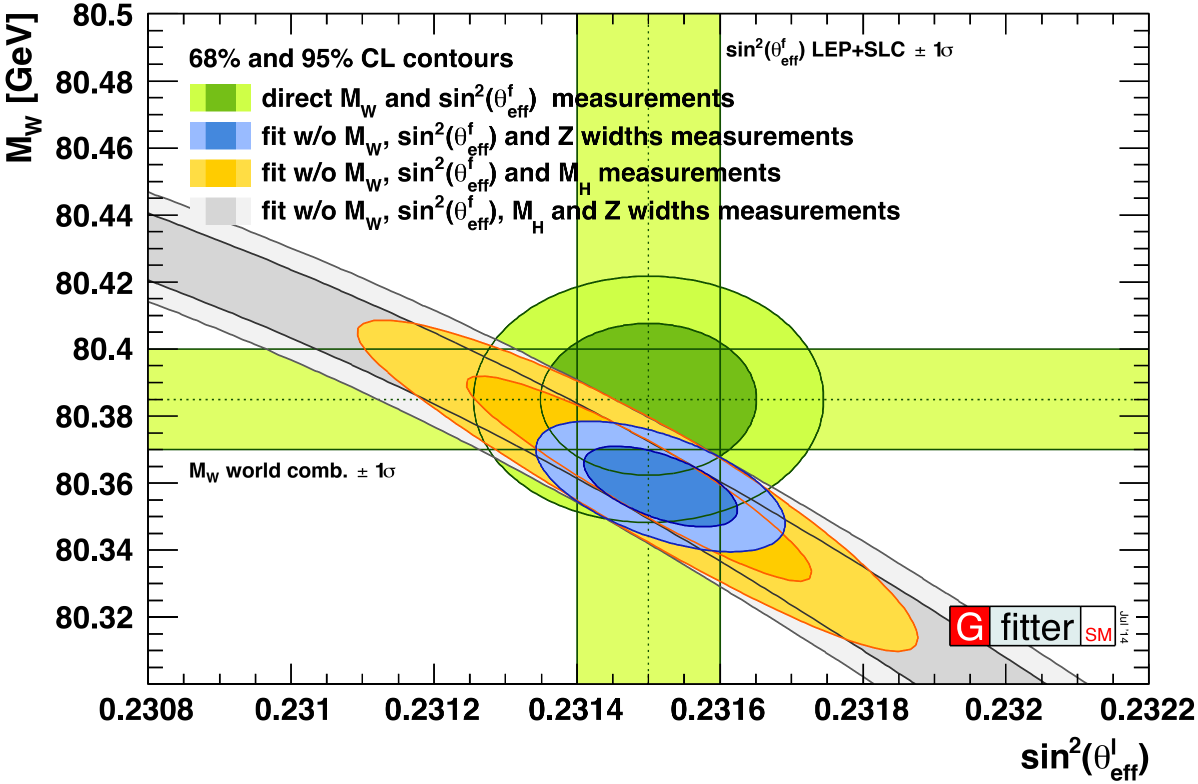


- Shown: scan of $\Delta\chi^2$ profile versus m_t (without m_t measurement)
  - M_H measurement allows for significant better constraint of m_t
  - Indirect determination consistent with direct measurements
    - Remember: fully obtained from radiative corrections!
- Indirect result: $m_t = 177.0^{+2.3}_{-2.4}$ GeV

Tevatron+LHC: 173.34 ± 0.76 GeV
new D0: 174.98 ± 0.76 GeV

State of the SM: W mass versus $\sin^2\theta^l_{eff}$

- Scan of M_W vs $\sin^2\theta^l_{eff}$, with direct measurements excluded from the fit.
- Again, significant reduction allowed indirect parameter space from Higgs mass measurement.



- M_W and $\sin^2\theta^l_{eff}$ have become *the* sensitive probes of new physics!
  - Reason: both are 'tree-level' SM predictions.

Constraints on BSM models

- If energy scale of NP is high, BSM physics could appear dominantly through vacuum polarization corrections.

- Described with STU parametrization

  [Peskin and Takeuchi, Phys. Rev. D46, 1 (1991)]

- SM: M_H = 125 GeV, m_t = 173 GeV
  - This defines (S,T,U) = (0,0,0)
- S, T depend logarithmically on M_H

- Fit result (with U floating):

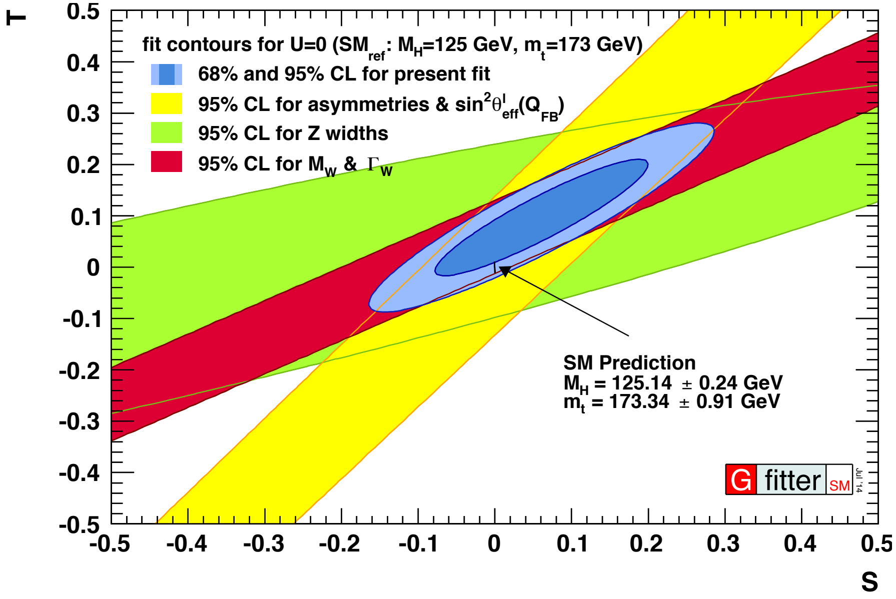
$S = 0.05 \pm 0.11$

$T = 0.09 \pm 0.13$

$U = 0.01 \pm 0.11$

	S	*T*	*U*
S	1	+0.90	-0.59
T		1	-0.83
U			1

- Stronger constraints with U=0.

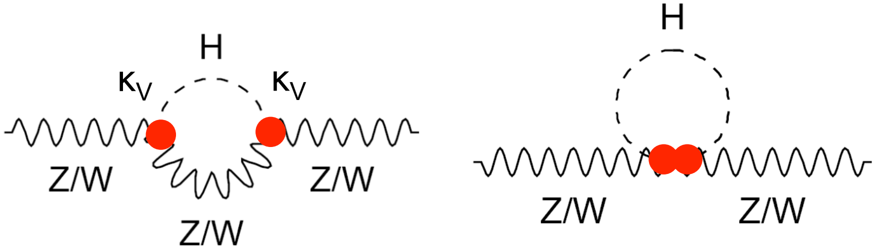


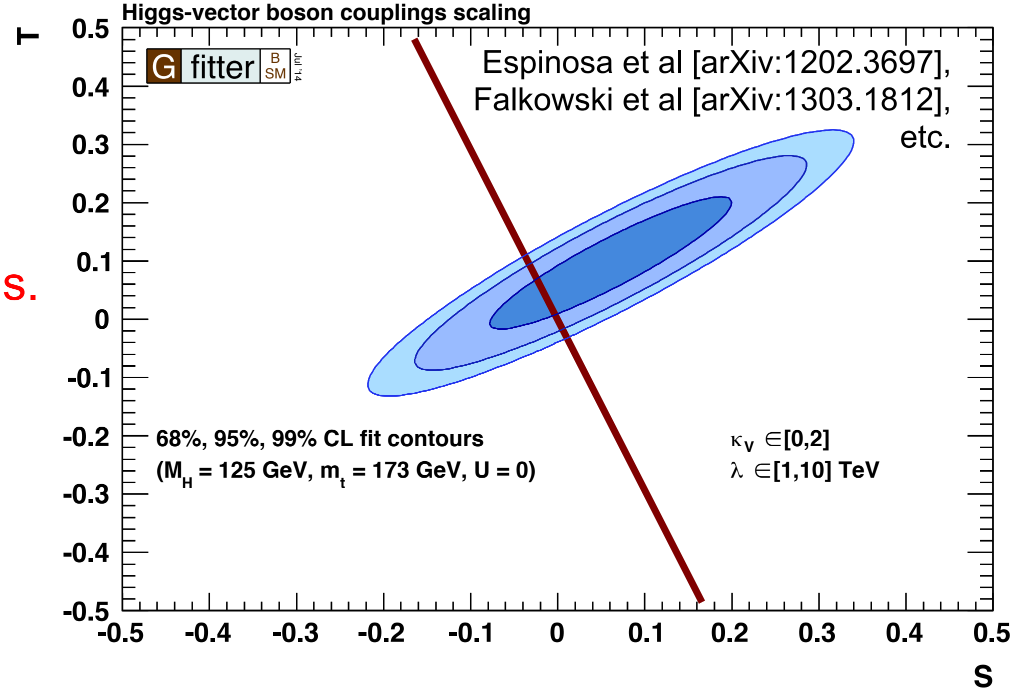
- Also results for Z→b$\bar{b}$ correction (see backup)

- *No indication for new physics.*
- Use this to constrain 4th gen, Ex-Dim, T-C, *Higgs couplings* (in backup)

Modified Higgs couplings

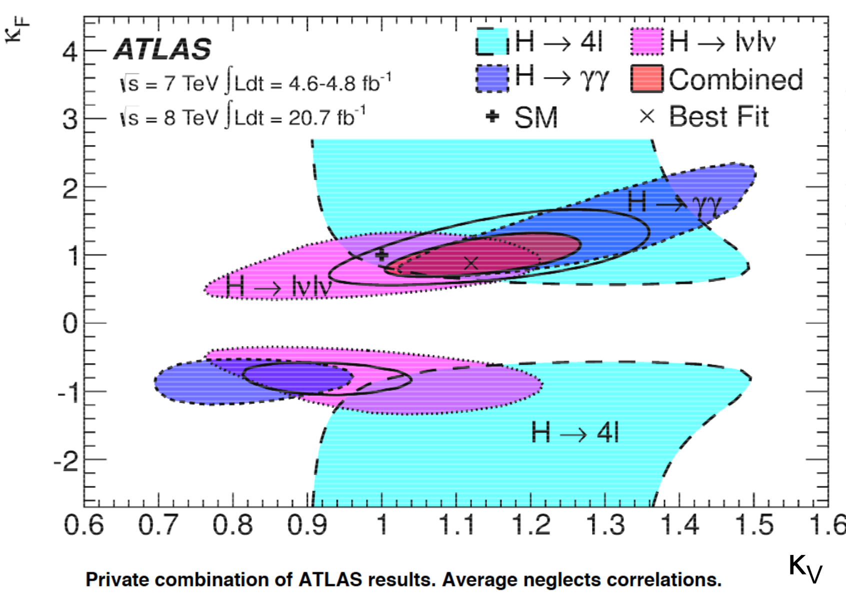
- Study of potential deviations of Higgs couplings from SM.
- BSM modeled as extension of SM through effective Lagrangian.
  - Consider leading corrections only.
- Model considered here:
  - Scaling of Higgs-vector boson (κ_V) and Higgs-fermion couplings (κ_F), with no invisible/undetectable widths.
  - (Custodial symmetry is assumed.)
  - *“Kappa parametrization”*
- Main effect on EWPO due to modified Higgs coupling to gauge bosons (κ_V).
  - Espinosa et al [arXiv:1202.3697], Falkowski et al [arXiv:1303.1812], etc.



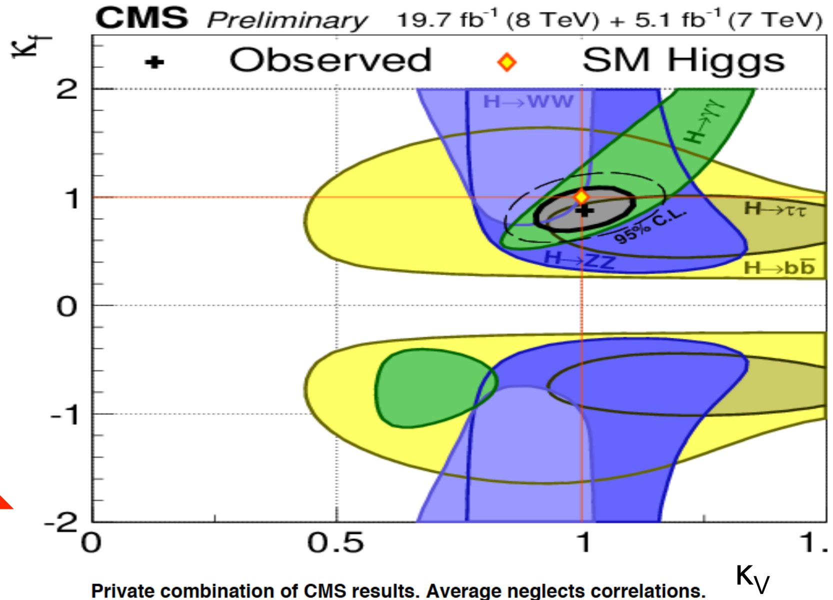


$$S = \frac{1}{12\pi}(1-\kappa_V^2)\log\left(\frac{\Lambda^2}{M_H^2}\right), \quad T = -\frac{3}{16\pi c_W^2}(1-\kappa_V^2)\log\left(\frac{\Lambda^2}{M_H^2}\right), \quad \Lambda = \frac{\lambda}{\sqrt{|1-\kappa_V^2|}}$$

Reproduction of ATLAS and CMS results

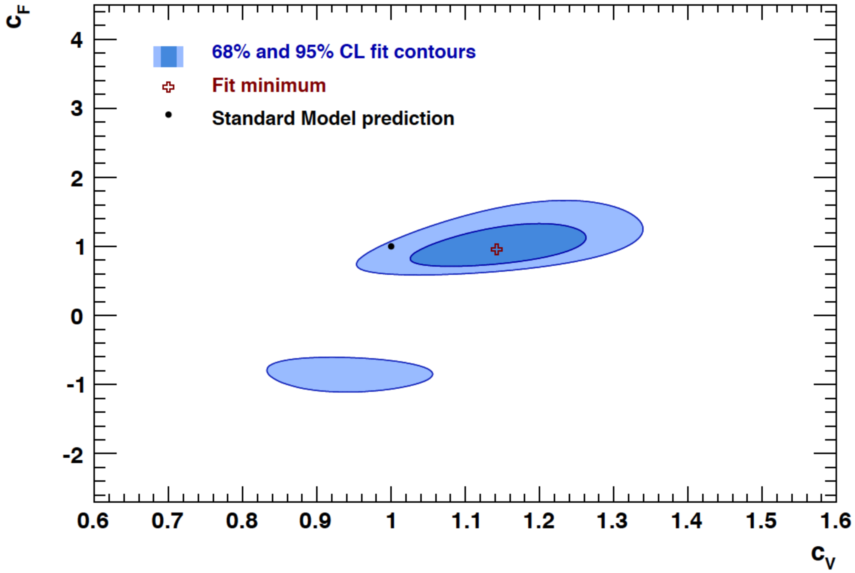


arXiv:1307.1427

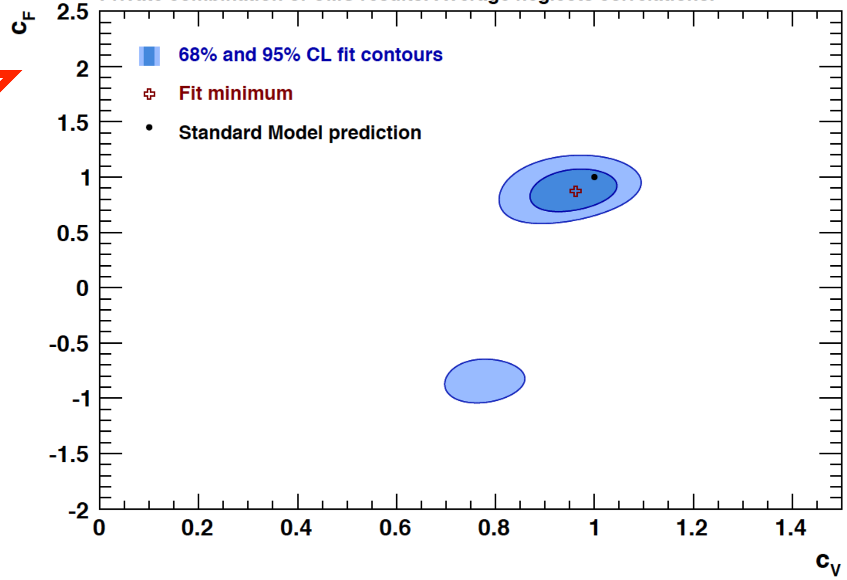


CMS-PAS-HIG-14-009

Private combination of ATLAS results. Average neglects correlations.



Private combination of CMS results. Average neglects correlations.

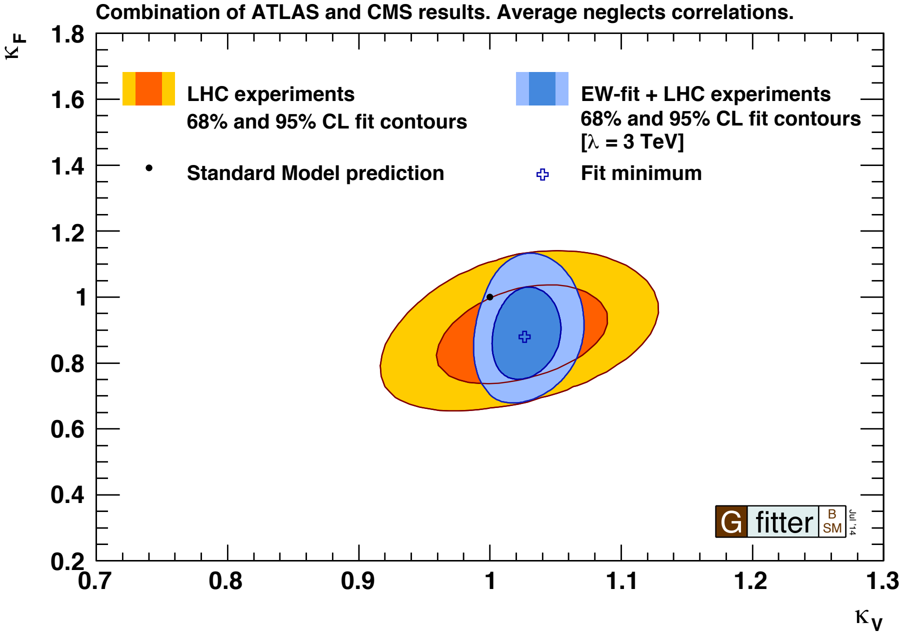


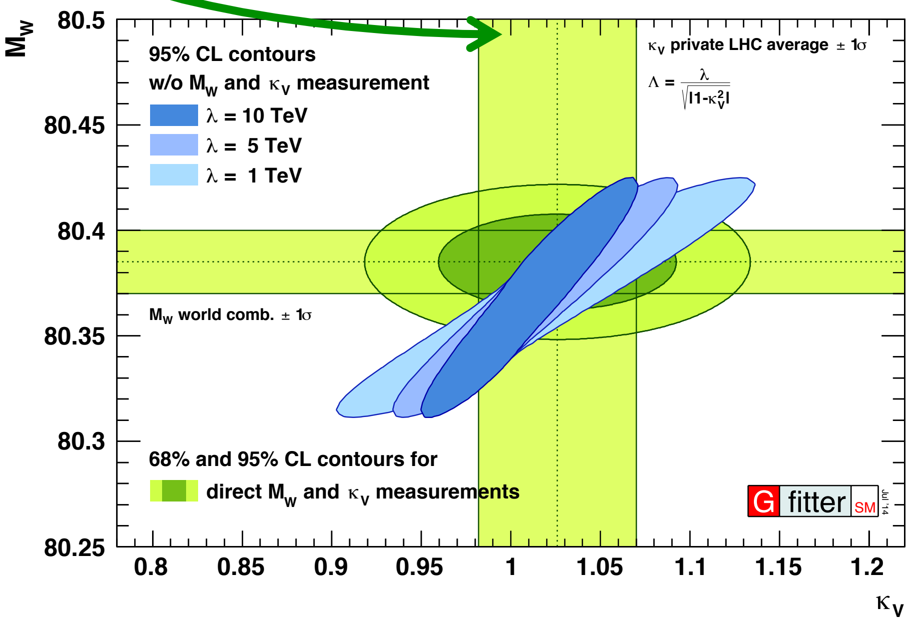
- Approximate reproduction of ATLAS/CMS results within limited public-info available.

Higgs coupling results

- Private LHC combination:
  - $\kappa_V = 1.026^{+0.043}_{-0.043}$
  - $\kappa_F = 0.88^{+0.10}_{-0.09}$

- Result from stand-alone EW fit:
  - $\kappa_V = 1.03 \pm 0.02$ (using λ=3 TeV)
  - *Implies NP-scale of $\Lambda \gtrsim 13$ TeV.*

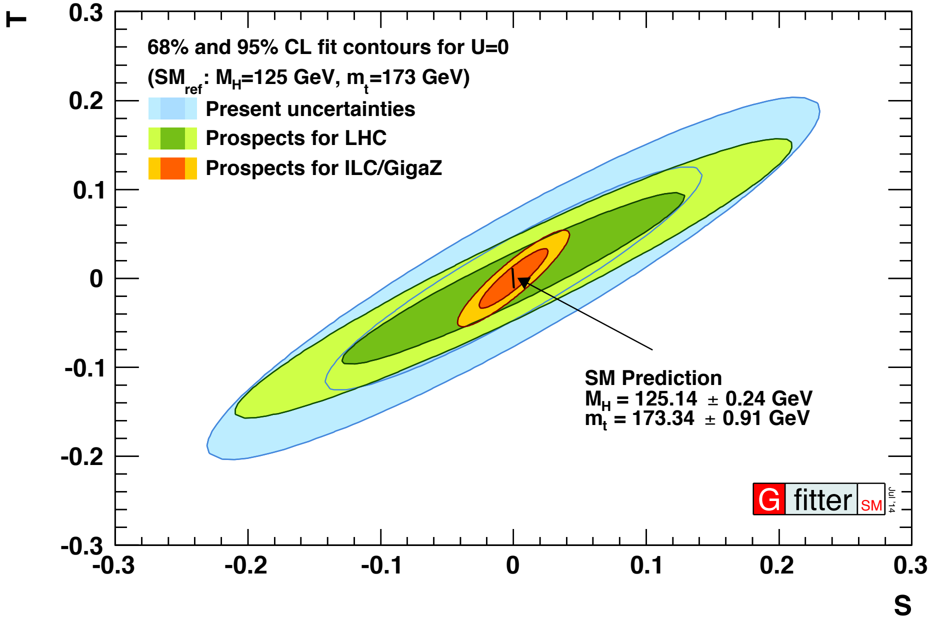


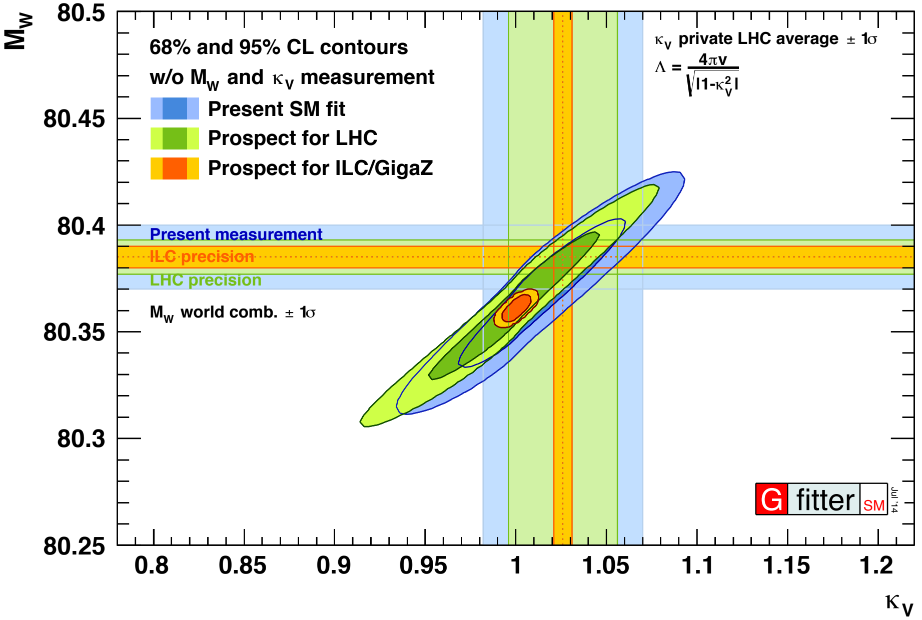


- Some dependency for κ_V in central value [1.02-1.04] and error [0.02-0.03] on cut-off scale λ [1-10 TeV].

1. EW fit sofar more precise result for κ_V than current LHC experiments.
2. EW fit has positive deviation of κ_V from 1.0.
   - (Many BSM models: $\kappa_V < 1$)

BSM prospects of EW fit

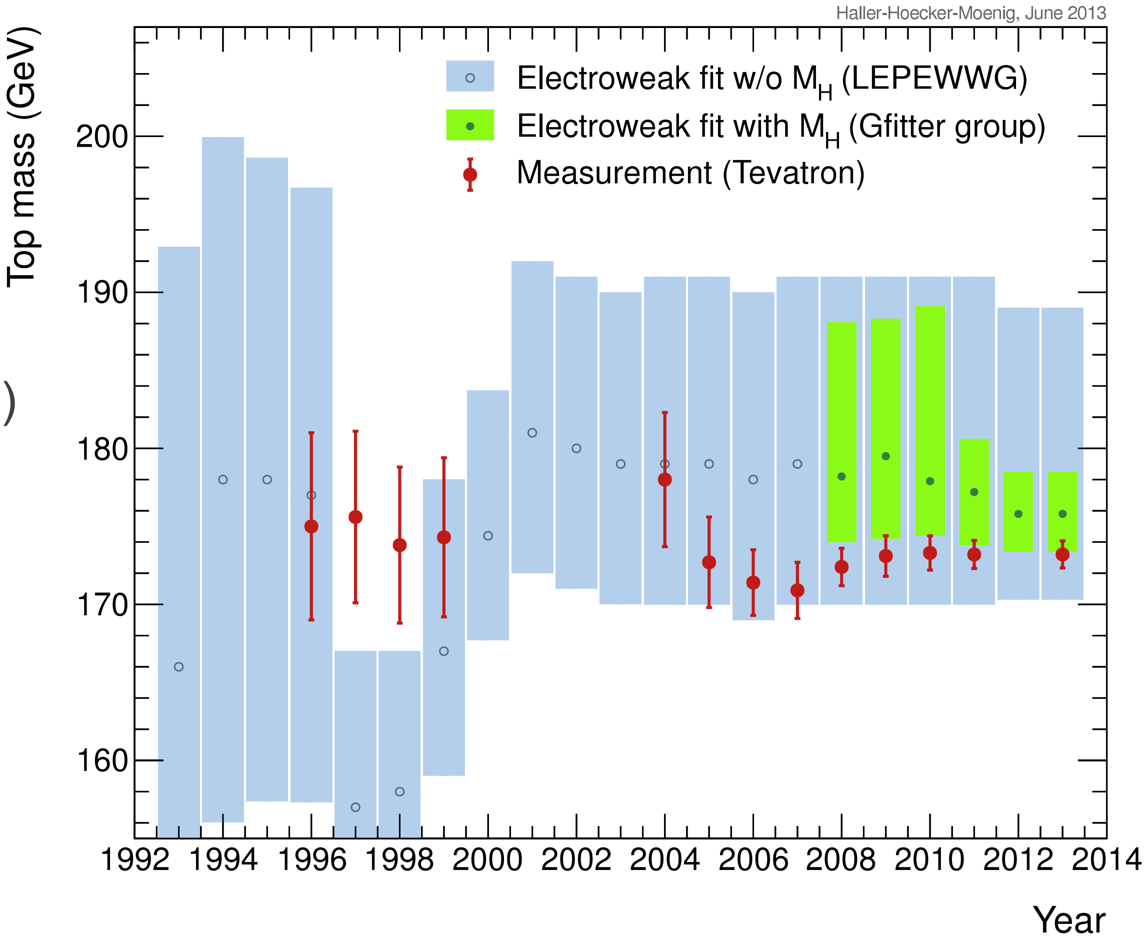




- For STU parameters, improvement of factor of >3 is possible at ILC.
- Again, at ILC a deviation between the SM predictions and direct measurements would be prominently visible.
- Competitive results between EW fit and Higgs coupling measurements!
  - (At level of 1%.)

Global EW fits: a long history

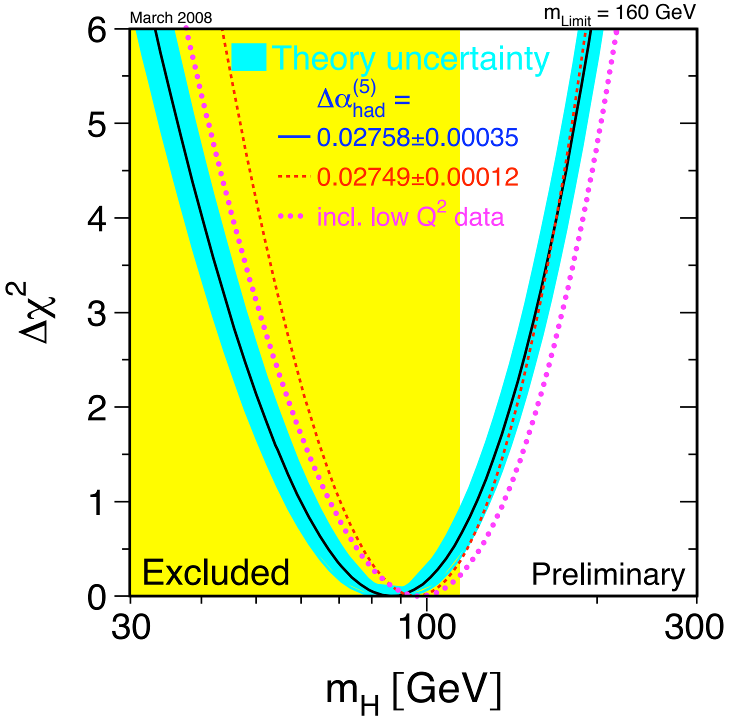
- Huge amount of pioneering work by many!
  - Needed to understand importance of loop corrections
    - Important observables (now) known at least at two-loop order, sometimes more.
  - High-precision Standard Model (SM) predictions and measurements required
    - First from LEP/SLC, then Tevatron, now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



- Top mass predictions from loop effects available since ~1990.
  - Official LEPEW fit since 1993.
- The EW fits have always been able to predict the top mass correctly!

Global EW fits: many fit codes

- EW fits performed by many groups in past and present.
  - D. Bardinet al. (ZFITTER), G. Passarino et al. (TOPAZ0), LEPEW WG (M. Grünewald, K. Mönig et al.), J. Erler (GAP), Bayesian fit (M. Ciuchini, L. Silvestrini et al.), etc …
  - Important results obtained!
- Several groups pursuing global beyond-SM fits, especially SUSY.
- Global SM fits also used at lower energies [CKM-matrix].



- Fits of the different groups agree very well.

- Some differences in treatment of theory errors, which just start to matter.
  - E.g. theoretical and experimental errors added linearly (= conservative) or quadratically.
    - In following: theoretical errors treated as Gaussian (quadratic addition.)

Two prospects scenarios: LHC, ILC/GigaZ

- Uncertainty estimates used:

	Experimental input $[\pm 1\sigma_{\mathrm{exp}}]$		
Parameter	Present	LHC	ILC/GigaZ
M_H [GeV]	0.4	< 0.1	< 0.1
M_W [MeV]	15	8	5
M_Z [MeV]	2.1	2.1	2.1
m_t [GeV]	0.8	0.6	0.1
$\sin^2\theta^{\ell}_{\mathrm{eff}}$ $[10^{-5}]$	16	16	1.3
$\Delta\alpha^5_{\mathrm{had}}(M_Z^2)$ $[10^{-5}]$	10	4.7	4.7
R^0_l $[10^{-3}]$	25	25	4
$\alpha_S(M_Z^2)$ $[10^{-4}]$	–	–	–
$S\vert_{U=0}$	–	–	–
$T\vert_{U=0}$	–	–	–
κ_V $(\lambda = 3\,\mathrm{TeV})$	0.05	0.03	0.01

  - ILC prospects from: ILC TDR (Vol-2).
  - Theoretical uncertainty estimates from recent Snowmass report

- Central values of input measurements adjusted to M_H = 126 GeV.

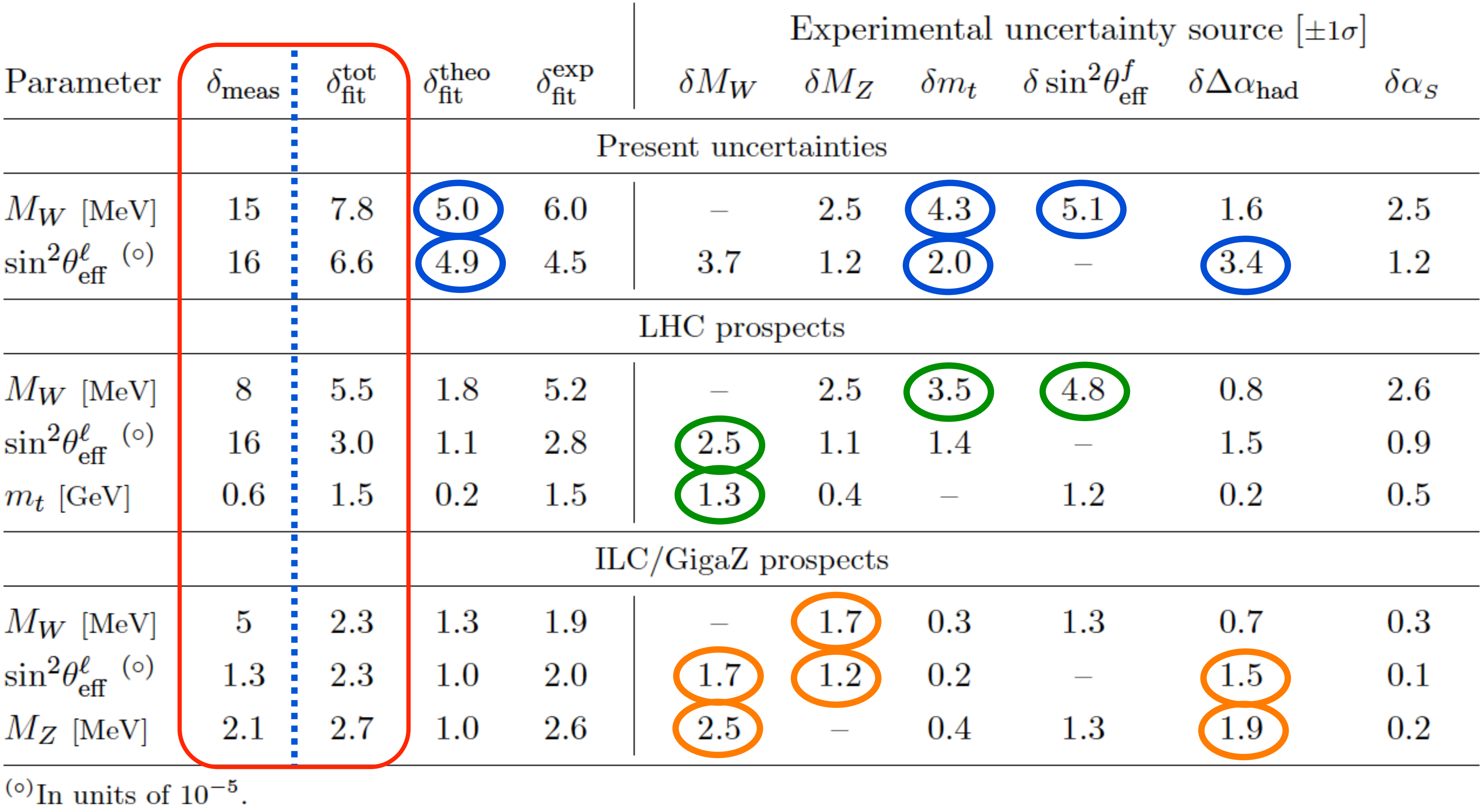
Summary of indirect predictions

	Experimental input $[\pm 1\sigma_{\rm exp}]$			Indirect determination $[\pm 1\sigma_{\rm exp}, \pm 1\sigma_{\rm theo}]$		
Parameter	Present	LHC	ILC/GigaZ	Present	LHC	ILC/GigaZ
M_H [GeV]	0.4	< 0.1	< 0.1	${}^{+31}_{-26}, {}^{+10}_{-8}$	${}^{+20}_{-18}, {}^{+3.9}_{-3.2}$	${}^{+6.9}_{-6.6}, {}^{+2.5}_{-2.3}$
M_W [MeV]	15	8	5	6.0, 5.0	5.2, 1.8	1.9, 1.3
M_Z [MeV]	2.1	2.1	2.1	11, 4	7.0, 1.4	2.6, 1.0
m_t [GeV]	0.8	0.6	0.1	2.4, 0.6	1.5, 0.2	0.7, 0.2
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	16	16	1.3	4.5, 4.9	2.8, 1.1	2.0, 1.0
$\Delta\alpha^5_{\rm had}(M_Z^2)$ $[10^{-5}]$	10	4.7	4.7	42, 13	36, 6	5.6, 3.0
R^0_l $[10^{-3}]$	25	25	4	–	–	–
$\alpha_S(M_Z^2)$ $[10^{-4}]$	–	–	–	40, 10	39, 7	6.4, 6.9
$S\|_{U=0}$	–	–	–	0.094, 0.027	0.086, 0.006	0.017, 0.006
$T\|_{U=0}$	–	–	–	0.083, 0.023	0.064, 0.005	0.022, 0.005
κ_V ($\lambda = 3$ TeV)	0.05	0.03	0.01	0.02	0.02	0.01

- M_W and $\sin^2\theta^l_{\rm eff}$ are (and will be) sensitive probes of new physics!

Impact of individual uncertainties

- Breakdown of individual contributions to errors of M_W and $\sin^2\theta^l_{eff}$



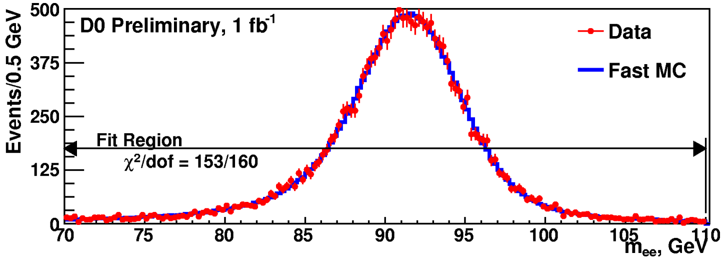
					Experimental uncertainty source [±1σ]					
Parameter	δ_{meas}	$\delta^{\text{tot}}_{\text{fit}}$	$\delta^{\text{theo}}_{\text{fit}}$	$\delta^{\text{exp}}_{\text{fit}}$	δM_W	δM_Z	δm_t	$\delta \sin^2\theta^f_{\text{eff}}$	$\delta\Delta\alpha_{\text{had}}$	$\delta\alpha_S$
					Present uncertainties					
M_W [MeV]	15	7.8	5.0	6.0	–	2.5	4.3	5.1	1.6	2.5
$\sin^2\theta^\ell_{\text{eff}}$ $^{(\circ)}$	16	6.6	4.9	4.5	3.7	1.2	2.0	–	3.4	1.2
					LHC prospects					
M_W [MeV]	8	5.5	1.8	5.2	–	2.5	3.5	4.8	0.8	2.6
$\sin^2\theta^\ell_{\text{eff}}$ $^{(\circ)}$	16	3.0	1.1	2.8	2.5	1.1	1.4	–	1.5	0.9
m_t [GeV]	0.6	1.5	0.2	1.5	1.3	0.4	–	1.2	0.2	0.5
					ILC/GigaZ prospects					
M_W [MeV]	5	2.3	1.3	1.9	–	1.7	0.3	1.3	0.7	0.3
$\sin^2\theta^\ell_{\text{eff}}$ $^{(\circ)}$	1.3	2.3	1.0	2.0	1.7	1.2	0.2	–	1.5	0.1
M_Z [MeV]	2.1	2.7	1.0	2.6	2.5	–	0.4	1.3	1.9	0.2

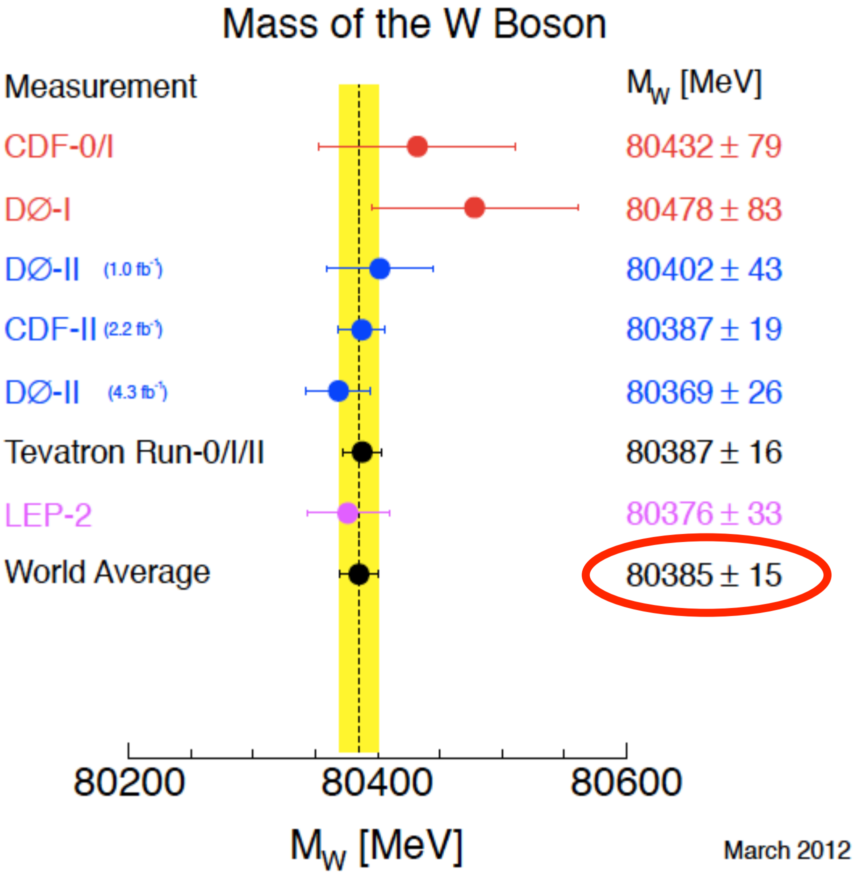
$^{(\circ)}$In units of 10^{-5}.

- M_W and $\sin^2\theta^l_{eff}$ are sensitive probes of new physics! For all scenarios.
- At ILC/GigaZ, precision of M_Z will become important again.

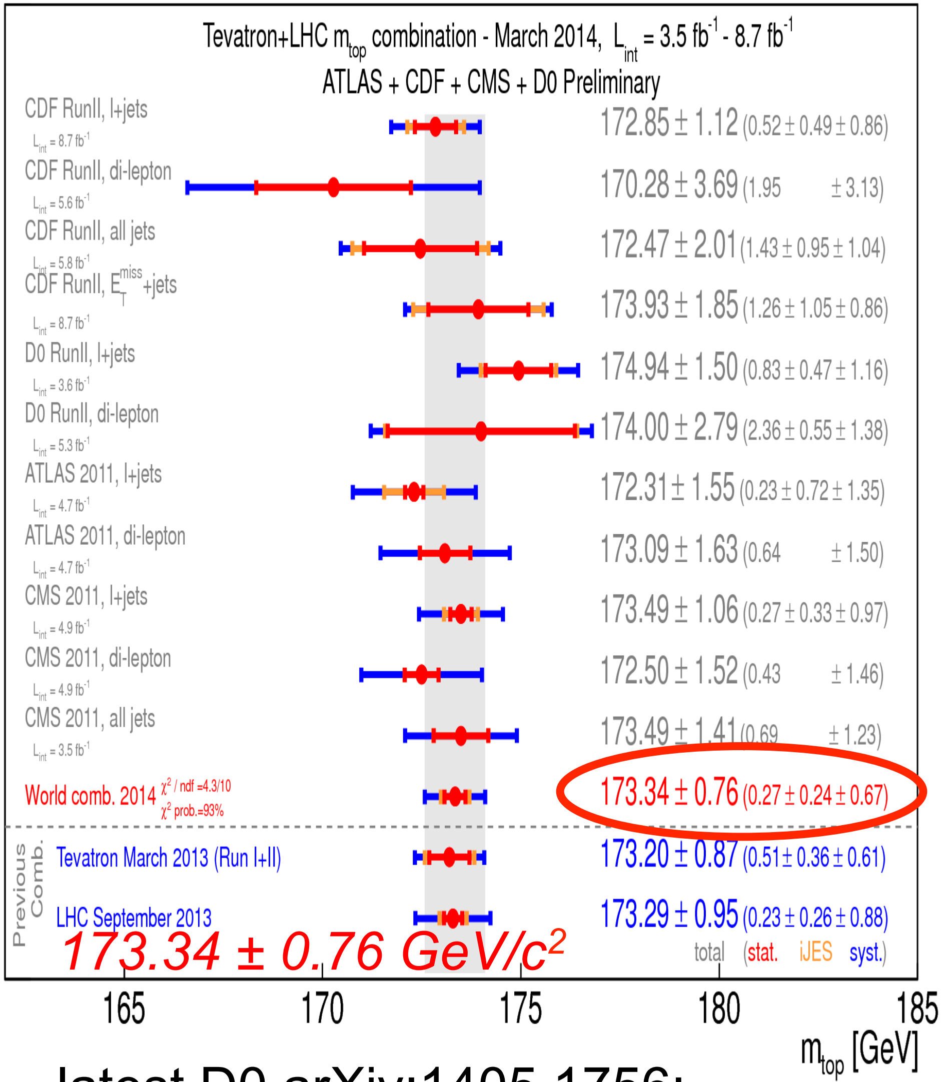
Latest averages for M_W and m_{top}

Latest Tevatron result from: arXiv:1204.0042





Top mass WA from: arXiv:1403.4427



173.34 ± 0.76 GeV/c^2

latest D0 arXiv:1405.1756:

174.98 ± 0.76 GeV/c^2

Electroweak precision tests: Theory *at NNLO*

- Radiative corrections are important!
  - E.g. consider tree-level EW unification relation:

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

    - This predicts: $M_W = (79.964 \pm 0.005)$ GeV
    - Experiment: $M_W = (80.385 \pm 0.015)$ GeV
- Without loop corrections: shift of 400 MeV, 27σ discrepancy!

1. Experimental precision (<1%), better than typical loop factor ($\alpha \approx 1/137$)
   → Requires radiative corrections at 2-loop level.

2. Before Higgs discovery: uncertainty on M_H largest uncertainty in EW fit.
   → *After:* inclusion of all relevant theoretical uncertainties.

(Part of focus of this talk …)