



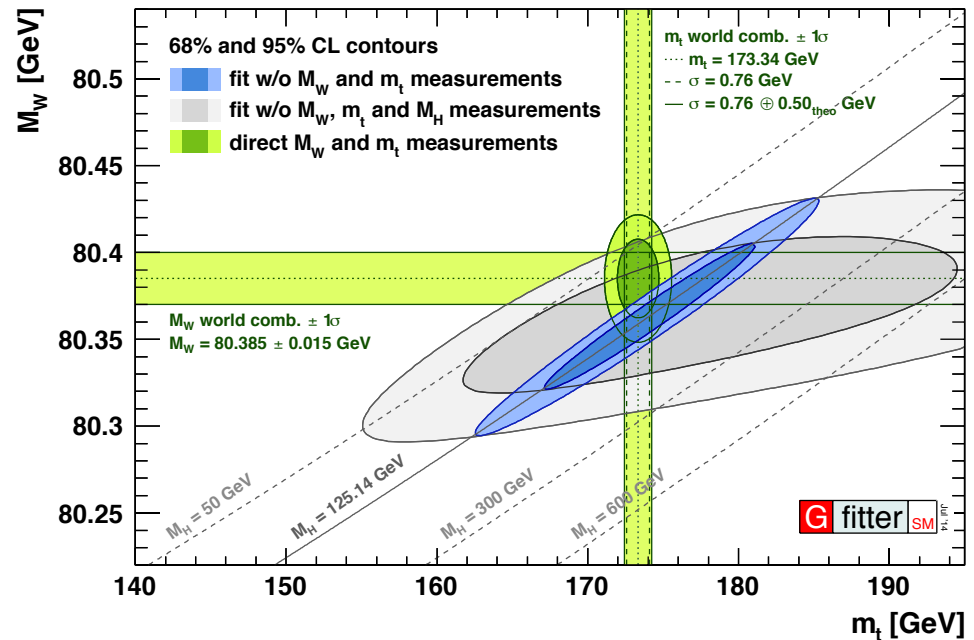
<http://cern.ch/Gfitter>

arXiv:1407.3792 (subm. to EPJC)

The global electroweak fit at NNLO Prospects for LHC and ILC

Outline:

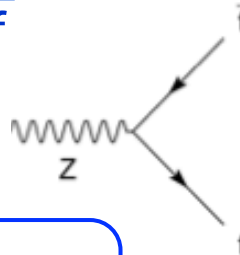
- ✓ What's new in the Electroweak Fit
- ✓ Prospects for LHC and ILC
- ? Higgs couplings



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 $Z \rightarrow f\bar{f}$

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

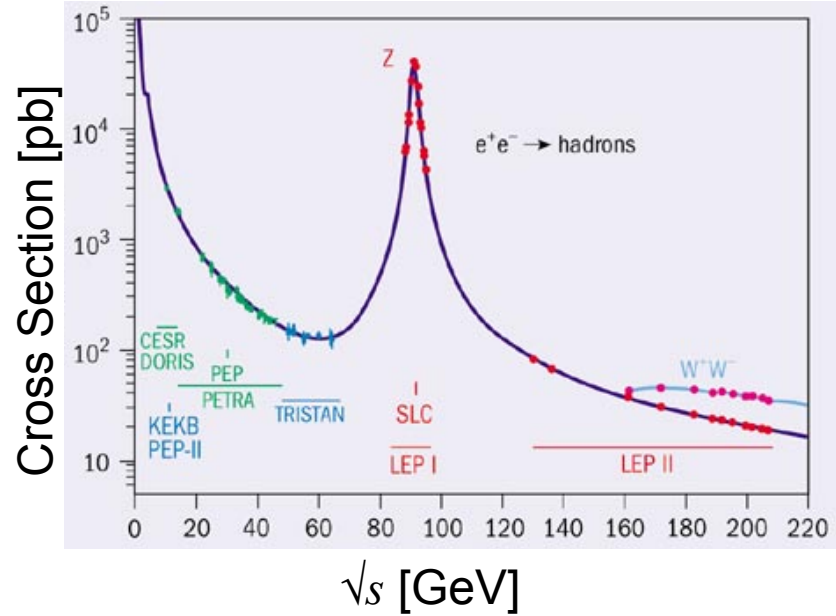


- Prediction EWSB at tree-level:

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

- The impact of loop corrections

- Absorbed into EW form factors: ρ , κ , Δr
- Effective couplings at the Z-pole
- Quadratically dependent on m_t , logarithmic dependence on M_H

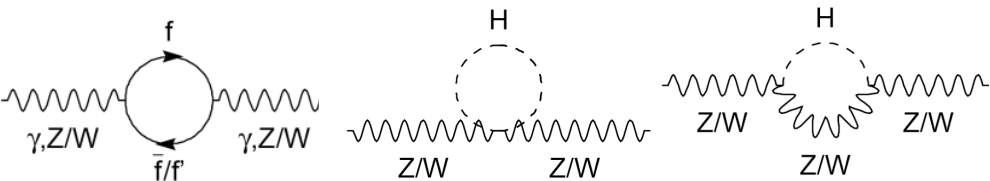


$$g_{V,f} = \sqrt{\rho_Z^f} (I_3^f - 2Q^f \sin^2 \theta_{\text{eff}}^f)$$

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

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

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



After the Higgs:

- *All free parameters of SM fit are known \Rightarrow fit now fully over-constrained.*
- *The electroweak observables can be unambiguously predicted at loop level.*
- *Paradigm shift for EW fit:
From Higgs mass prediction \Rightarrow Powerful predictions of key observables now possible (much better than w/o M_H)*

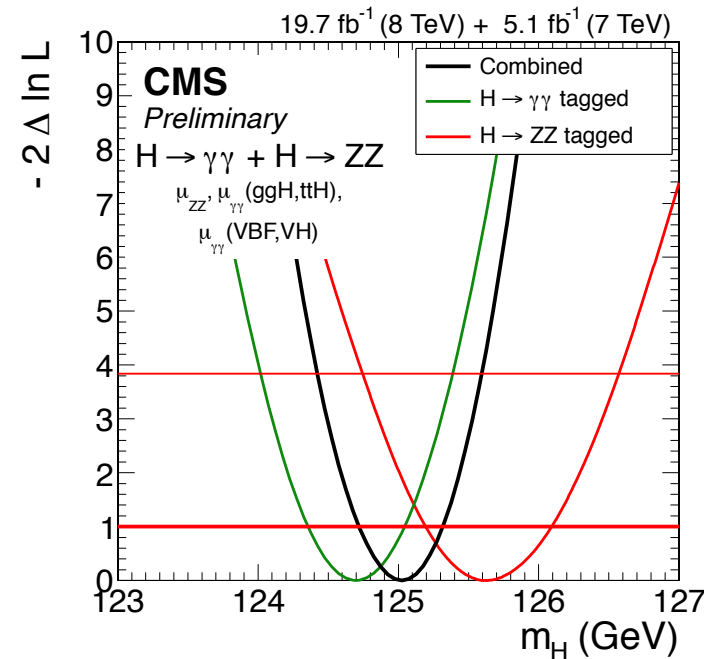
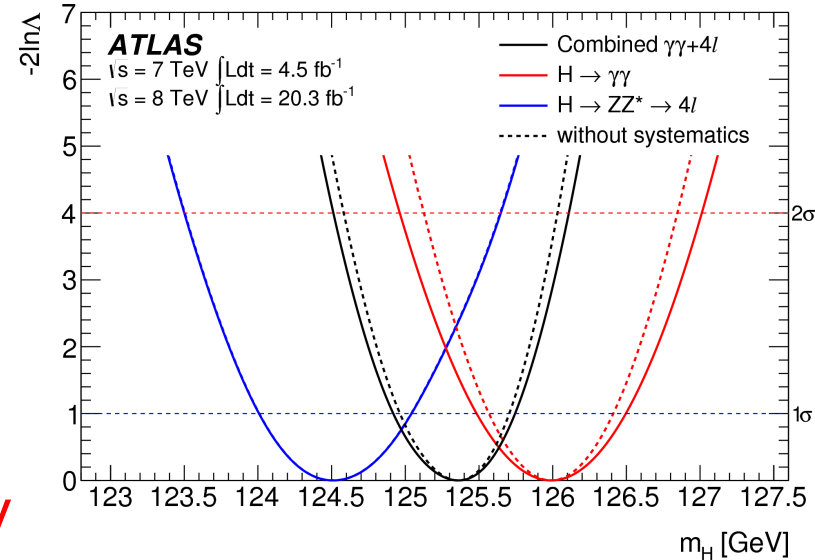
Can now test for:

- ✓ Self-consistency of SM.
- ✓ Possible contributions from BSM models.

The SM fit with Gfitter, including the Higgs



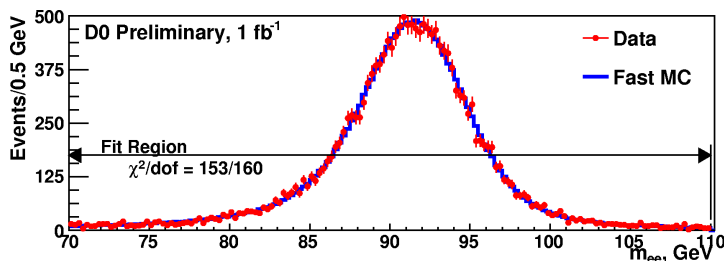
- Discovery of Higgs-like boson at LHC
 - Cross section, production rate time branching ratios, spin, parity sofar compatible with SM Higgs boson.
- This talk: assume boson is SM Higgs.
- Use in EW fit: $M_H = 125.14 \pm 0.24 \text{ GeV}$
 - ATLAS: $M_H = 125.36 \pm 0.37 \pm 0.18 \text{ GeV}$
 - CMS: $M_H = 125.03 \pm 0.27 \pm 0.14 \text{ GeV}$ [arXiv:1406.3827, CMS-PAS-HIG-14-009]
- Change in average between fully uncorrelated and fully correlated systematic uncertainties is minor: $\delta M_H : 0.24 \rightarrow 0.32 \text{ GeV}$
 - EW fit unaffected at this level of precision



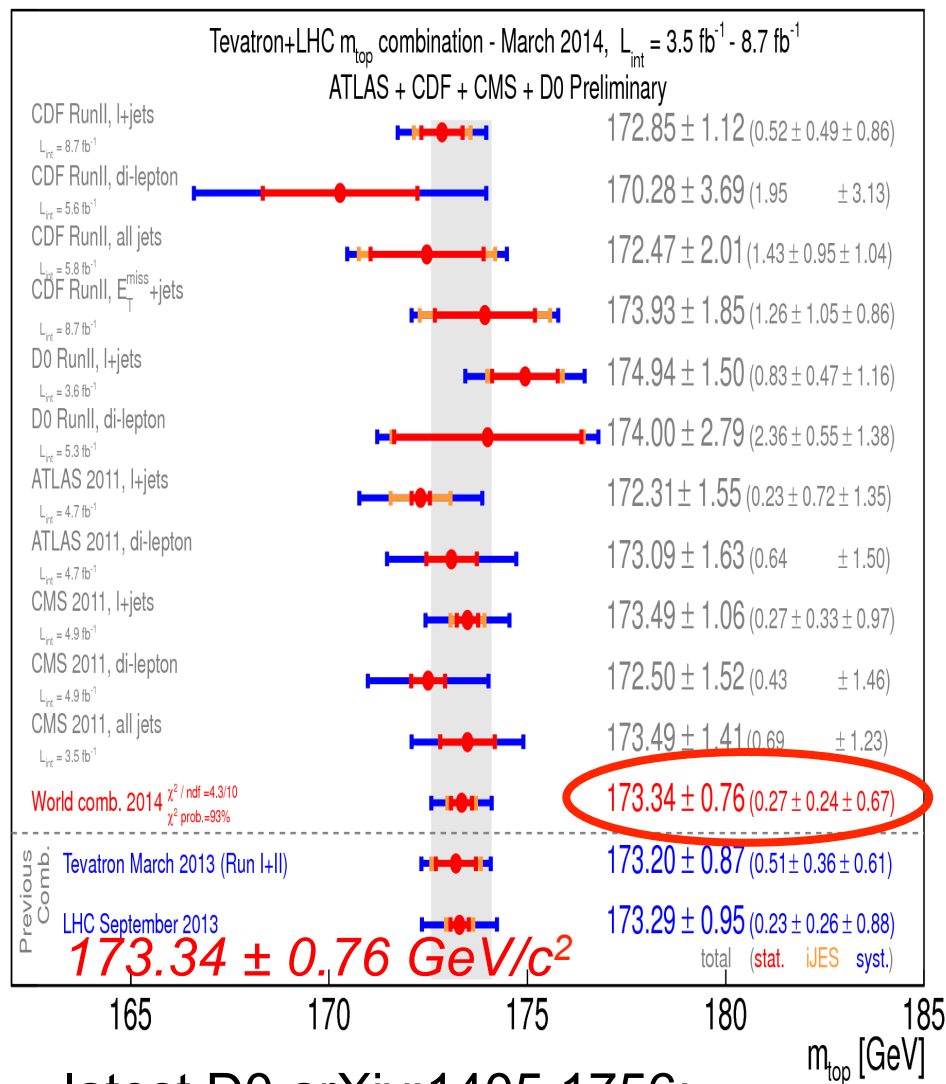
Latest averages for M_W and m_{top}



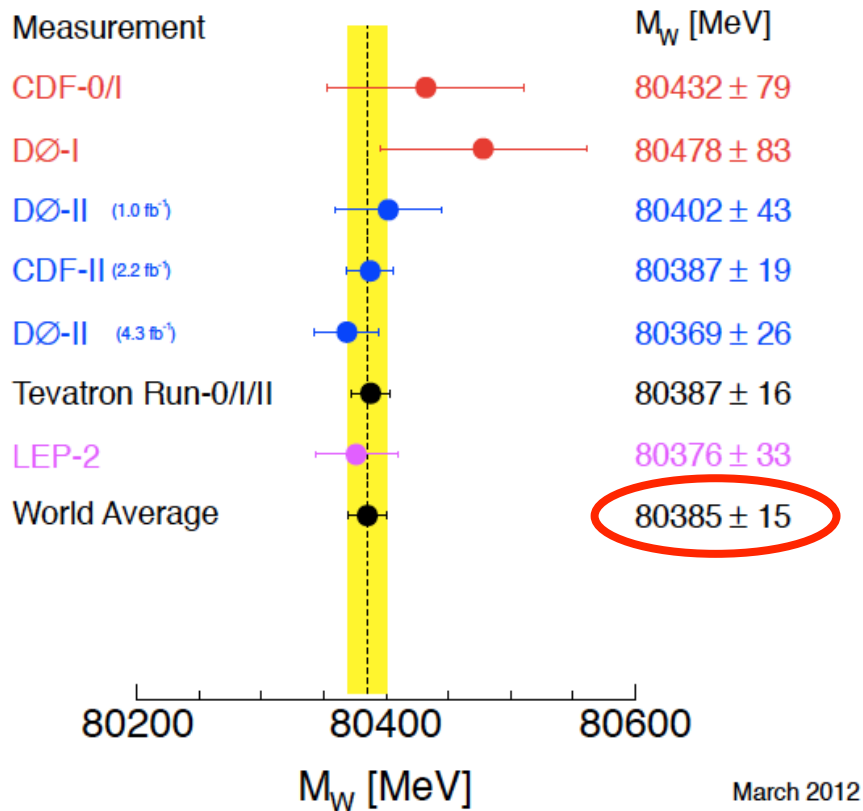
Latest Tevatron result from: arXiv:1204.0042



Top mass WA from: arXiv:1403.4427



Mass of the W Boson



latest D0 arXiv:1405.1756:
 174.98 ± 0.76 GeV/c²

March 2012

- 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: $M_W = (79.964 \pm 0.005) \text{ GeV}$
- Experiment: $M_W = (80.385 \pm 0.015) \text{ GeV}$

- 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 ...)

- 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: $M_W = (79.964 \pm 0.005) \text{ GeV}$
- Experiment: $M_W = (80.385 \pm 0.015) \text{ GeV}$

- Without loop corrections: shift of 400 MeV, 27σ discrepancy!

- In EW fit with Gfitter we use state-of-the-art calculations:

- $\sin^2\theta_{\text{eff}}^f$ 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

- 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 N³LO [P. A. Baikov et al., PRL108, 222003 (2012)]

- N³LO prediction of the hadronic cross section

- Γ_i Partial Z decay widths and BRs **at NNLO** ← **New! full fermionic 2-loop calc.**
[A. Freitas, JHEP04, 070 (2014)]

- *New: all EWPOs^(*) now described at 2-loop level or better!*

Theory uncertainties from unknown HO terms



Most important observables:



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

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

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

New in EW fit

Newly included:

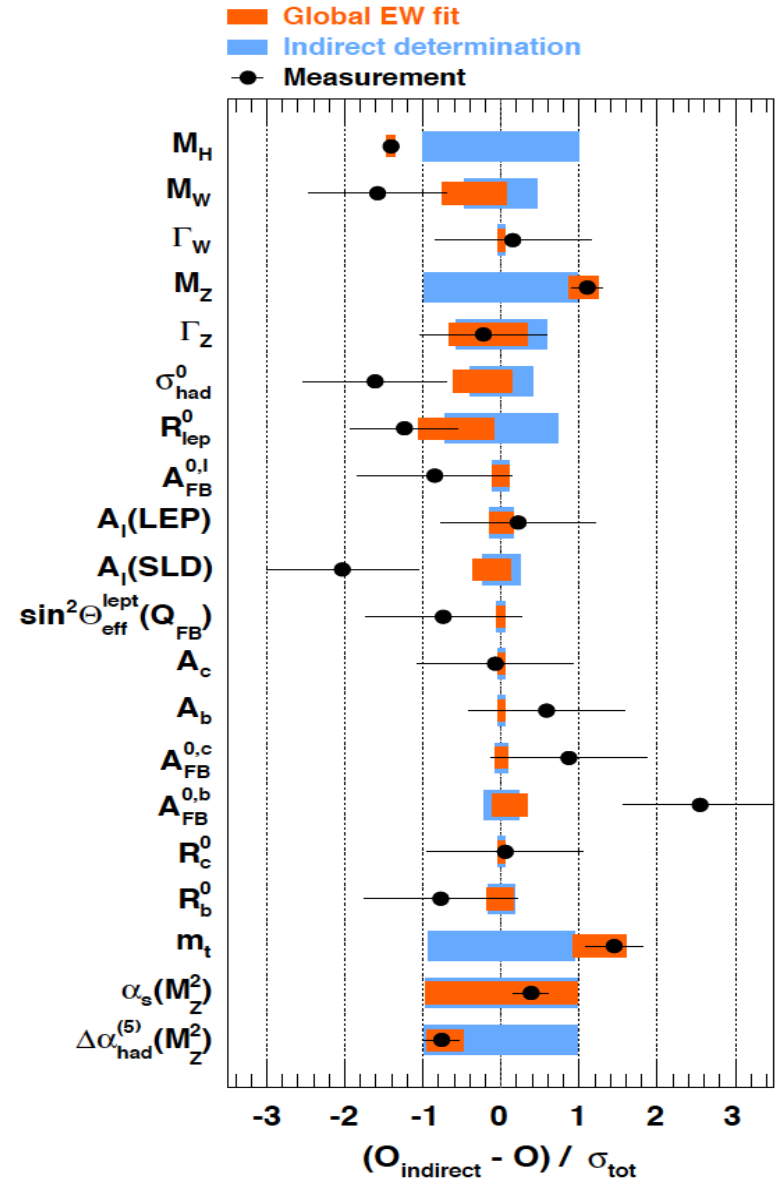
- Full fermionic 2-loop corrections of partial Z decay widths (A. Freitas)
 - 6 corresponding nuisance parameters. ($\delta\Gamma_Z = 0.5 \text{ MeV}$)
- Γ_{had} QCD Adler functions at N³LO
 - 2 nuisance parameters.
- Top quark mass: conversion from measurement to MS-bar mass
 - Agnostic value used here: $\delta_{\text{theo}} m_t = 0.5 \text{ GeV}$. (more later)

- 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)]
 - **$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$** including α_S dependency
[Davier et al., EPJC 71, 1515 (2011)]
 - **M_H** from LHC
[arXiv:1406.3827, CMS-PAS-HIG-14-009]

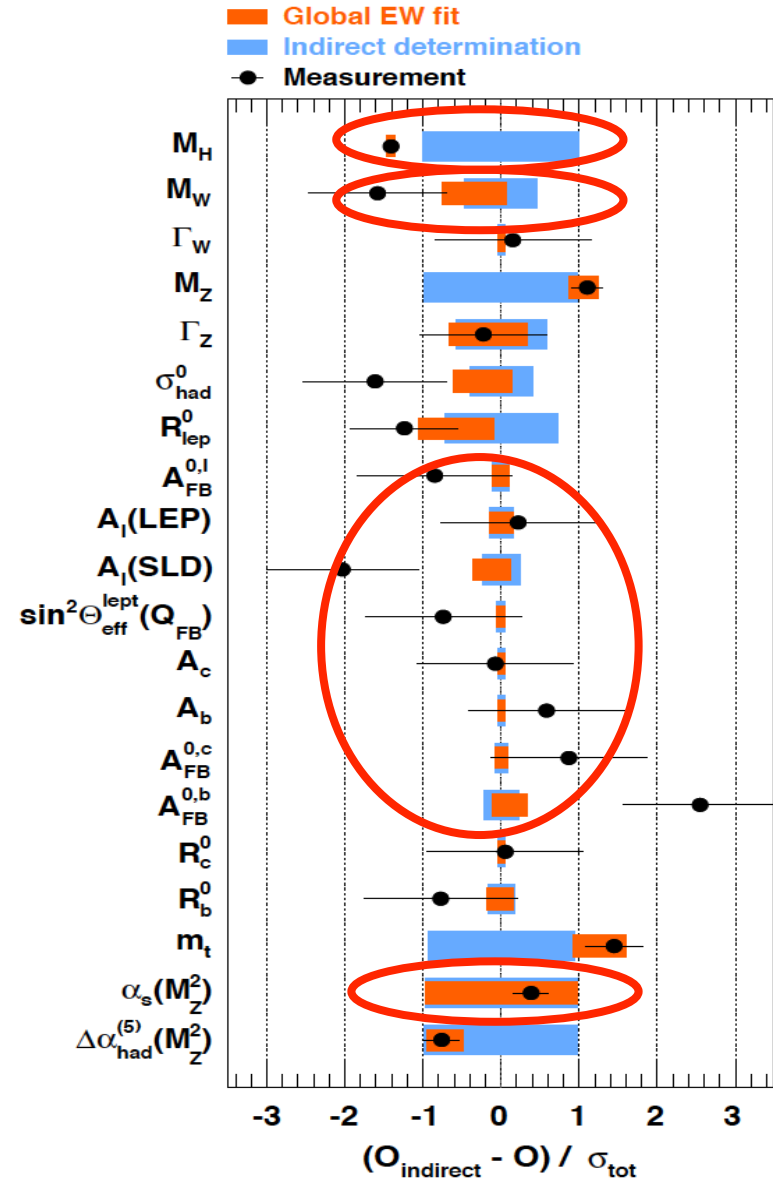
- 7 (+10) free fit parameters:
 - $M_H, M_Z, \alpha_S(M_Z^2), \Delta\alpha_{\text{had}}^{(5)}(M_Z^2), m_t, m_c, m_b$
 - 10 theory nuisance parameters
 - e.g. δM_W (4 MeV), $\delta \sin^2\theta_{\text{eff}}^l$ (4.7×10^{-5})

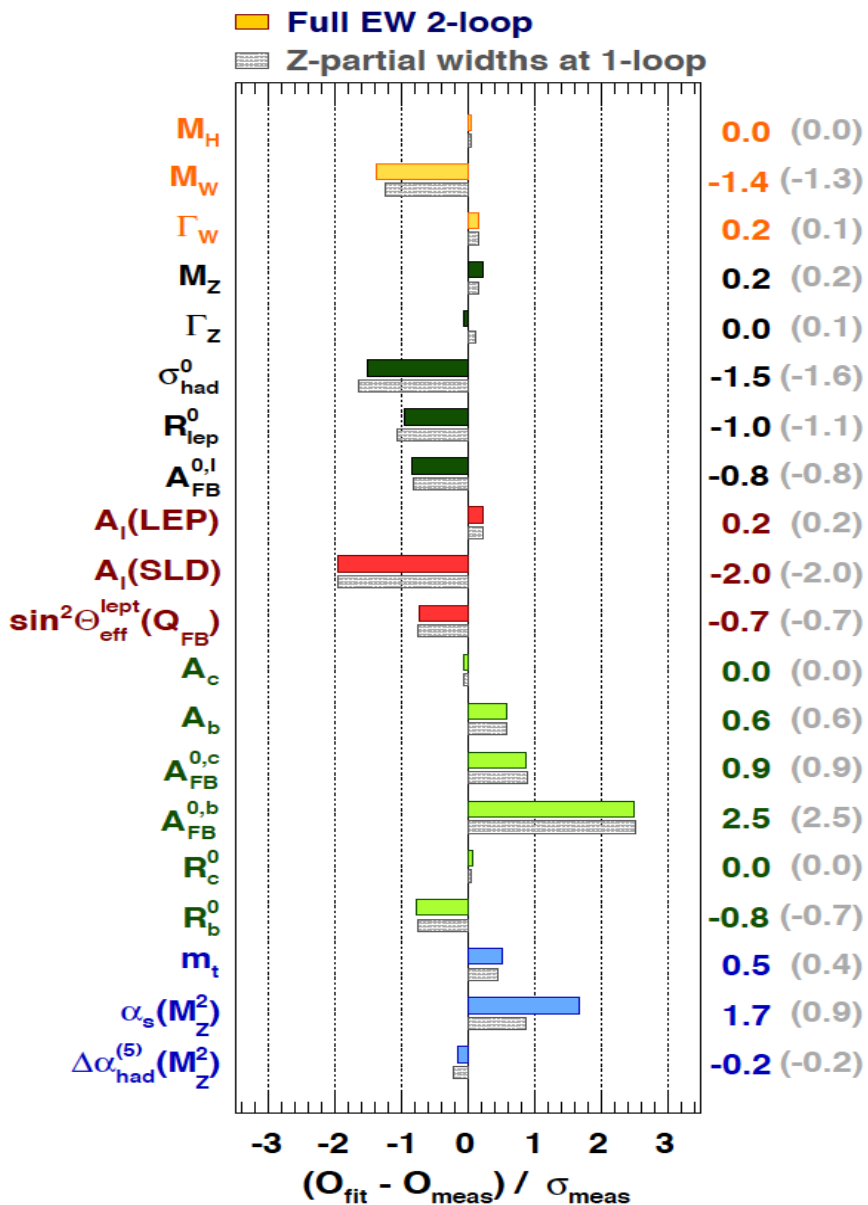
M_H [GeV] ^(o)	125.14 ± 0.24	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	
σ_{had}^0 [nb]	41.540 ± 0.037	
R_ℓ^0	20.767 ± 0.025	
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	SLC
A_ℓ (*)	0.1499 ± 0.0018	
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	0.2324 ± 0.0012	SLC
A_c	0.670 ± 0.027	
A_b	0.923 ± 0.020	SLC
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	LEP
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	
R_c^0	0.1721 ± 0.0030	
R_b^0	0.21629 ± 0.00066	
\bar{m}_c [GeV]	$1.27^{+0.07}_{-0.11}$	Tevatron + LHC
\bar{m}_b [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.34 ± 0.76	
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$ (†△)	2757 ± 10	

- 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!*



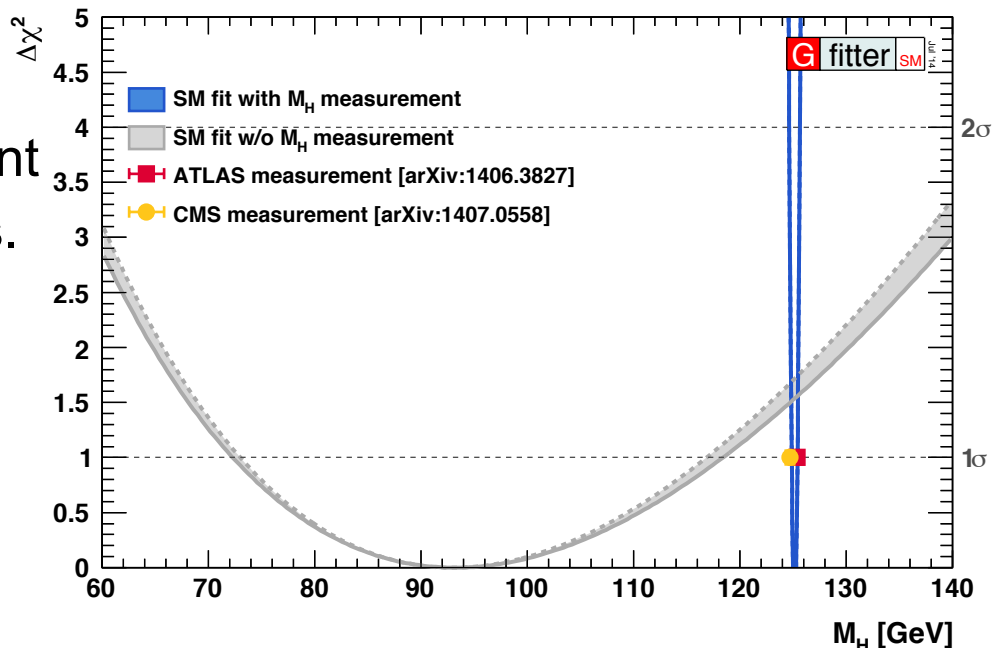
- Results drawn as *pull values*:
→ deviations to the *indirect* determinations, divided by *total error*.
- Total error:
error of direct measurement plus error from indirect determination.
- Black: direct measurement (data)
- Orange: full fit
- Light-blue: fit excluding input from the row
- The prediction (light blue) is often more precise than the measurement!*





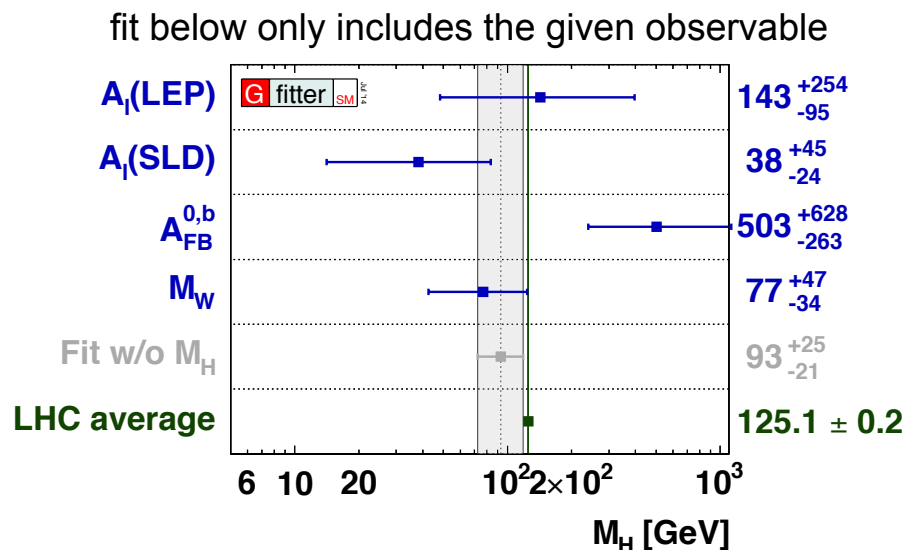
- No individual value exceeds 3σ
- Largest deviations in b-sector: $A_{FB}^{0,b}$ with 2.5σ
 - \rightarrow largest contribution to χ^2
- Small pulls for M_H , M_Z , $\Delta\alpha_{had}^{(5)}(M_Z^2)$, \overline{m}_c , \overline{m}_b indicate that input accuracies exceed fit requirements
- Goodness of fit – p-value:
 - $\chi^2_{min} = 17.8 \rightarrow \text{Prob}(\chi^2_{min}, 14) = 21\%$
 - Pseudo experiments: 21 ± 2 (theo) %
- Only small changes from switching between 1 and 2-loop calc. for partial Z widths and small M_W correction.
 - $\chi^2_{min}(1\text{-loop Z width}) = 18.0$
 - $\chi^2_{min}(\text{no } M_W \text{ correction}) = 17.4$
 - $\chi^2_{min}(\text{no extra theory errors}) = 18.2$

- 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.



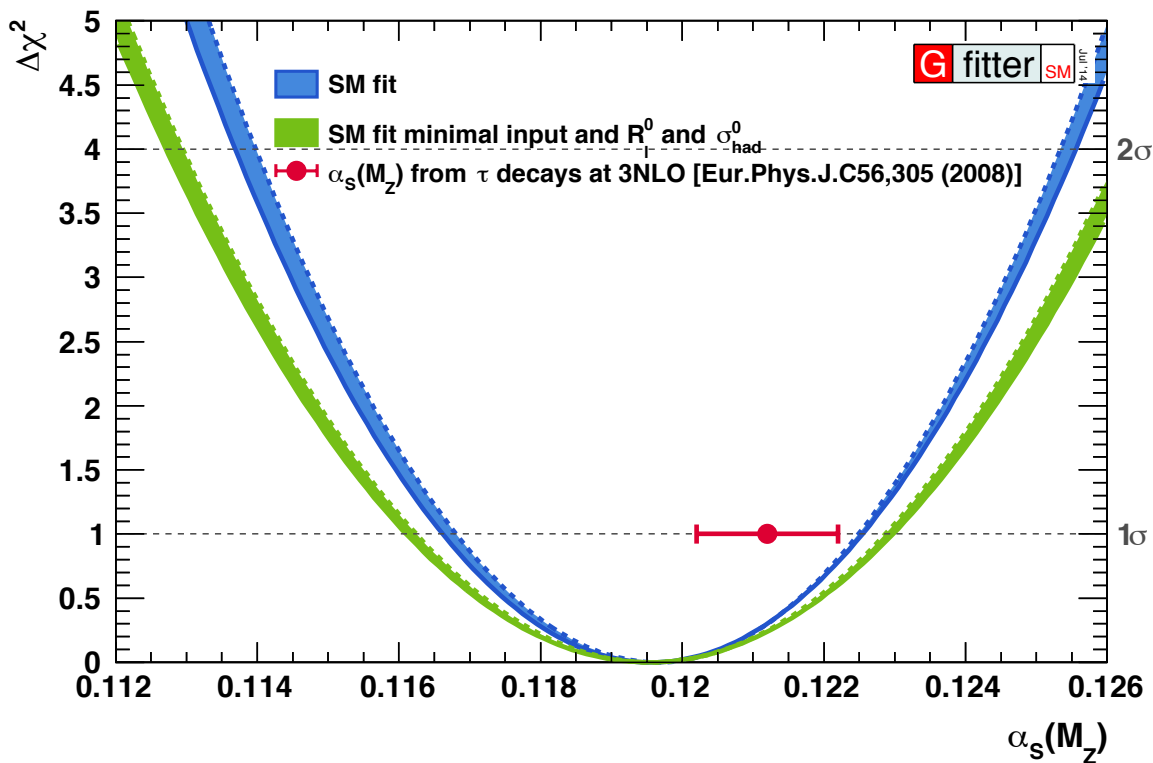
- Bottom plot: impact of other most sensitive Higgs observables

- Determination of M_H removing all sensitive observables except the given one.
- Known tension (2.5σ) between $A_1(\text{SLD})$, $A_{\text{FB}}^{0,b}$, and M_W clearly visible.



Prediction for $\alpha_s(M_Z)$ from $Z \rightarrow \text{hadrons}$

- Scan of $\Delta\chi^2$ versus α_s
 - Also shown: SM fit with minimal inputs: M_Z , G_F , $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, M_H , and fermion masses
- Determination of α_s at full $N^2\text{LO}$ and partial $N^3\text{LO}$.
 - Most sensitive through total hadronic cross-section σ_{had}^0 and partial leptonic width R_0^1



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

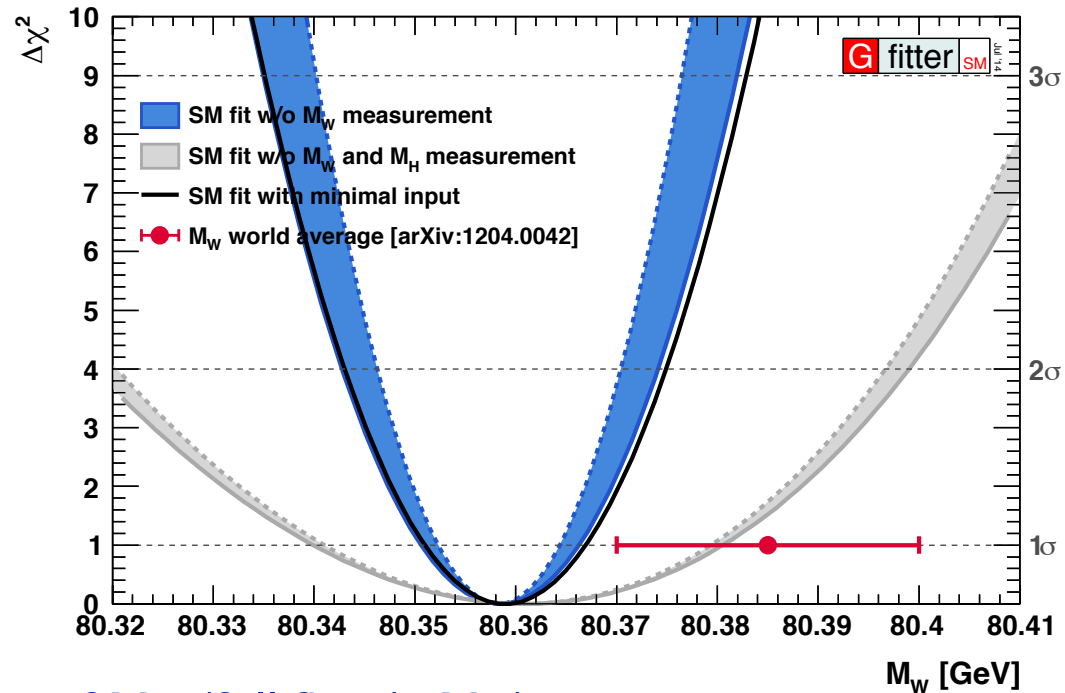
$$= 0.1196 \pm 0.0030_{\text{tot}},$$

Most affected by new theory uncertainties

Before: $\delta_{\text{theo}} = 0.0001$

- *In good agreement with value from τ decays, at $N^3\text{LO}$, and with WA.*
 - (Improvements in precision only expected with ILC/GigaZ. See later.)

- Scan of $\Delta\chi^2$ profile versus M_W
 - Also shown: SM fit with minimal inputs: M_Z , G_F , $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, 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):

$$\begin{aligned}
 M_W &= 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\text{theo}} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\text{had}}} \\
 &\quad \pm 0.0020_{\alpha_s} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\text{theo}} M_W} \text{ GeV}, \\
 &= 80.358 \pm 0.008_{\text{tot}} \text{ GeV}.
 \end{aligned}$$

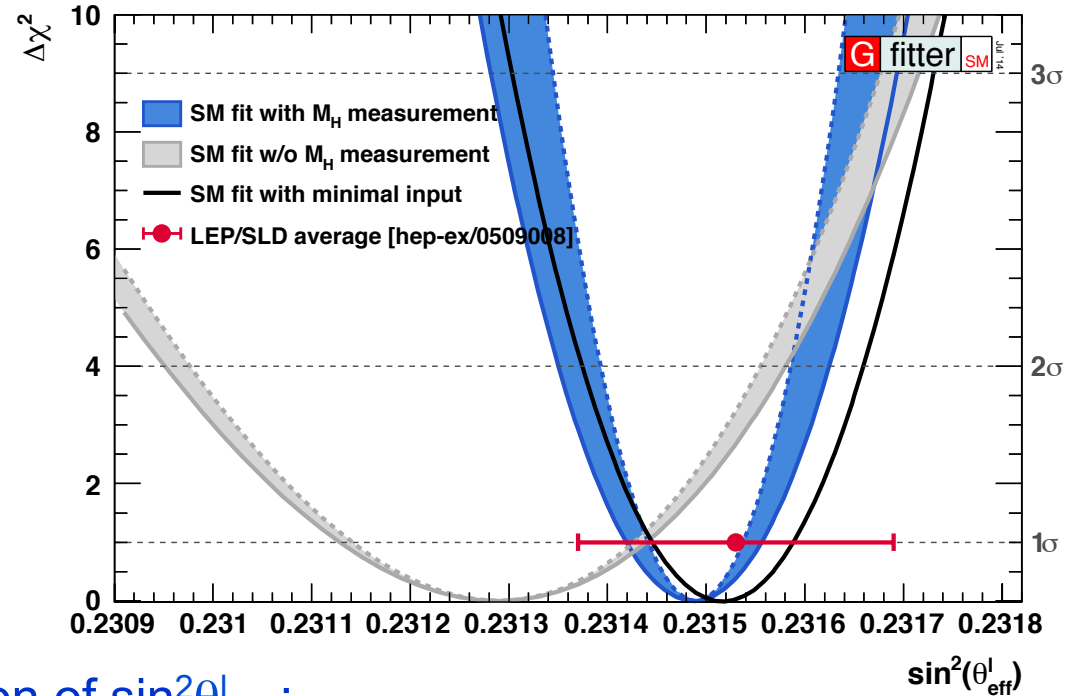
- **More precise estimate of M_W than the direct measurements!**

- Uncertainty on world average measurement: 15 MeV

Obtained with simple error propagation

Indirect effective weak mixing angle

- Right: scan of $\Delta\chi^2$ profile versus $\sin^2\theta_{\text{eff}}^l$
 - All sensitive measurements removed from the SM fit.
 - Also shown: SM fit with minimal inputs
- M_H measurement allows for very precise constraint on $\sin^2\theta_{\text{eff}}^l$
- Fit result for indirect determination of $\sin^2\theta_{\text{eff}}^l$:



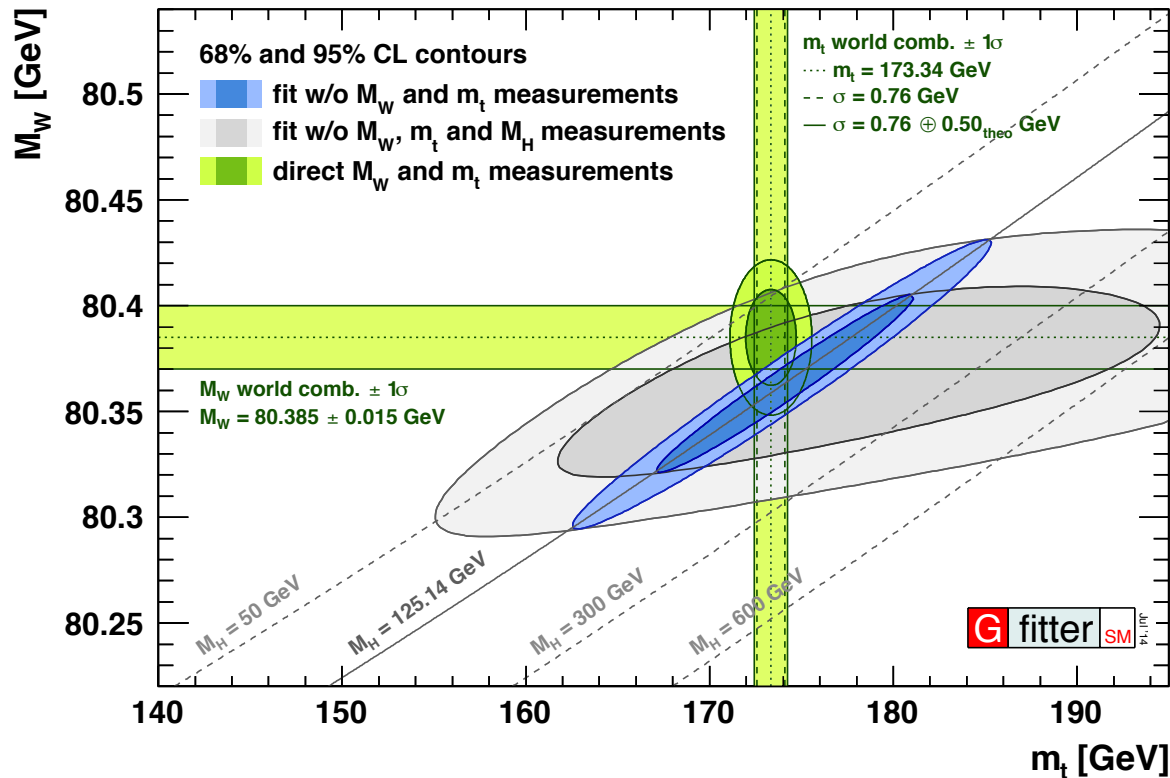
$$\begin{aligned} \sin^2\theta_{\text{eff}}^l &= 0.231488 \pm 0.000024_{m_t} \pm 0.000016_{\delta_{\text{theo}} m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\text{had}}} \\ &\quad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm 0.000047_{\delta_{\text{theo}} \sin^2\theta_{\text{eff}}^f}, \\ &=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



Obtained with simple error propagation

More precise than direct determination (from LEP/SLD) !
 • Uncertainty on LEP/SLD average: 1.6×10^{-4}

- 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 \rightarrow corners the SM!

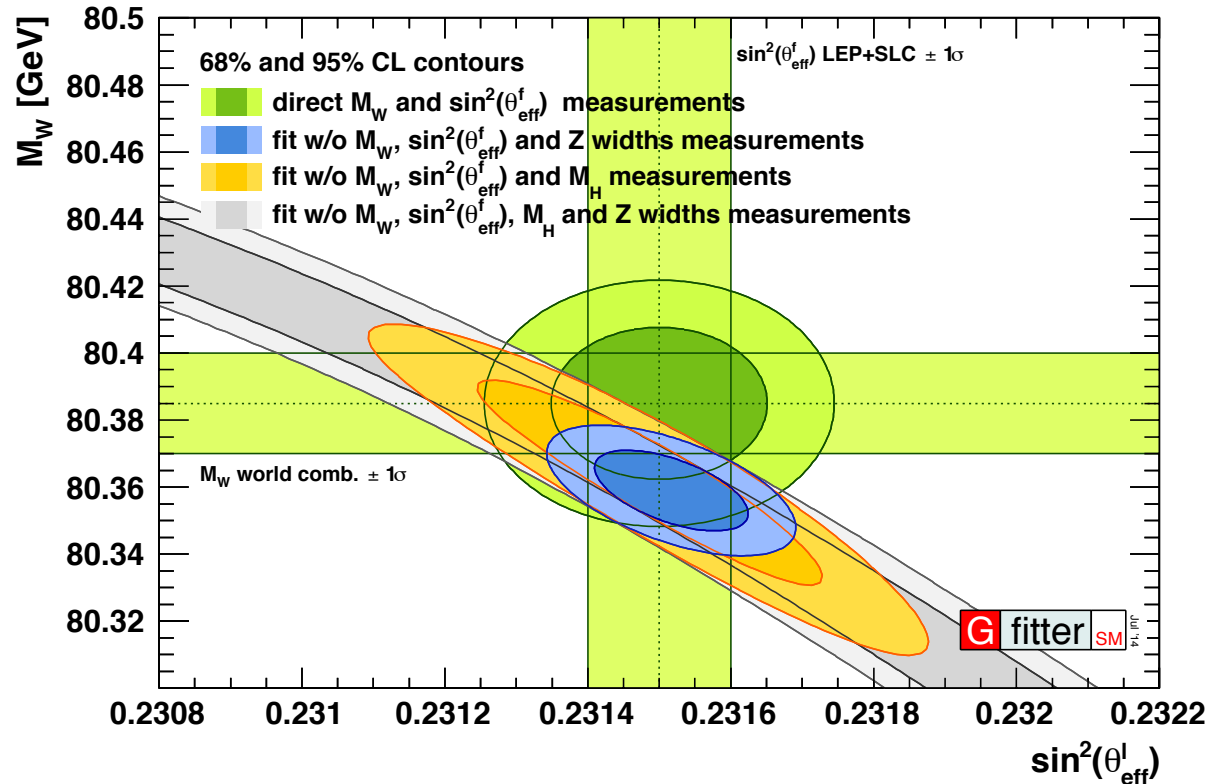


- Observed agreement demonstrates impressive consistency of the SM!

State of the SM: M_W mass versus $\sin^2\theta_{\text{eff}}^l$

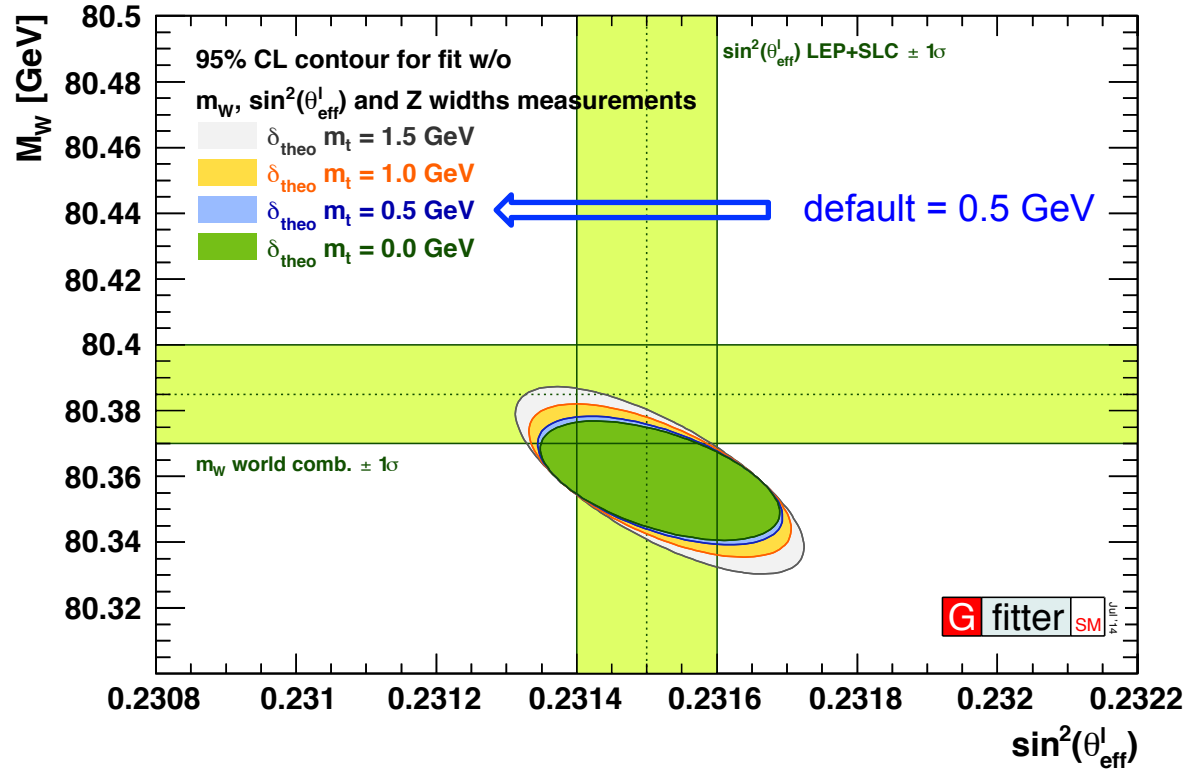


- Scan of M_W vs $\sin^2\theta_{\text{eff}}^l$, with direct measurements excluded from the fit.
- Again, significant reduction allowed indirect parameter space from Higgs mass measurement.



- M_W and $\sin^2\theta_{\text{eff}}^l$ have become *the* sensitive probes of new physics!
 - Reason: both are ‘tree-level’ SM predictions.

Theoretical uncertainty on m_{top}



See talk:
Hiroshi
Yokoya



- $\delta_{\text{theo}} m_t$: *unc. on conversion measured top mass to \overline{MS} -bar mass*
 - Sources: ambiguity top mass definition, fragmentation process, pole→ \overline{MS} conv.
 - Predictions for $\delta_{\text{theo}} m_t$: *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]
 - $\delta_{\text{theo}} m_t$ varied here between 0 and 1.5 GeV, in steps of 0.5 GeV.
- *Better assessment of $\delta_{\text{theo}} m_t$ of relevance for the EW fit.*

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

- Described with STU parametrization

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

- SM: $M_H = 125 \text{ GeV}$, $m_t = 173 \text{ GeV}$

- This defines $(S, T, U) = (0, 0, 0)$

- S , T depend logarithmically on M_H

- Fit result (with U floating):

$$S = 0.05 \pm 0.11$$

$$T = 0.09 \pm 0.13$$

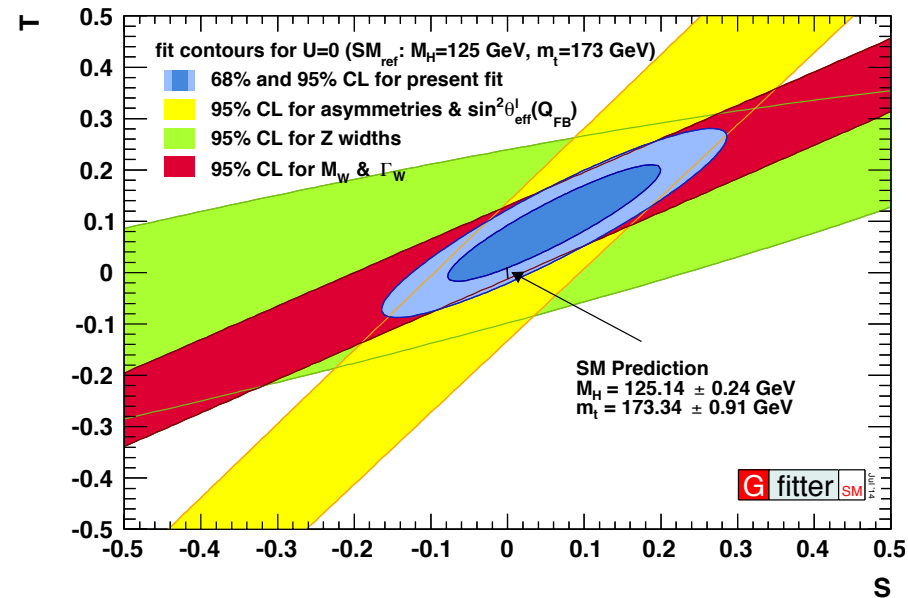
$$U = 0.01 \pm 0.11$$

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

- No indication for new physics.*

- Can now use this constrain 4th gen, Ex-Dim, T-C, *Higgs couplings*...

- Stronger constraints with $U=0$.



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

See talk:
Kiwoon
Choi

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.)*

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

- *WW threshold scan + kinematic reconstruction, to obtain M_W*
 - From threshold scan: $\delta M_W : 15 \rightarrow 5 \text{ MeV}$
- *t \bar{t} threshold scan, to obtain m_t*
 - Obtain m_t indirectly from production cross section: $\delta m_t : 0.8 \rightarrow 0.1 \text{ GeV}$
 - Dominated by conversion from threshold to $M_{S\bar{t}}$ 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 \rightarrow ZZ and H \rightarrow WW couplings: measured at 1% precision.*

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

LHC Phase-1 (300/fb)

- *W mass measurement* : $\delta M_W : 15 \rightarrow 8 \text{ MeV}$
- *Final top mass measurement* m_t : $\delta m_t : 0.8 \rightarrow 0.6 \text{ GeV}$
- *H \rightarrow ZZ and H \rightarrow WW couplings*: measured at 3% precision.

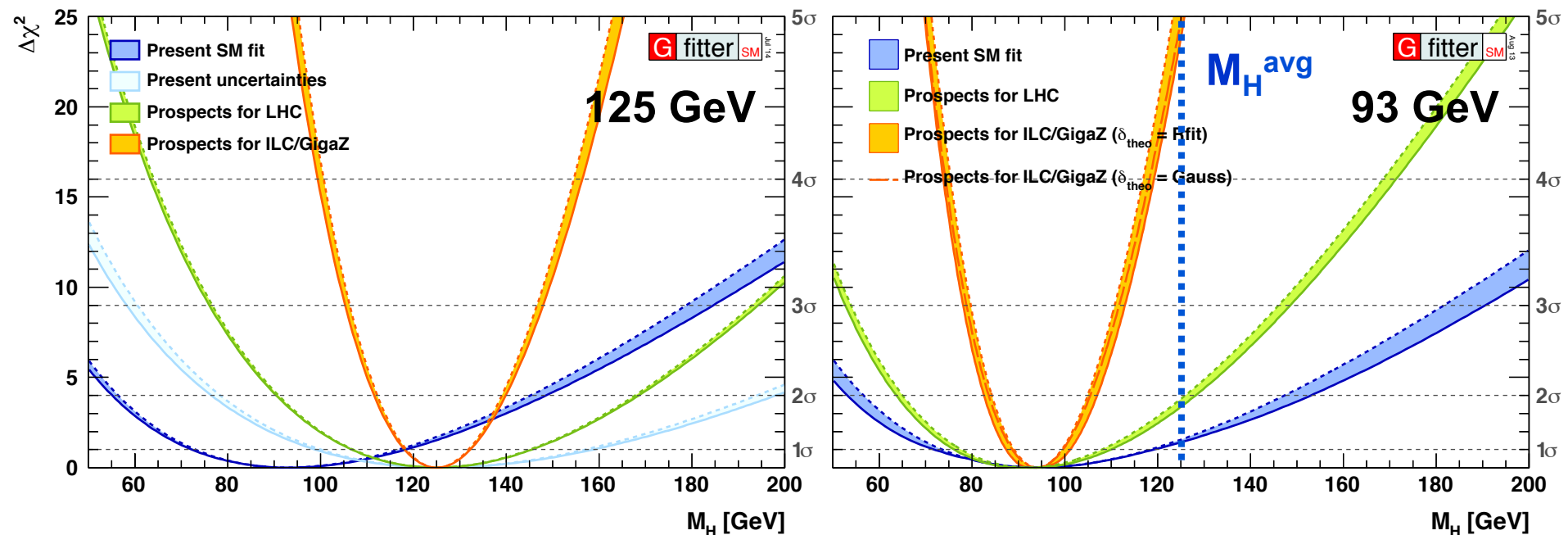
LHC prospects: possibly optimistic scenario, but not impossible.

LHC Phase-1 (300/fb)

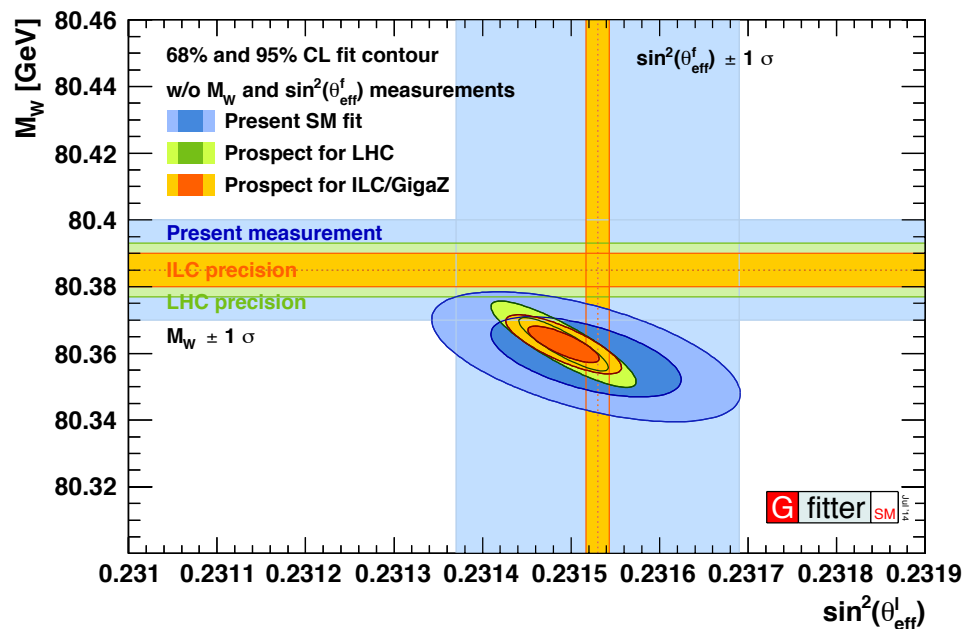
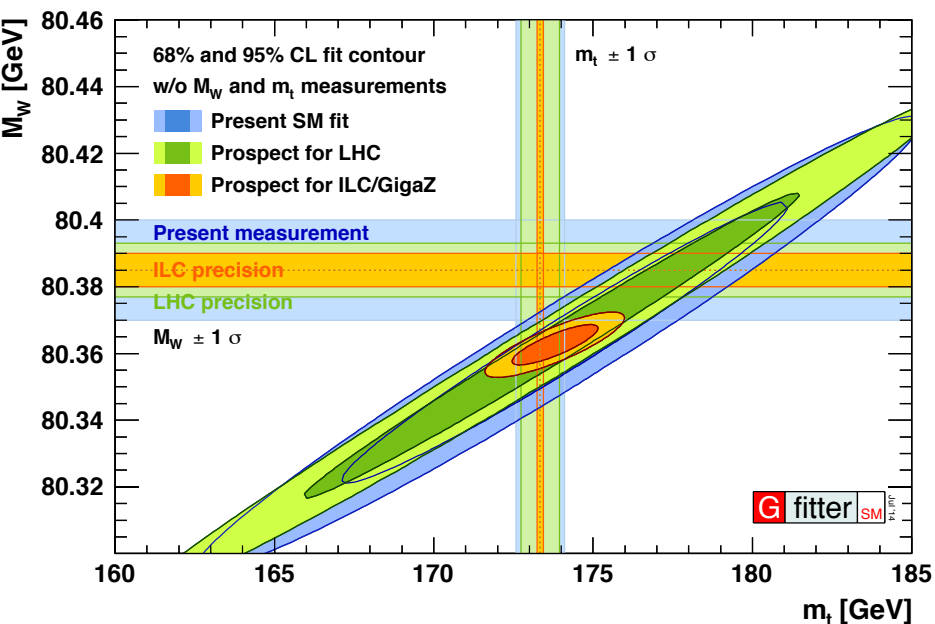
- *W mass measurement* : δM_W : 15 \rightarrow 8 MeV
- *Final top mass measurement* m_t : δm_t : 0.8 \rightarrow 0.6 GeV
- *H \rightarrow ZZ and H \rightarrow WW couplings*: measured at 3% precision.

For both LHC and ILC:

- Low-energy data results to improve $\Delta\alpha_{\text{had}}$:
 - 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 (from reliable Lattice predictions): $\Delta\alpha_{\text{had}}$: $10^{-4} \rightarrow 5 \cdot 10^{-5}$
- Assuming $\sim 25\%$ of today's theoretical uncertainties on M_W and $\sin^2\theta_{\text{eff}}^l$
 - *Implies ambitions three-loop electroweak calculations!*
 - δM_W (4 \rightarrow 1 MeV), $\delta \sin^2\theta_{\text{eff}}^l$ ($4.7 \times 10^{-5} \rightarrow 1 \times 10^{-5}$) (from Snowmass report)
 - Partial Z decay widths at 3-loop level: factor 4 improvement
 - LHC: top quark mass theo uncertainty: 0.50 \rightarrow 0.25 GeV



- Logarithmic dependency on $M_H \rightarrow$ cannot compete with direct M_H meas.
- 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
- If EWP-data central values unchanged, i.e. keep favoring low value of Higgs mass (93 GeV), $\sim 5\sigma$ discrepancy with measured Higgs mass.



- Huge reduction of uncertainty on indirect determinations of m_t , m_W , and $\sin^2\theta_{\text{eff}}^l$, 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.

Impact of individual uncertainties

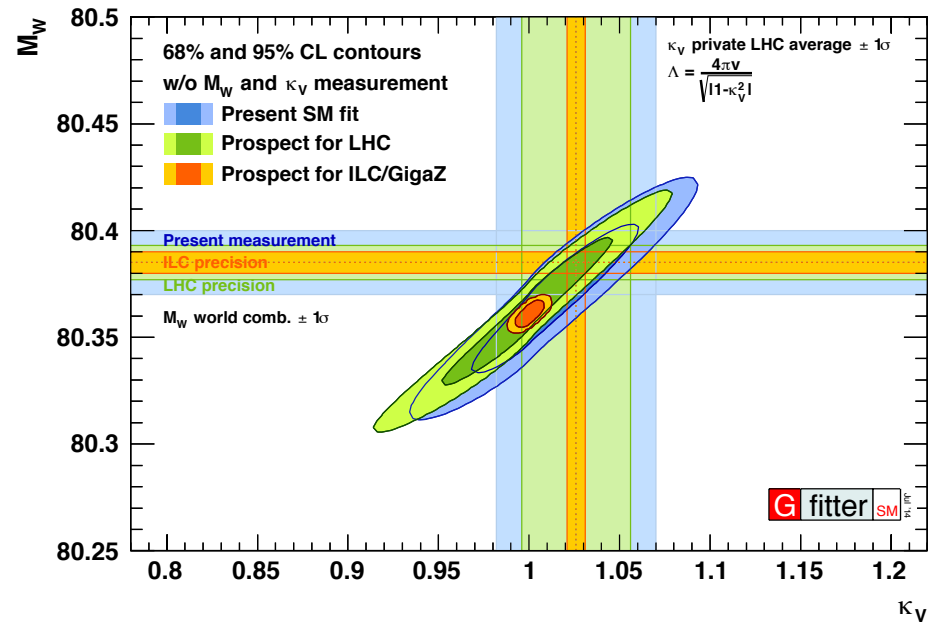
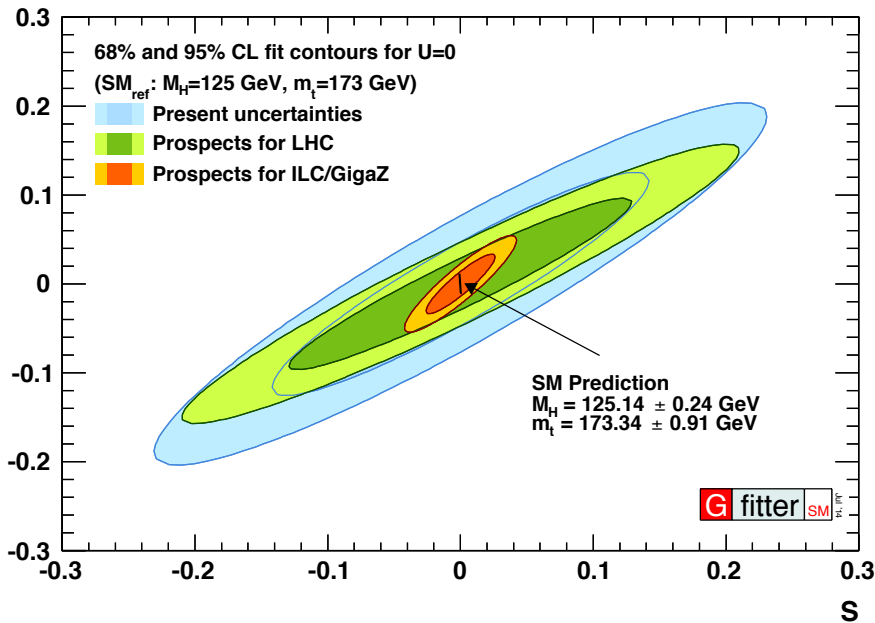


- Breakdown of individual contributions to errors of M_W and $\sin^2\theta_{\text{eff}}^l$

Parameter	δ_{meas}	$\delta_{\text{fit}}^{\text{tot}}$	$\delta_{\text{fit}}^{\text{theo}}$	$\delta_{\text{fit}}^{\text{exp}}$	Experimental uncertainty source [$\pm 1\sigma$]					
					δM_W	δM_Z	δm_t	$\delta \sin^2\theta_{\text{eff}}^f$	$\delta \Delta\alpha_{\text{had}}$	$\delta\alpha_S$
Present uncertainties										
M_W [MeV]	15	7.8	5.0	6.0	–	2.5	4.3	5.1	1.6	2.5
$\sin^2\theta_{\text{eff}}^l$ ($^{\circ}$)	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
$\sin^2\theta_{\text{eff}}^l$ ($^{\circ}$)	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
$\sin^2\theta_{\text{eff}}^l$ ($^{\circ}$)	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 $\sin^2\theta_{\text{eff}}^l$ are sensitive probes of new physics! For all scenarios.
- At ILC/GigaZ, precision of M_Z will become important again.



- 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%.)

Modified Higgs couplings

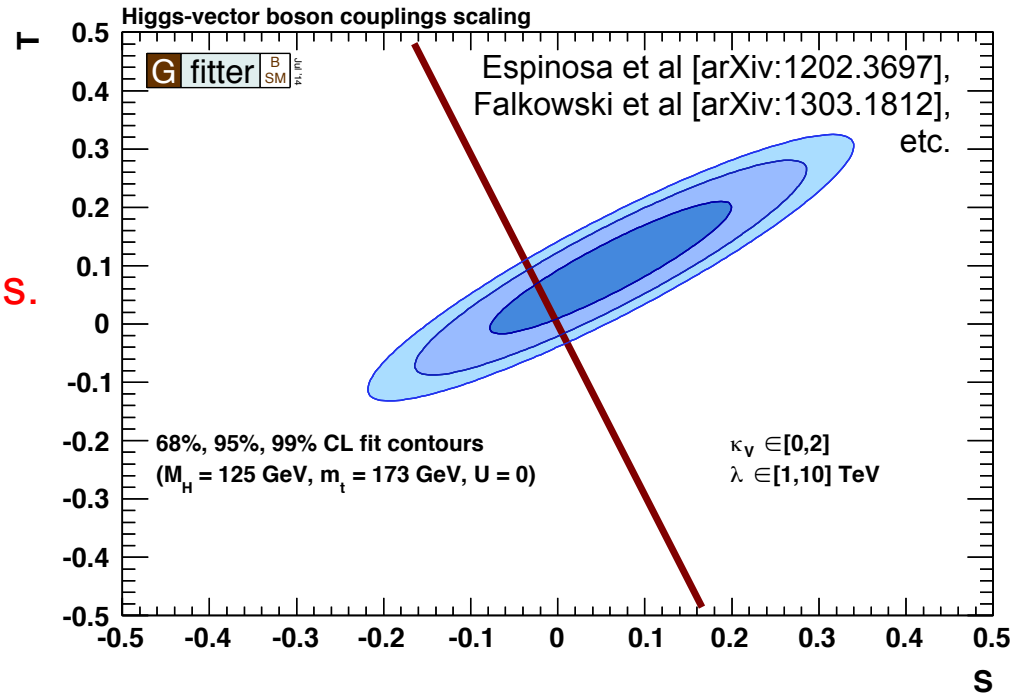
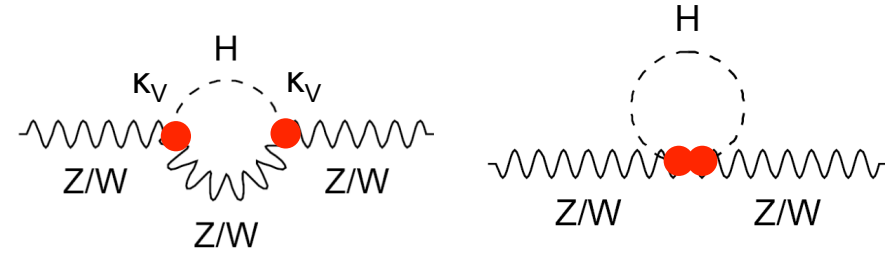
- Study of potential deviations of Higgs couplings from SM.
- BSM modeled as extension of SM through effective Lagrangian.
 - Consider leading corrections only.

- Model considered here:

- Scaling of Higgs-vector boson (κ_V) and Higgs-fermion couplings (κ_F), with no invisible/undetachable widths.
- (Custodial symmetry is assumed.)
- “*Kappa parametrization*”

- Main effect on EWPO due to modified Higgs coupling to gauge bosons (κ_V).

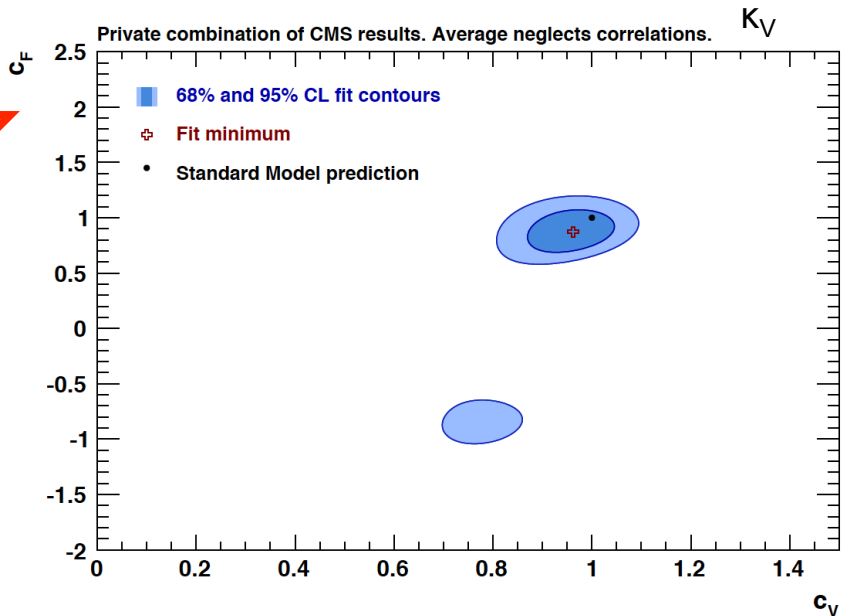
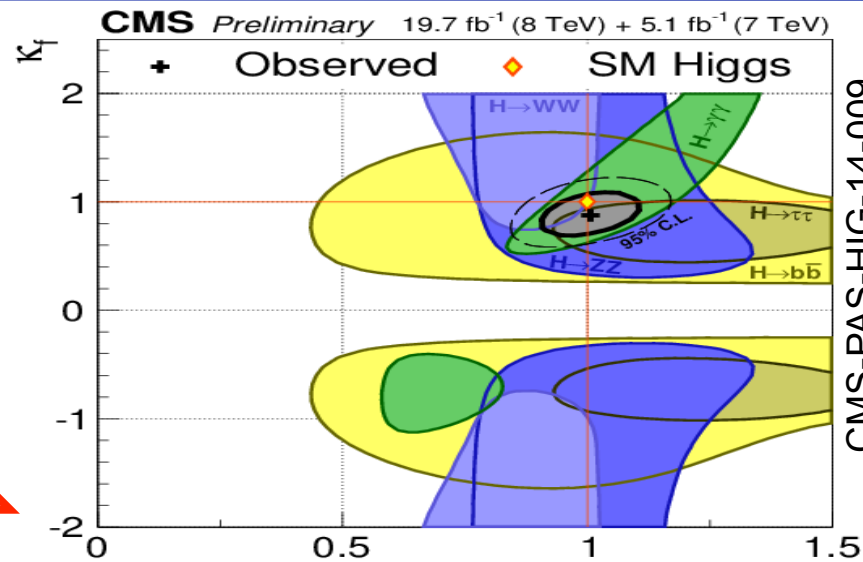
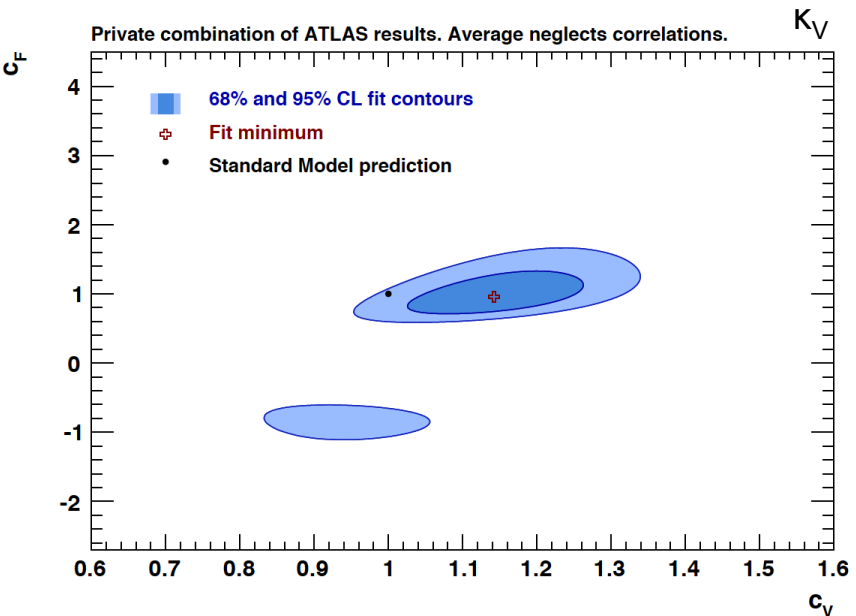
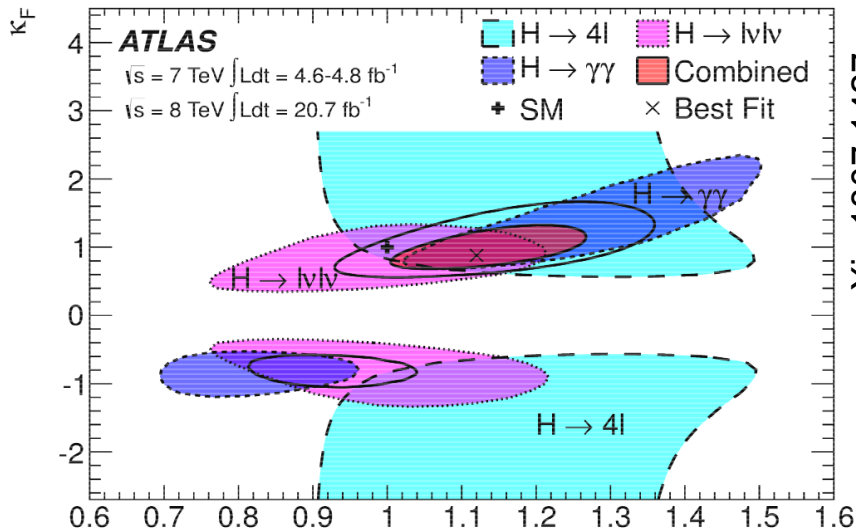
- Espinosa et al [arXiv:1202.3697], Falkowski et al [arXiv:1303.1812], etc.



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

Reproduction of ATLAS and CMS results

arXiv:1307.1427



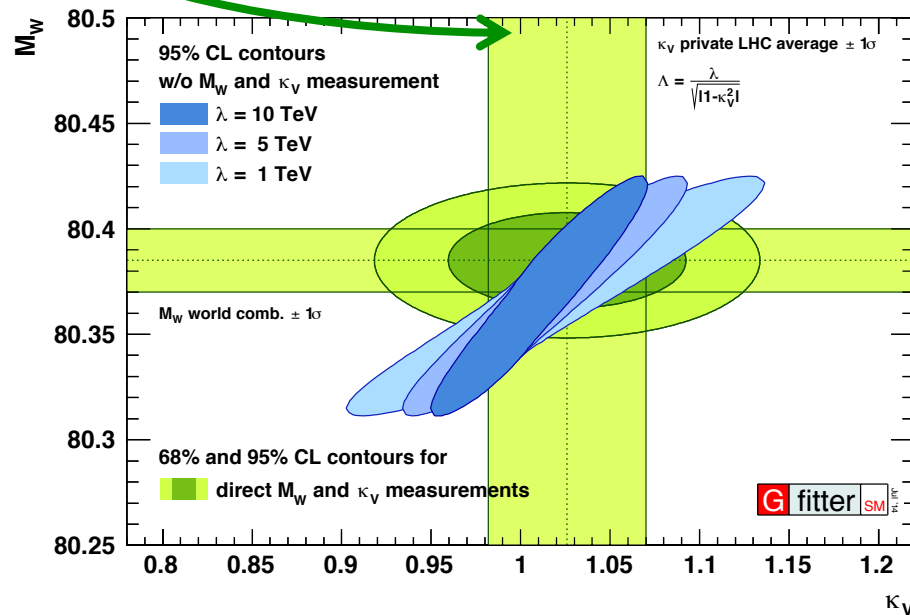
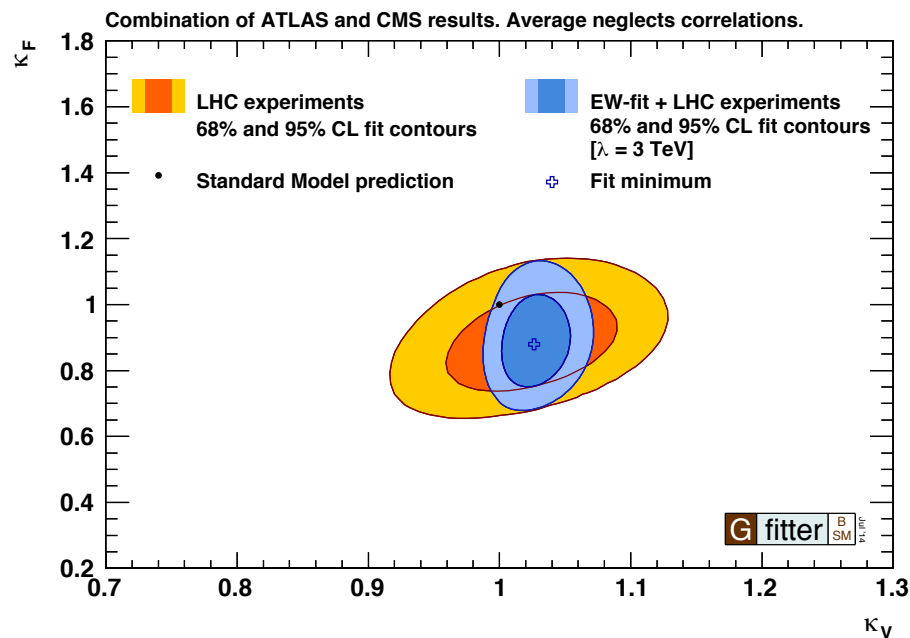
■ Approximate reproduction of ATLAS/CMS results within limited public-info available.

- Private LHC combination:

- $K_V = 1.026^{+0.043}_{-0.043}$
- $K_F = 0.88^{+0.10}_{-0.09}$

- Result from stand-alone EW fit:

- $\kappa_V = 1.03 \pm 0.02$ (using $\lambda=3$ 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].

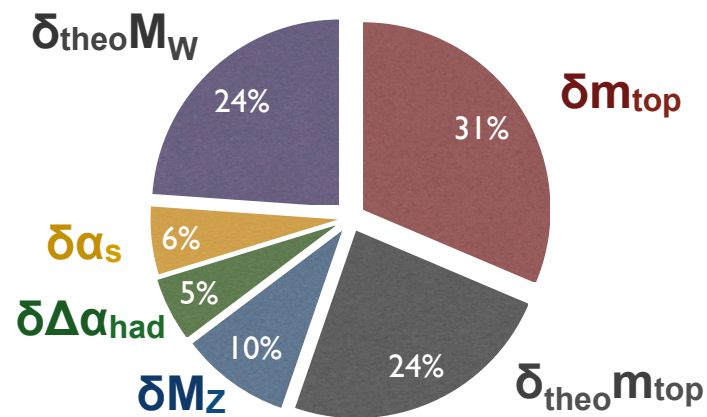
- EW fit sofar more precise result for κ_V than current LHC experiments.
- EW fit has positive deviation of κ_V from 1.0.
 - (Many BSM models: $\kappa_V < 1$)

- 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: N²LO calcs and theo. uncertainties for all relevant observables.
 - $\delta_{\text{theo}} m_t$ starting to become relevant.
- Knowledge of M_H dramatically improves SM prediction of key observables
 - M_W ($28 \rightarrow 11$ MeV), $\sin^2\theta_{\text{eff}}^l$ ($2.3 \times 10^{-5} \rightarrow 1.0 \times 10^{-5}$), m_t ($6.2 \rightarrow 2.5$ 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



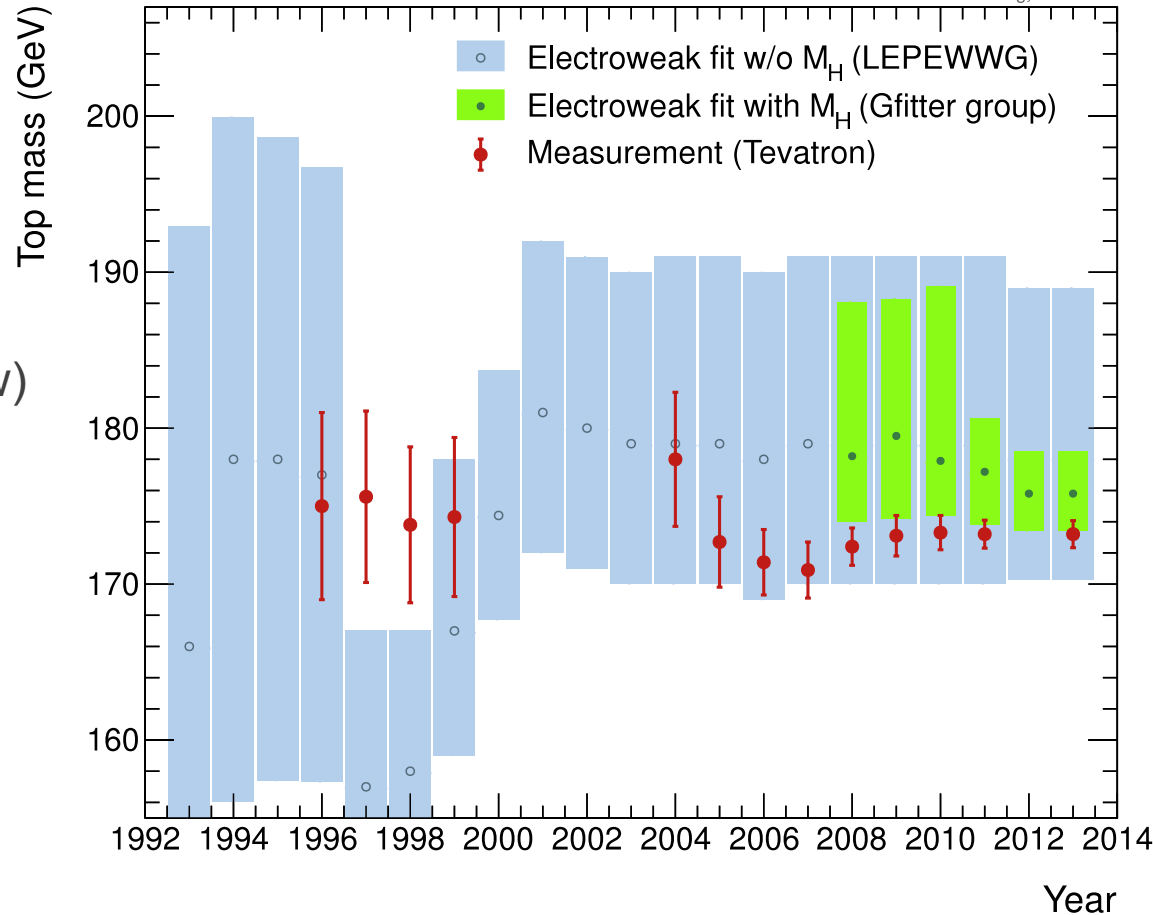
- δM_W (direct) = 15 MeV



- Including new data electroweak fits remain very interesting in the next years!
- Latest results always available at: <http://cern.ch/Gfitter>

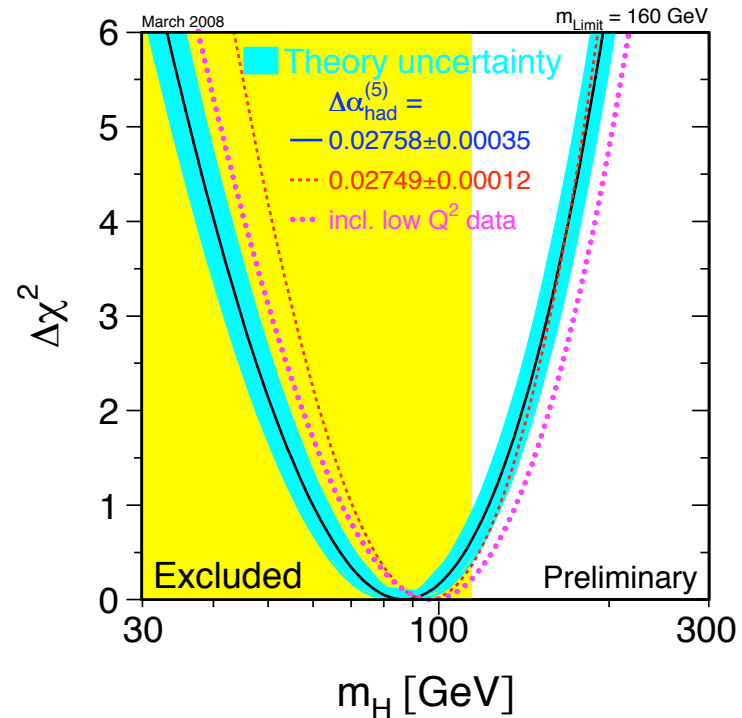
Thanks!

- 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!

- 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.)

- Uncertainty estimates used:

Parameter	Experimental input [$\pm 1\sigma_{\text{exp}}$]		
	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
$\sin^2\theta_{\text{eff}}^\ell$ [10^{-5}]	16	16	1.3
$\Delta\alpha_{\text{had}}^5(M_Z^2)$ [10^{-5}]	10	4.7	4.7
R_l^0 [10^{-3}]	25	25	4
$\alpha_S(M_Z^2)$ [10^{-4}]	–	–	–
$S _{U=0}$	–	–	–
$T _{U=0}$	–	–	–
κ_V ($\lambda = 3 \text{ TeV}$)	0.05	0.03	0.01

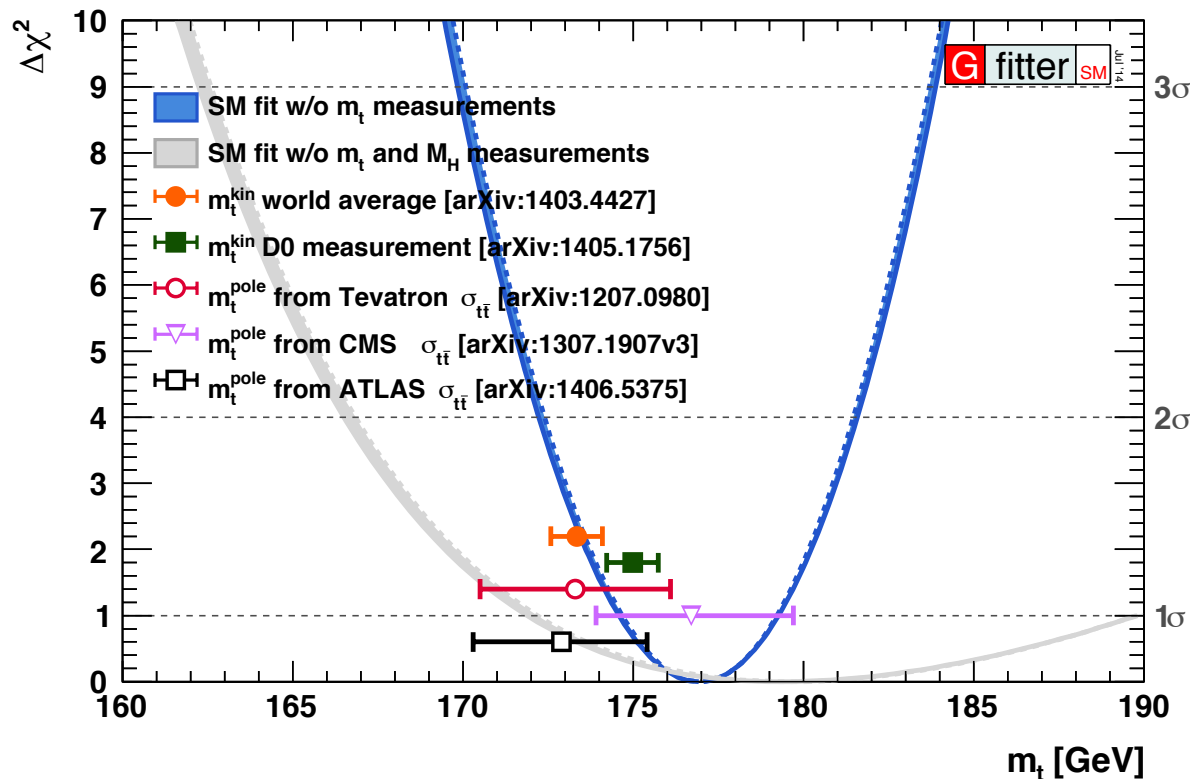
- ILC prospects from: ILC TDR (Vol-2).
- Theoretical uncertainty estimates from recent Snowmass report
- Central values of input measurements adjusted to $M_H = 126 \text{ GeV}$.

Summary of indirect predictions



Parameter	Experimental input [$\pm 1\sigma_{\text{exp}}$]			Indirect determination [$\pm 1\sigma_{\text{exp}}, \pm 1\sigma_{\text{theo}}$]		
	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
$\sin^2\theta_{\text{eff}}^{\ell}$ [10^{-5}]	16	16	1.3	4.5, 4.9	2.8, 1.1	2.0, 1.0
$\Delta\alpha_{\text{had}}^5(M_Z^2)$ [10^{-5}]	10	4.7	4.7	42, 13	36, 6	5.6, 3.0
R_l^0 [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 ($\lambda = 3\text{TeV}$)	0.05	0.03	0.01	0.02	0.02	0.01

- M_W and $\sin^2\theta_{\text{eff}}^{\ell}$ are (and will be) sensitive probes of new physics!



- 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