Electroweak global analysis

Impact of recent M_W and m_t measurements on precision fits of the Standard Model

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Based on work in collaboration with: J. de Blas, A. Goncalves, M. Pierini, L. Silvestrini, and members of the HEPfit collaboration.

arXiv:2112.07274, arXiv:2204.04204

See also A. Goncalves's talk at Pheno 2022 (9-11 May 2022)

The role of electroweak global fits

- The symmetry structure of the Standard Model defines specific relations among couplings and masses.

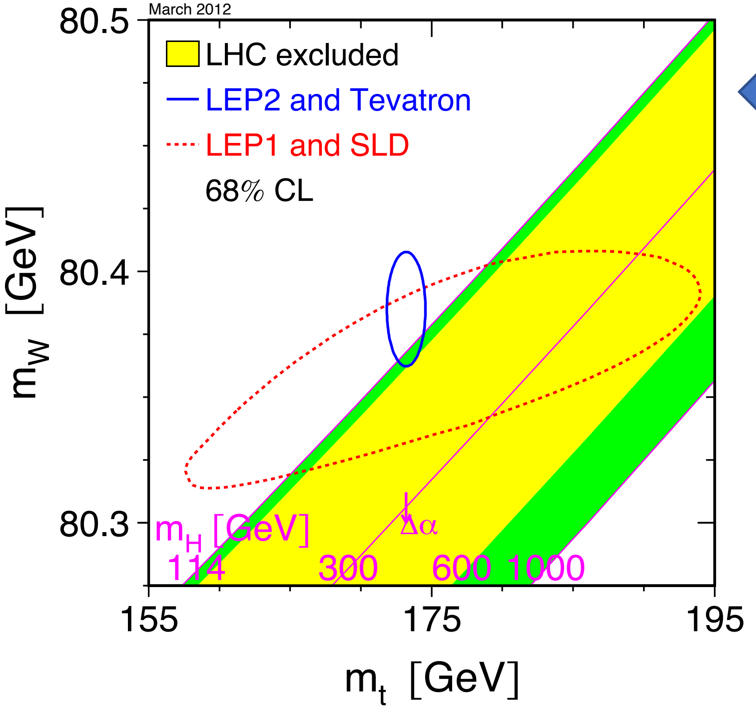
- The renormalizability of the theory assures that tree-level relations are modified by finite calculable corrections.

- **Precision measurements** of masses and couplings:
  - Test the consistency of the theory at the quantum level
  - Indirectly probe new physics via virtual effects

A comprehensive program of EW precision physics combined with emerging precision programs (top, Higgs) can be a very powerful tool to explore physics beyond the Standard Model

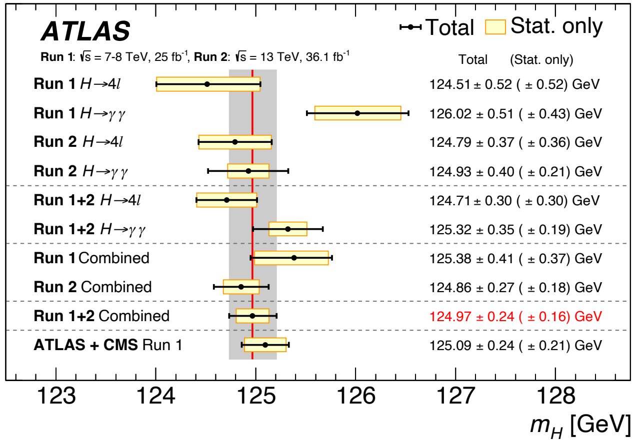
A very successful history

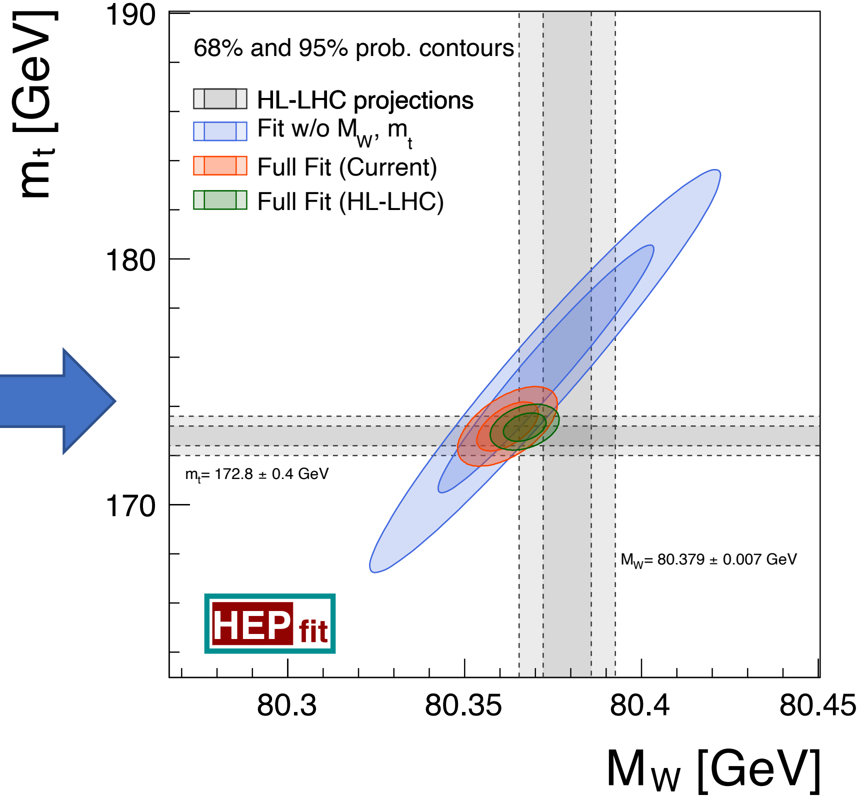
Global fits of precision EW observables gave us strong indications of where to find the SM Higgs boson and we now use its mass as one of the EW precision observables of the EW global fit to constrain new physics.



$$M_H = 94^{+29}_{-24}\ \mathrm{GeV}$$

$$M_H < 152\,(171)\ \mathrm{GeV}$$





EW Global fit: general framework

- Set of input parameters (α scheme):
  - Fixed: G_F, α
  - Floating: M_Z, M_H, m_t, $\alpha_s(M_Z)$, $\Delta\alpha_{had}^{(5)}$
- Compute EW Precision observables (EWPO), including all known higher-order SM corrections:
  - Z-pole observables (LEP/SLD): Γ_Z, $\sin^2\theta_{eff}$, A_l, A_{FB}, …
  - W observables (LEP II, Tevatron, LHC): M_W, Γ_W
  - m_t, M_H, $\sin^2\theta_{eff}$ (Tevatron/LHC)
- Perform best fit to EW precision data (EWPD) through different fitting procedures and compare with experimental measurements.
- Parametrize new physics effects on EWPO (tree-level) and constrain deviations in terms of chosen parameters:
  - Oblique parameters : S,T, U
  - Effective interactions: SMEFT
  - ….

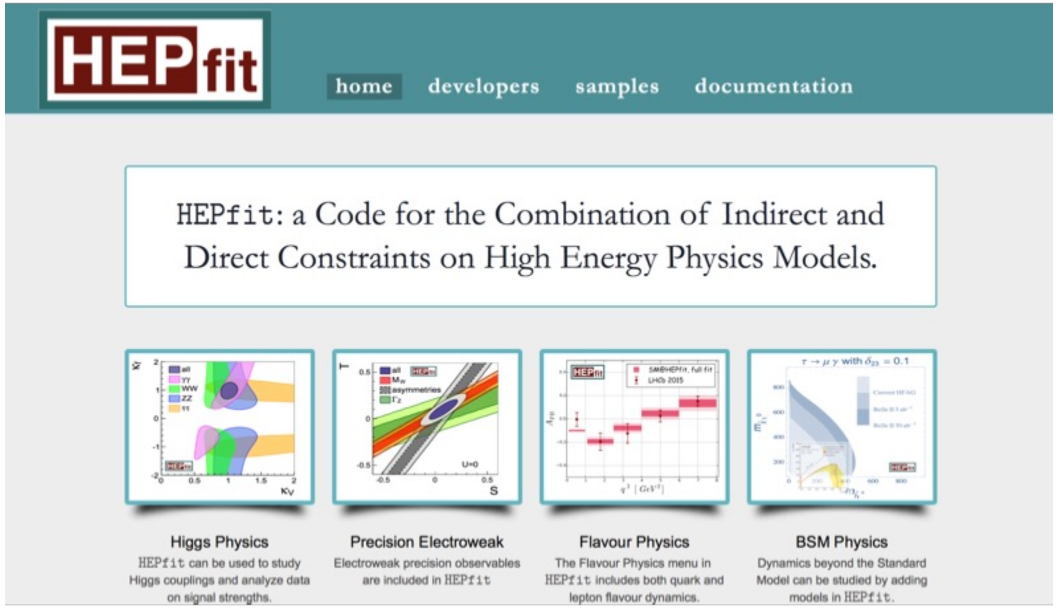
Framework we used

Open-source tool

Statistical framework based on a Bayesian MCMC analysis as implemented in
BAT (Bayesian Analysis Toolkit)
Caldwell et al., arXiv:0808.2552

Supports SM (fully implemented) and BSM models (some already implemented)

Includes EW, Higgs, flavor, top observables



http://hepfit.roma1.infn.it

For these papers/talk: fit limited to EW precision observables

arXiv:2112.07274 : De Blas et al., *Global analysis of electroweak data in the Standard Model* (update of arXiv:1608:01509)
arXiv:2204.04204 : De Blas et al., *Impact of recent measurements of the top-quark and W-boson mass on electroweak precision fits*

The second paper updates m_t and M_W and study the impact of the new measurements.

Experimental inputs

- Input parameters: α, G_F , $\alpha_s(M_Z)$, M_Z, M_H, m_t, $\Delta\alpha_{had}^{(5)}$
  (fixed: α, G_F)

- To get $\alpha(M_Z)$ ⟶ $\Delta\alpha_{had}^{(5)}$: from Lattice QCD + perturbative running
- **For m_t we combine**:
  - 2016 Tevatron combination
  - ATLAS Run 1 and Run2 results
  - CMS Run 1 and Run 2 results
  - Recent CMS l+j measurement [m_t=(171.77±0.38) GeV]

(before: first three items; after: all four items)

previous average
m_t=172.58 ±0.45 GeV

⟶

new average
m_t=171.79 ± 0.38 GeV
"standard"

new average
m_t=171.79 ±1.00 GeV
"conservative"

New CMS measurement dominates *"standard"* average but shows 3.5σ tension with respect to Tevatron average (m_t = 174.34 ± 0.64 GeV) ⟶ consider *"conservative"* scenario as well

Experimental inputs

- **For M_W we combine:**
  - All LEP 2 measurements
  - Previous Tevatron average
  - ATLAS and LHCb measurements
  - Recent CDF measurement [M_W=(80.4335±0.0094) GeV]

before (first three items) — after (all four items)

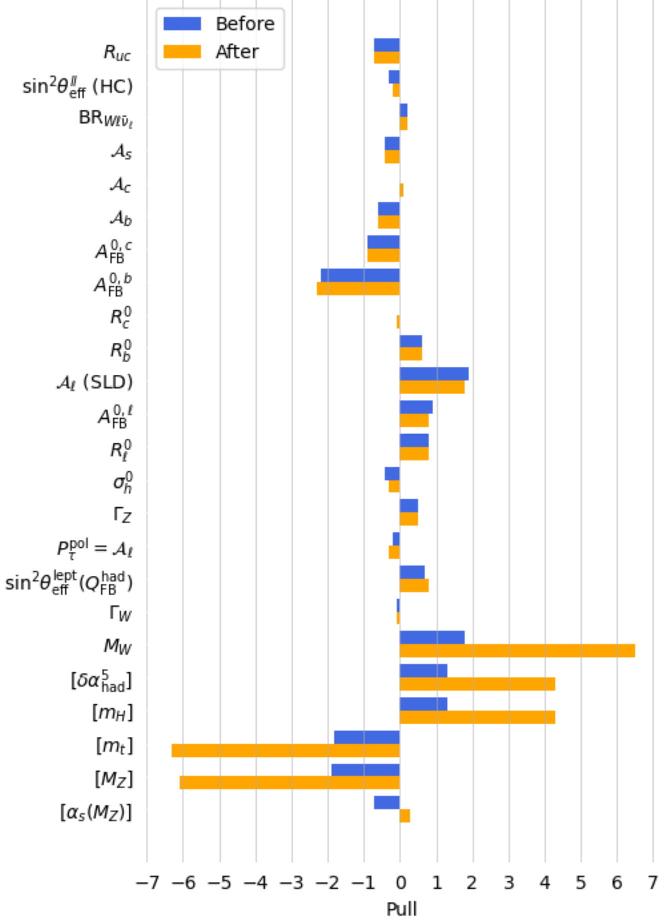
previous average: M_W = 80.379 ± 0.012 GeV ⟶ new average: M_W = 80.4133 ± 0.0088 GeV *"standard"* — new average: M_W = 80.4133 ± 0.015 GeV *"conservative"*

New CDF results dominates standard average but tensions between LEP 2, Tevatron, and LHC results ⟶ consider "conservative" scenario

From global SM fit, omitting the experimental information on MW (previous pull: 1.8 σ) ⟶

Model	Pred. M_W [GeV] *standard average*	Pull	Pred. M_W [GeV] *conservative average*	Pull
SM	80.3499 ± 0.0056	$6.5\,\sigma$	80.3505 ± 0.0077	$3.7\,\sigma$

Results of global fit



``standard'' scenario

	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11762 ± 0.00095 [0.11576, 0.11946]	0.11685 ± 0.00278 [0.11145, 0.12233]	0.3	0.12181 ± 0.00470 [0.1126, 0.1310]	−0.8	0.1177 ± 0.0010 [0.1157, 0.1197]	–
$\Delta\alpha_{\rm had}^{(5)}(M_Z)$	0.02766 ± 0.00010	0.027535 ± 0.000096 [0.027349, 0.027726]	0.026174 ± 0.000334 [0.025522, 0.026826]	4.3	0.028005 ± 0.000675 [0.02667, 0.02932]	−0.5	0.02766 ± 0.00010 [0.02746, 0.02786]	–
M_Z [GeV]	91.1875 ± 0.0021	91.1911 ± 0.0020 [91.1872, 91.1950]	91.2314 ± 0.0069 [91.2178, 91.2447]	−6.1	91.2108 ± 0.0390 [91.136, 91.288]	−0.6	91.1875 ± 0.0021 [91.1834, 91.1916]	–
m_t [GeV]	171.79 ± 0.38	172.36 ± 0.37 [171.64, 173.09]	181.45 ± 1.49 [178.53, 184.42]	−6.3	187.58 ± 9.52 [169.1, 206.1]	−1.7	171.80 ± 0.38 [171.05, 172.54]	–
m_H [GeV]	125.21 ± 0.12	125.20 ± 0.12 [124.97, 125.44]	93.36 ± 4.99 [82.92, 102.89]	4.3	247.98 ± 125.35 [100.8, 640.4]	−0.9	125.21 ± 0.12 [124.97, 125.45]	–
M_W [GeV]	80.4133 ± 0.0080	80.3706 ± 0.0045 [80.3617, 80.3794]	80.3499 ± 0.0056 [80.3391, 80.3610]	6.5	80.4129 ± 0.0080 [80.3973, 80.4284]	0.1	80.3496 ± 0.0057 [80.3386, 80.3608]	6.5
Γ_W [GeV]	2.085 ± 0.042	2.08903 ± 0.00053 [2.08800, 2.09006]	[illegible]	[illegible]	2.09430 ± 0.00224 [2.0900, 2.0988]	−0.2	2.08744 ± 0.00059 [illegible]	0.0
$\sin^2\theta_{\rm eff}^{\rm lept}$ ([illegible]	[illegible]	0.231471 ± 0.000055 [0.231362, 0.231580]	[illegible]	[illegible]	0.231460 ± 0.000138 [0.23119, 0.23173]	0.8	[illegible]	[illegible]
$P_\tau^{\rm pol} = \mathcal{A}$[illegible]	[illegible]	0.14742 ± 0.00044 [0.14656, 0.14827]	[illegible]	[illegible]	0.14750 ± 0.00108 [0.1454, 0.1496]	−0.3	[illegible]	[illegible]
Γ_Z [GeV]	[illegible]	2.49455 ± 0.00065 [2.49329, 2.49581]	[illegible]	[illegible]	2.49530 ± 0.00204 [2.4912, 2.4993]	0.0	[illegible] [2.49262, 2.49531]	[illegible]
σ_h^0 [nb]	41.480 ± 0.033	41.4892 ± 0.0077 [41.4741, 41.5041]	[illegible] [41.4757, 41.5070]	[illegible]	[illegible]	[illegible]	[illegible]	−0.4
R_ℓ^0	20.767 ± 0.025	20.7487 ± 0.0080 [illegible]	20.7451 ± 0.0087 [20.7281, 20.7621]	0.8	[illegible]	[illegible]	[illegible]	0.7
$A_{FB}^{0,\ell}$	0.0171 ± 0.0010	[illegible]	0.016291 ± 0.000096 [0.016102, 0.016480]	0.8	[illegible]	[illegible]	[illegible]	1.0
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	[illegible]	0.14745 ± 0.00045 [0.14656, 0.14834]	1.8	[illegible]	[illegible]	[illegible]	2.1
R_b^0	0.21629 ± 0.00066	0.215892 ± 0.000100 [0.215696, 0.216089]	0.215886 ± 0.000102 [0.215688, 0.216086]	0.6	[illegible] [0.21469, 0.21611]	[illegible]	[illegible] [0.21571, 0.21611]	0.6
R_c^0	0.1721 ± 0.0030	0.172198 ± 0.000054 [0.172093, 0.172302]	0.172197 ± 0.000054 [0.172094, 0.172303]	−0.1	0.172404 ± 0.000183 [0.17206, 0.17278]	−0.1	0.172189 ± 0.000054 [0.172084, 0.172295]	−0.1
$A_{FB}^{0,b}$	0.0996 ± 0.0016	0.10335 ± 0.00030 [0.10276, 0.10396]	0.10337 ± 0.00032 [0.10275, 0.10400]	−2.3	0.10338 ± 0.00077 [0.10189, 0.10490]	−2.1	0.10288 ± 0.00034 [0.10220, 0.10354]	−2.0
$A_{FB}^{0,c}$	0.0707 ± 0.0035	0.07385 ± 0.00023 [0.07341, 0.07430]	0.07387 ± 0.00023 [0.07341, 0.07434]	−0.9	0.07392 ± 0.00059 [0.07275, 0.07507]	−0.9	0.07348 ± 0.00025 [0.07298, 0.07398]	−0.8
$\mathcal{A}_b$	0.923 ± 0.020	0.934770 ± 0.000039 [0.934693, 0.934847]	0.934772 ± 0.000040 [0.934693, 0.934849]	−0.6	0.934593 ± 0.000166 [0.93426, 0.93491]	−0.6	0.934721 ± 0.000041 [0.934642, 0.934801]	−0.6
$\mathcal{A}_c$	0.670 ± 0.027	0.66796 ± 0.00021 [0.66754, 0.66838]	0.66797 ± 0.00021 [0.66755, 0.66839]	0.1	0.66817 ± 0.00054 [0.66712, 0.66922]	0.1	0.66766 ± 0.00022 [0.66722, 0.66810]	0.1
$\mathcal{A}_s$	0.895 ± 0.091	0.935678 ± 0.000039 [0.935600, 0.935755]	0.935677 ± 0.000040 [0.935599, 0.935754]	−0.4	0.935716 ± 0.000098 [0.935523, 0.935909]	−0.5	0.935621 ± 0.000041 [0.935541, 0.935702]	−0.5
$BR_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108388 ± 0.000022 [0.108345, 0.108431]	0.108388 ± 0.000022 [0.108345, 0.108431]	0.2	0.108291 ± 0.000109 [0.10808, 0.10851]	0.3	0.108386 ± 0.000023 [0.108340, 0.108432]	0.2
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025	0.231471 ± 0.000055 [0.231362, 0.231580]	0.231474 ± 0.000056 [0.231363, 0.231584]	−0.2	0.231460 ± 0.000138 [0.23119, 0.23173]	−0.1	0.231558 ± 0.000062 [0.231436, 0.231679]	−0.5
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000031 [0.172159, 0.172282]	0.172220 ± 0.000032 [0.172159, 0.172282]	−0.7	0.172424 ± 0.000180 [0.17209, 0.17279]	−0.7	0.172212 ± 0.000032 [0.172149, 0.172275]	−0.7

Experimental values used as inputs

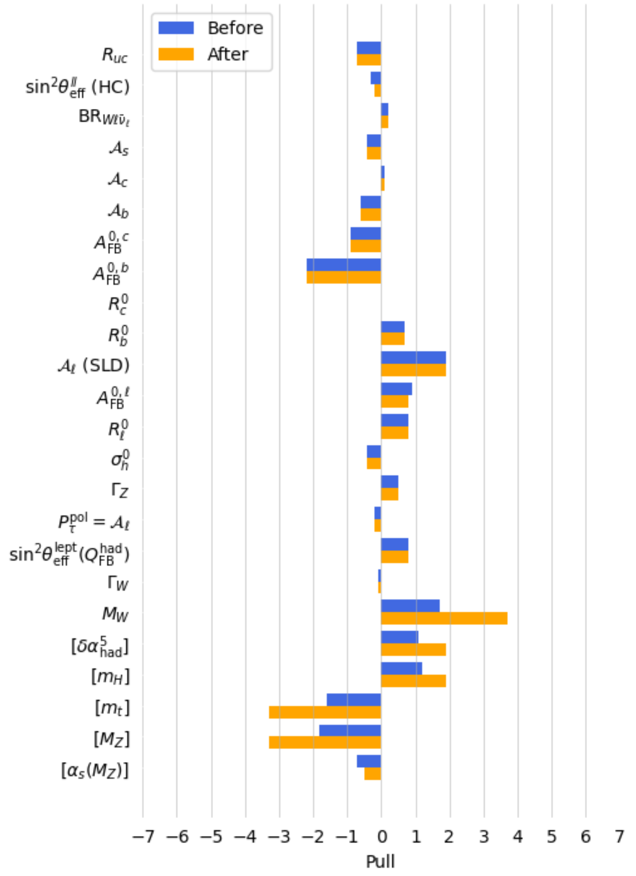
Results of the global fit

Result of the fit not using the corresponding measurement

Result of the fit not using any measurements of SM parameters

Predictions using measurements of SM parameters

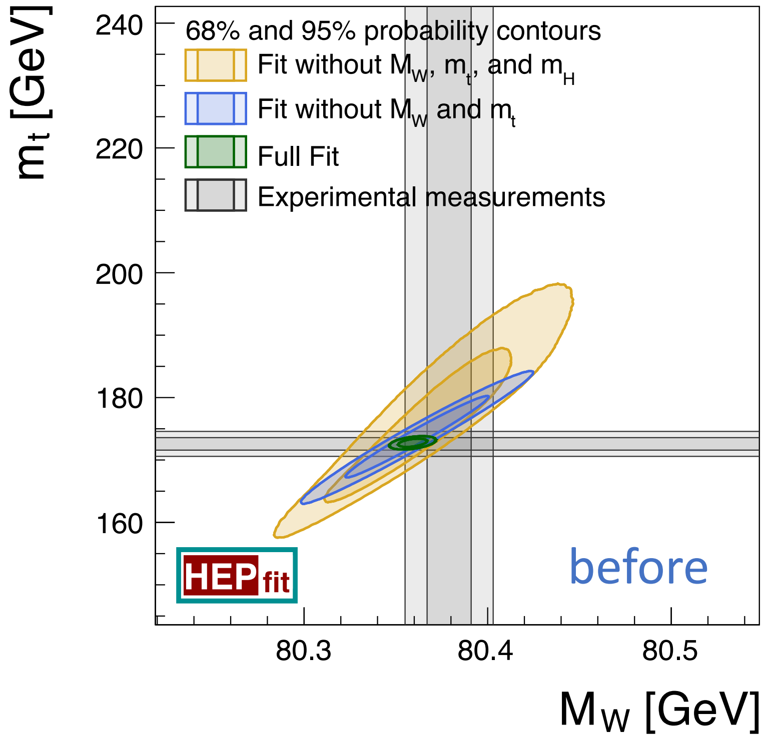
Results of global fit



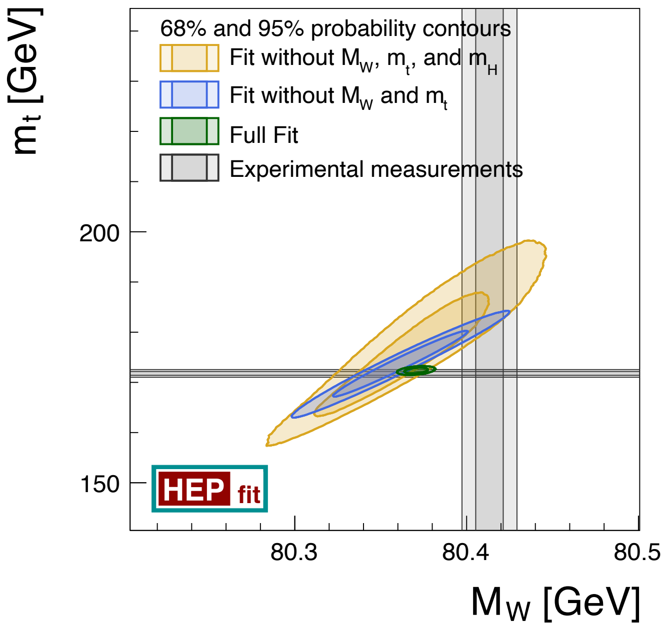
“conservative” scenario

	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11786 ± 0.00095 $[0.11603, 0.11972]$	0.11930 ± 0.00281 $[0.11371, 0.12482]$	-0.5	0.12174 ± 0.00473 $[0.1126, 0.1311]$	-0.8	0.1177 ± 0.0010 $[0.1157, 0.1197]$	–
$\Delta\alpha_{\rm had}^{(5)}(M_Z)$	0.02766 ± 0.00010	0.027614 ± 0.000097 $[0.027422, 0.027804]$	0.026895 ± 0.000394 $[0.026123, 0.027677]$	1.9	0.027987 ± 0.000699 $[0.02661, 0.02935]$	-0.5	0.02766 ± 0.00010 $[0.02747, 0.02786]$	–
M_Z [GeV]	91.1875 ± 0.0021	91.1887 ± 0.0021 $[91.1847, 91.1927]$	91.2227 ± 0.0105 $[91.2024, 91.2434]$	-3.3	91.2111 ± 0.0390 $[91.135, 91.289]$	-0.6	91.1875 ± 0.0021 $[91.1834, 91.1916]$	–
m_t [GeV]	171.8 ± 1.0	173.12 ± 0.92 $[171.30, 174.92]$	180.10 ± 2.25 $[175.66, 184.55]$	-3.3	187.16 ± 9.83 $[167.9, 206.4]$	-1.6	171.8 ± 1.0 $[169.8, 173.8]$	–
m_H [GeV]	125.21 ± 0.12	125.21 ± 0.12 $[124.97, 125.45]$	102.19 ± 9.79 $[87.01, 127.30]$	1.9	245.25 ± 125.35 $[98.1, 640.4]$	-0.9	125.21 ± 0.12 $[124.97, 125.45]$	–
M_W [GeV]	80.413 ± 0.015	80.3634 ± 0.0068 $[80.3500, 80.3769]$	80.3505 ± 0.0077 $[80.3355, 80.3655]$	3.7	80.4116 ± 0.0146 $[80.383, 80.440]$	0.0	80.3497 ± 0.0079 $[80.3342, 80.3653]$	3.7
Γ_W [GeV]	2.085 ± 0.042	2.08859 ± 0.00066 $[2.08731, 2.08988]$	2.08859 ± 0.00066 $[2.08732, 2.08988]$	-0.1	2.09426 ± 0.00245 $[2.0894, 2.0990]$	-0.2	2.08743 ± 0.00073 $[2.08601, 2.08889]$	0.0
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.231491 ± 0.000059 $[0.231376, 0.231608]$	0.231490 ± 0.000059 $[0.231374, 0.231607]$	0.8	0.231461 ± 0.000136 $[0.23119, 0.23173]$	0.8	0.231558 ± 0.000068 $[0.231426, 0.231691]$	0.7
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14725 ± 0.00046 $[0.14634, 0.14817]$	0.14727 ± 0.00047 $[0.14635, 0.14820]$	-0.2	0.14750 ± 0.00108 $[0.1454, 0.1496]$	-0.3	0.14674 ± 0.00053 $[0.14570, 0.14779]$	-0.1
Γ_Z [GeV]	2.4955 ± 0.0023	2.49453 ± 0.00066 $[2.49324, 2.49584]$	2.49434 ± 0.00070 $[2.49295, 2.49572]$	0.5	2.49528 ± 0.00205 $[2.4912, 2.4993]$	0.1	2.49396 ± 0.00072 $[2.49257, 2.49538]$	0.6
σ_h^0 [nb]	41.480 ± 0.033	41.4908 ± 0.0077 $[41.4757, 41.5059]$	41.4929 ± 0.0080 $[41.4772, 41.5087]$	-0.4	41.4616 ± 0.0304 $[41.402, 41.522]$	0.4	41.4924 ± 0.0080 $[41.4767, 41.5083]$	-0.4
R_ℓ^0	20.767 ± 0.025	20.7491 ± 0.0080 $[20.7333, 20.7649]$	20.7458 ± 0.0086 $[20.7287, 20.7627]$	0.8	20.7589 ± 0.0218 $[20.716, 20.802]$	0.2	20.7470 ± 0.0087 $[20.7297, 20.7638]$	0.8
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.01626 ± 0.00010 $[0.01606, 0.01647]$	0.01625 ± 0.00010 $[0.01605, 0.01646]$	0.8	0.01631 ± 0.00024 $[0.01585, 0.01679]$	0.8	0.01615 ± 0.00012 $[0.01592, 0.01638]$	1.0
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14725 ± 0.00046 $[0.14634, 0.14817]$	0.14728 ± 0.00049 $[0.14632, 0.14824]$	1.9	0.14750 ± 0.00108 $[0.1454, 0.1496]$	1.6	0.14674 ± 0.00053 $[0.14570, 0.14779]$	2.1
R_b^0	0.21629 ± 0.00066	0.21587 ± 0.00010 $[0.21566, 0.21607]$	0.21586 ± 0.00011 $[0.21565, 0.21607]$	0.7	0.21542 ± 0.00037 $[0.21467, 0.21613]$	1.2	0.21591 ± 0.00011 $[0.21570, 0.21611]$	0.6
R_c^0	0.1721 ± 0.0030	0.172210 ± 0.000054 $[0.172102, 0.172316]$	0.172210 ± 0.000054 $[0.172103, 0.172317]$	0.0	0.172400 ± 0.000185 $[0.17205, 0.17277]$	-0.1	0.172190 ± 0.000055 $[0.172082, 0.172297]$	-0.1
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016	0.10324 ± 0.00033 $[0.10259, 0.10388]$	0.10325 ± 0.00035 $[0.10258, 0.10393]$	-2.2	0.10338 ± 0.00076 $[0.10188, 0.10489]$	-2.1	0.10287 ± 0.00037 $[0.10214, 0.10361]$	-2.0
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07377 ± 0.00024 $[0.07328, 0.07425]$	0.07377 ± 0.00026 $[0.07327, 0.07428]$	-0.9	0.07391 ± 0.00059 $[0.07275, 0.07507]$	-0.9	0.07348 ± 0.00028 $[0.07293, 0.07403]$	-0.8
$\mathcal{A}_b$	0.923 ± 0.020	0.934746 ± 0.000040 $[0.934668, 0.934825]$	0.934746 ± 0.000040 $[0.934668, 0.934826]$	-0.6	0.934594 ± 0.000169 $[0.93426, 0.93492]$	-0.6	0.934721 ± 0.000041 $[0.934640, 0.934802]$	-0.6
$\mathcal{A}_c$	0.670 ± 0.027	0.66789 ± 0.00023 $[0.66743, 0.66834]$	0.66789 ± 0.00023 $[0.66743, 0.66835]$	0.1	0.66816 ± 0.00054 $[0.66712, 0.66922]$	0.1	0.66766 ± 0.00024 $[0.66718, 0.66814]$	0.1
$\mathcal{A}_s$	0.895 ± 0.091	0.935663 ± 0.000043 $[0.935580, 0.935746]$	0.935663 ± 0.000043 $[0.935580, 0.935746]$	-0.4	0.935714 ± 0.000099 $[0.935522, 0.935909]$	-0.5	0.935622 ± 0.000045 $[0.935533, 0.935709]$	-0.5
$\mathrm{BR}_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108382 ± 0.000022 $[0.108339, 0.108425]$	0.108382 ± 0.000022 $[0.108339, 0.108425]$	0.2	0.108293 ± 0.000110 $[0.10808, 0.10851]$	0.3	0.108386 ± 0.000023 $[0.108340, 0.108432]$	0.2
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025	0.231491 ± 0.000059 $[0.231376, 0.231608]$	0.231496 ± 0.000061 $[0.231376, 0.231616]$	-0.2	0.231461 ± 0.000136 $[0.23119, 0.23173]$	-0.1	0.231558 ± 0.000068 $[0.231426, 0.231691]$	-0.5
R_{uc}	0.1660 ± 0.0090	0.172231 ± 0.000033 $[0.172167, 0.172295]$	0.172231 ± 0.000033 $[0.172168, 0.172296]$	-0.7	0.172424 ± 0.000180 $[0.17208, 0.17279]$	-0.7	0.172211 ± 0.000034 $[0.172145, 0.172277]$	-0.7

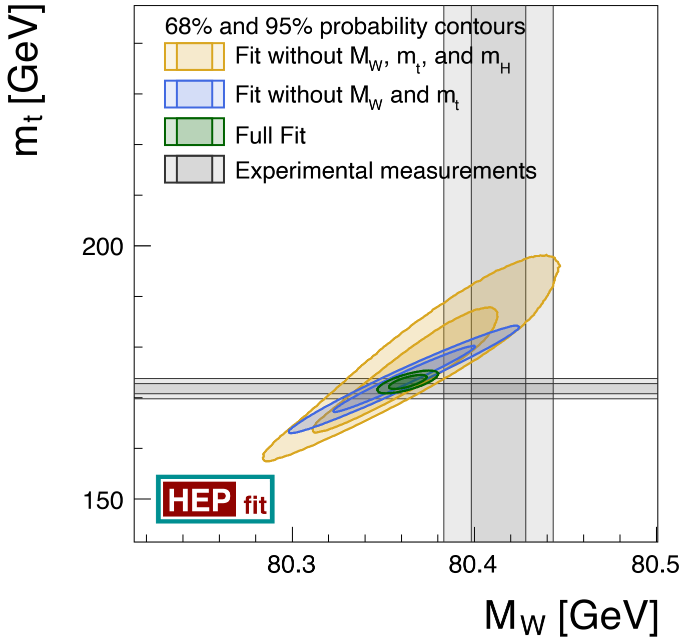
Interplay between m_t and M_W



Custodial SU(2) violated by Yukawa interactions
$\rho = M_W^2 / M_Z^2 c_W^2 = 1$ tree-level prediction
modified by loop corrections $\propto G_F m_t^2$.

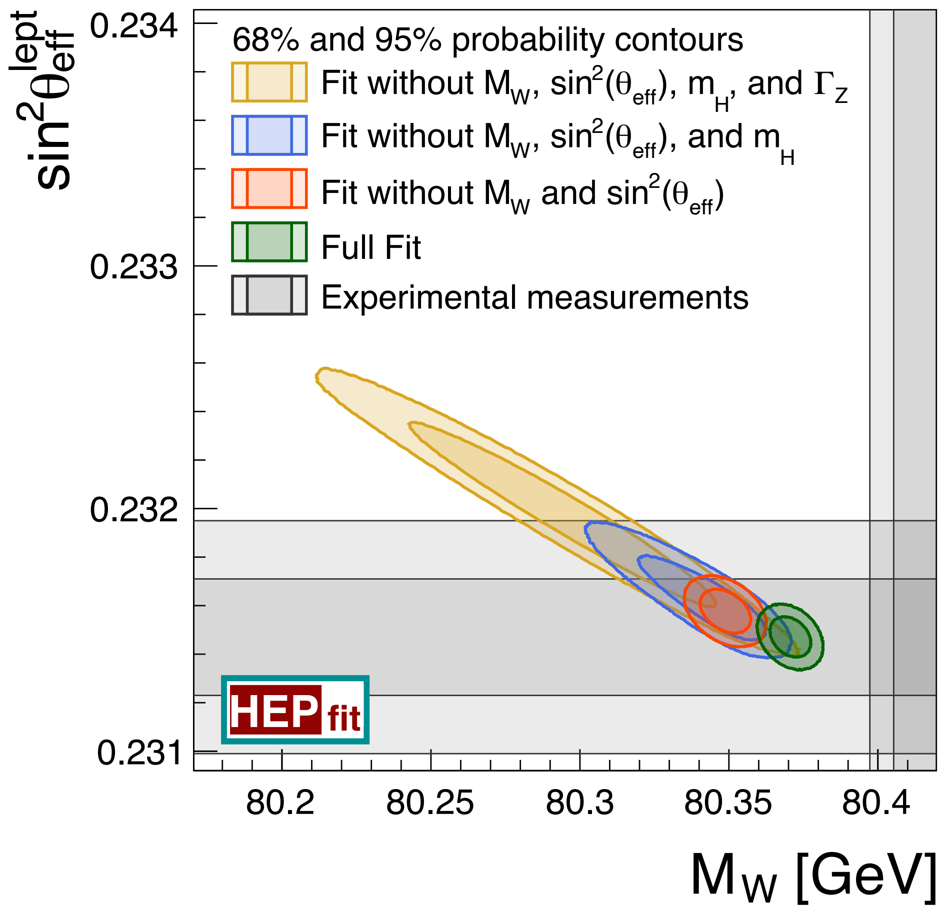


after
“standard”

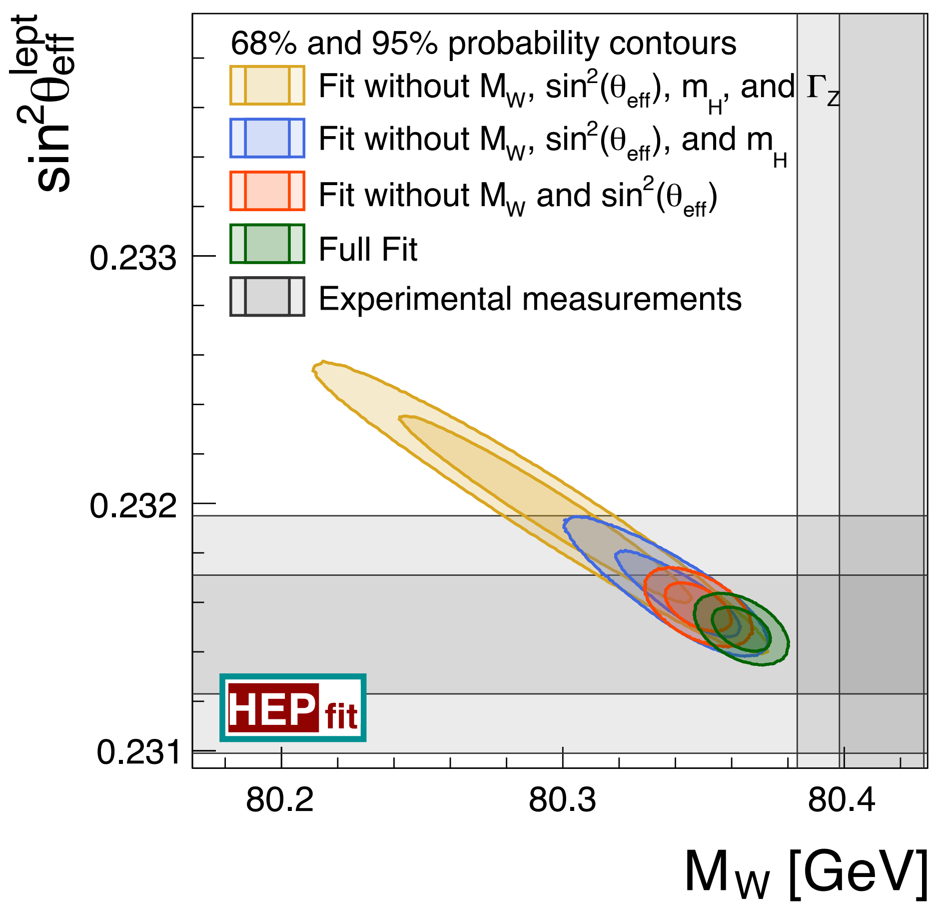


after
“conservative”

Interplay between M_W and $\sin^2\theta_{eff}$



"standard" scenario



"conservative" scenario

Theory and parametric errors

Theory intrinsic uncertainties on input parameters

$\delta_{th}M_W$ = 4 MeV , $\delta_{th}\sin^2 q_W = 5 \times 10^{-5}$

$\delta_{th}\Gamma_Z$ = 0.4 MeV, $\delta_{th}\sigma^0_{had}$ = 6 pb

$\delta_{th}R^0_l$ = 0.006, $\delta_{th}R^0_c$ = 0.00005

$\delta_{th}R^0b$ = 0.0001

Still small compared to experimental uncertainties.
Small impact on fit's outcome.

Parametric uncertainties

	Prediction	$\alpha_s(M_Z^2)$	$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	M_Z	*standard* scenario m_t	*standard* scenario Total	*conservative* scenario m_t	*conservative* scenario Total
M_W [GeV]	80.3545	±0.0006	±0.0018	±0.0027	±0.0027	±0.0042	±0.0060	±0.0069
Γ_W [GeV]	2.08782	±0.00040	±0.00014	±0.00021	±0.00021	±0.00052	±0.00047	±0.00066
$\mathrm{BR}_{W\to\ell\bar\nu_\ell}$	0.108386	±0.000024	±0.000000	±0.000000	±0.000000	±0.000024	±0.000000	±0.000024
$\sin^2\theta^{\rm lept}_{\rm eff}$	0.231534	±0.000003	±0.000035	±0.000015	±0.000013	±0.000041	±0.000030	±0.000048
Γ_Z [GeV]	2.49414	±0.00049	±0.00010	±0.00021	±0.00010	±0.00056	±0.00023	±0.00060
σ_h^0 [nb]	41.4929	±0.0049	±0.0001	±0.0020	±0.0003	±0.0053	±0.0007	±0.0053
R^0_ℓ	20.7464	±0.0062	±0.0006	±0.0003	±0.0002	±0.0063	±0.0004	±0.0063
$A^{0,\ell}_{\rm FB}$	0.016191	±0.000006	±0.000060	±0.000026	±0.000023	±0.000070	±0.000052	±0.000084
$\mathcal{A}_\ell$	0.14692	±0.00003	±0.00028	±0.00012	±0.00010	±0.00032	±0.00023	±0.00038
R^0_b	0.215880	±0.000011	±0.000001	±0.000000	±0.000015	±0.000019	±0.000034	±0.000035
R^0_c	0.172198	±0.000020	±0.000002	±0.000001	±0.000005	±0.000020	±0.000011	±0.000023
$A^{0,b}_{\rm FB}$	0.10300	±0.00002	±0.00020	±0.00008	±0.00007	±0.00023	±0.00016	±0.00027
$A^{0,c}_{\rm FB}$	0.07358	±0.00001	±0.00015	±0.00006	±0.00006	±0.00018	±0.00013	±0.00021
$\mathcal{A}_b$	0.934727	±0.000001	±0.000023	±0.000010	±0.000003	±0.000025	±0.000007	±0.000026
$\mathcal{A}_c$	0.66775	±0.00001	±0.00012	±0.00005	±0.00005	±0.00014	±0.00011	±0.00017
$\mathcal{A}_s$	0.935637	±0.000002	±0.000022	±0.000010	±0.000009	±0.000026	±0.000020	±0.000031
R_{uc}	0.172220	±0.000019	±0.000002	±0.000001	±0.000005	±0.000020	±0.000011	±0.000023

Beyond the SM

Very broadly, two main options:

- Add new physics that breaks residual $SU(2)_V$ custodial symmetry and allows $\rho \neq 1$ at tree level $\longrightarrow$ not considered here
- Add heavy new physics that decouples and leaves virtual effects:
  - Mainly in gauge boson propagators: "Oblique corrections" ("oblique" models)
    - **S,T,U parameters**
  - In a complete set of gauge-invariant higher dimension effective operators
    - Example: **SMEFT**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i,d} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Beyond the SM: {S,T,U}

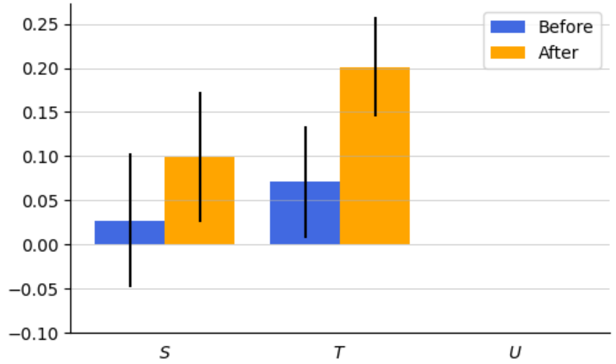
$$S = -16\pi\Pi_{30}^{\mathrm{NP}\prime}(0) = 16\pi[\Pi_{33}^{\mathrm{NP}\prime}(0) - \Pi_{3Q}^{\mathrm{NP}\prime}(0)]$$

$$T = \frac{4}{s_W^2 c_W^2 M_Z^2}[\Pi_{11}^{\mathrm{NP}}(0) - \Pi_{33}^{\mathrm{NP}}(0)]$$

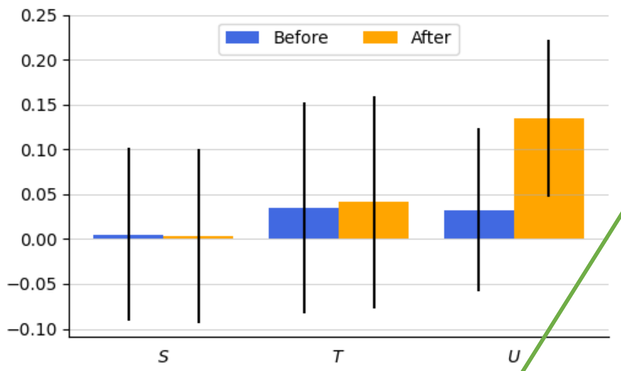
$$U = 16\pi[\Pi_{11}^{NP\prime} - \Pi_{33}^{\mathrm{NP}\prime}(0)]$$

$$g_{\mathrm{SM}} + \Delta g \begin{cases} \Delta g^{Zf\bar{f}} \propto (S,T) \\ \Delta g^{Wf'\bar{f}} \propto (S,T,U) \end{cases}$$

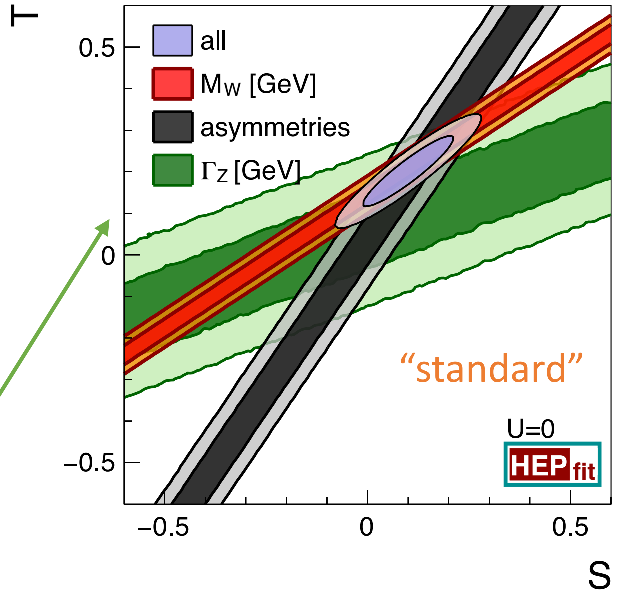
$$\mathcal{O} = \mathcal{O}_{\mathrm{SM}} + \Delta\mathcal{O}_{\mathrm{NP}}(S,T,U)$$

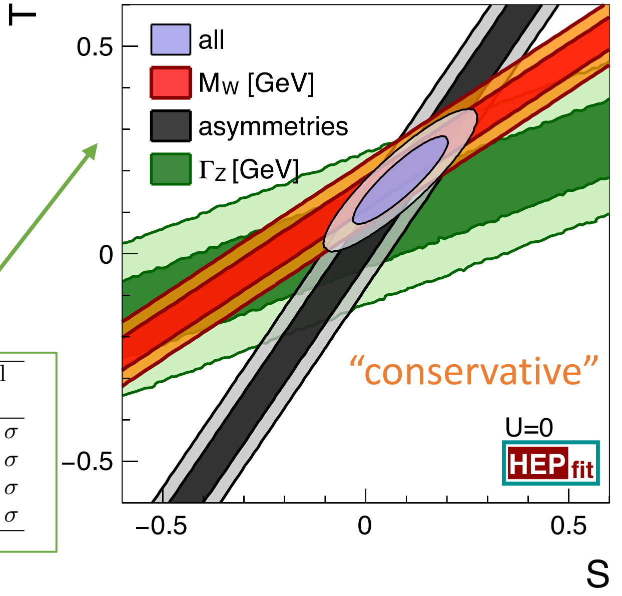


U=0, (S,T) reabsorb impact of M_W



U≠0, U reabsorb impact of M_W





	Result	Correlation		Result	Correlation		
	($IC_{ST}/IC_{SM} = 25.0/80.2$)			($IC_{STU}/IC_{SM} = 25.3/80.2$)			
S	0.100 ± 0.073	1.00		0.005 ± 0.096	1.00		
T	0.202 ± 0.056	0.93	1.00	0.040 ± 0.120	0.91	1.00	
U	–	–	–	0.134 ± 0.087	−0.65	−0.88	1.00

Model	Pred. M_W [GeV] *standard average*	Pull	Pred. M_W [GeV] *conservative average*	Pull
SM	80.3499 ± 0.0056	$6.5\,\sigma$	80.3505 ± 0.0077	$3.7\,\sigma$
ST	80.366 ± 0.029	$1.6\,\sigma$	80.367 ± 0.029	$1.4\,\sigma$
STU	80.32 ± 0.54	$0.2\,\sigma$	80.32 ± 0.54	$0.2\,\sigma$
SMEFT	80.66 ± 1.68	$-0.1\,\sigma$	80.66 ± 1.68	$-0.1\,\sigma$

Beyond the SM: SMEFT (d=6)

$$\mathcal{O}_{\phi l}^{(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{l}_L \gamma^\mu l_L) \ ,$$
$$\mathcal{O}_{\phi l}^{(3)} = (\phi^\dagger i \overleftrightarrow{D}^i_\mu \phi)(\bar{l}_L \, \sigma_i \gamma^\mu l_L) \ ,$$
$$\mathcal{O}_{\phi e} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{e}_R \gamma^\mu e_R) \ ,$$
$$\mathcal{O}_{\phi q}^{(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_L \gamma^\mu q_L) \ ,$$
$$\mathcal{O}_{\phi q}^{(3)} = (\phi^\dagger i \overleftrightarrow{D}^i_\mu \phi)(\bar{q}_L \, \sigma_i \gamma^\mu q_L)$$
$$\mathcal{O}_{\phi u} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}_R \gamma^\mu u_R) \ ,$$
$$\mathcal{O}_{\phi d} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{d}_R \gamma^\mu d_R) \ ,$$

Zff/Wff vertex corrections

$$\mathcal{O}_{\phi WB} = (\phi^\dagger \sigma_i \phi) \, W^i_{\mu\nu} B^{\mu\nu} \ ,$$
$$\mathcal{O}_{\phi D} = (\phi^\dagger D^\mu \phi)^* \, (\phi^\dagger D_\mu \phi) \ ,$$

W/Z propagators ↔ S,T

$$\mathcal{O}_{ll} = (\bar{l}_L \gamma^\mu l_L)(\bar{l}_L \gamma^\mu l_L)$$

→ G_F

Only 8 independent combinations enter EWPO

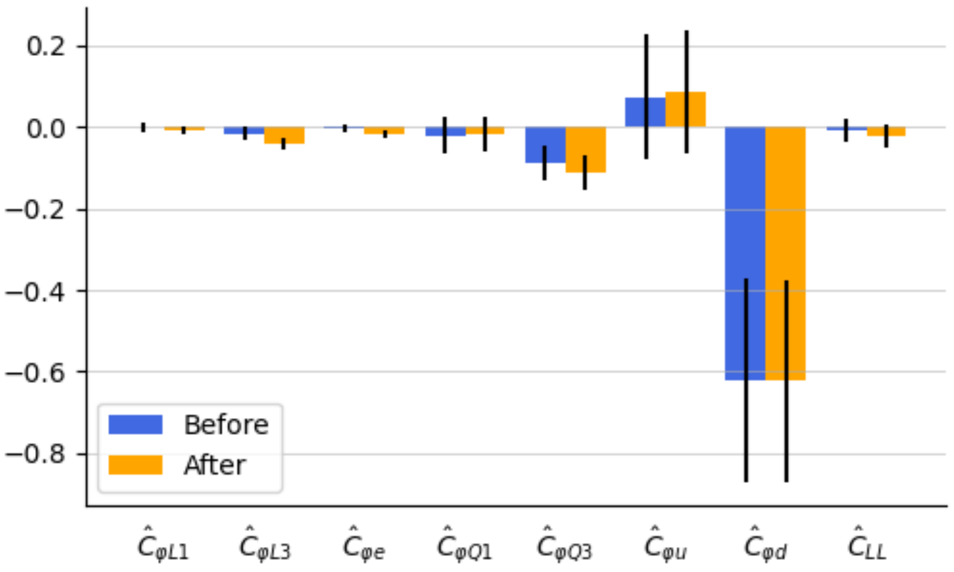
$$\hat{C}^{(1)}_{\varphi f} = C^{(1)}_{\varphi f} - \frac{Y_f}{2} C_{\varphi D}, \quad f = l, q, e, u, d,$$
$$\hat{C}^{(3)}_{\varphi f} = C^{(3)}_{\varphi f} + \frac{c_w^2}{4 s_w^2} C_{\varphi D} + \frac{c_w}{s_w} C_{\varphi WB}, \quad f = l, q,$$
$$\hat{C}_{ll} = \frac{1}{2}((C_{ll})_{1221} + (C_{ll})_{2112}) = (C_{ll})_{1221},$$

	$C_{\varphi D}$	$C_{\varphi WB}$	$C^{(3)}_{\varphi L}$	C_{LL}	$C^{(1)}_{\varphi L}$	$C_{\varphi e}$	$C^{(1)}_{\varphi Q}$	$C^{(3)}_{\varphi Q}$	$C_{\varphi u}$	$C_{\varphi d}$
M_W	✓	✓	✓	✓						
$\sin^2\theta_{eff,l}$	✓	✓	✓	✓	✓	✓				
Γ_W	✓	✓	✓	✓	✓		✓			✓
⋮										
Γ_Z	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

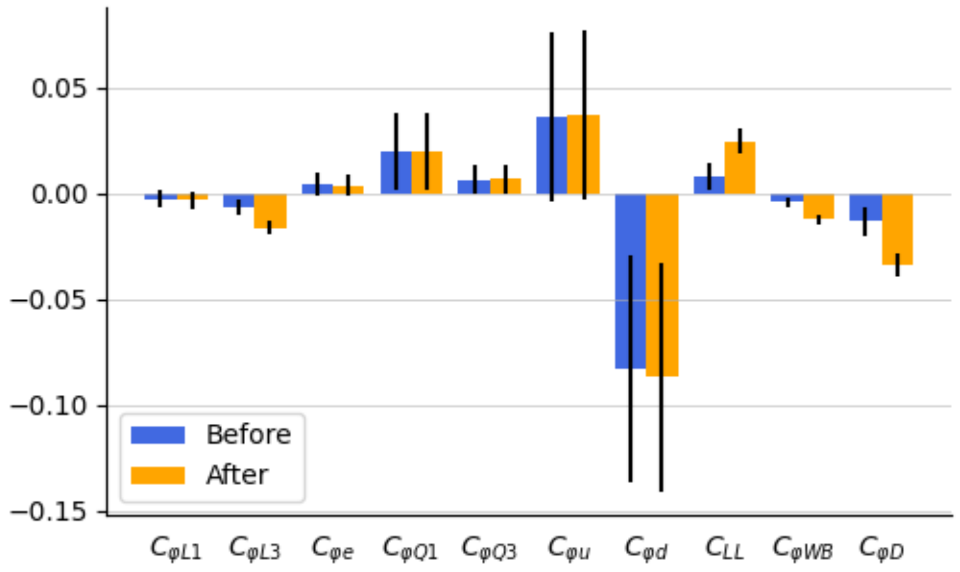
Very loose prediction of M_W from $\Gamma_W(M_W)$

Model	Pred. M_W [GeV] *standard average*	Pull	Pred. M_W [GeV] *conservative average*	Pull
SMEFT	80.66 ± 1.68	$-0.1\,\sigma$	80.66 ± 1.68	$-0.1\,\sigma$

Global fit of all coefficients



Fit of individual coefficients



No substantial impact of new mt and MW measurements, within uncertainty of the fit.

Adding Higgs and top observables will lift the degeneracy

⬇

All 10 coefficients constrained independently by the global fit

	$C_{\varphi D}$	$C_{\varphi WB}$	$C_{\varphi L}^{(3)}$	C_{LL}	$C_{\varphi L}^{(1)}$	$C_{\varphi e}$	$C_{\varphi Q}^{(1)}$	$C_{\varphi Q}^{(3)}$	$C_{\varphi u}$	$C_{\varphi d}$
M_W	✓	✓	✓	✓						
$\sin^2\theta_{eff,l}$	✓	✓	✓	✓	✓	✓				
Γ_W	✓	✓	✓	✓	✓		✓			✓
⋮										
Γ_Z	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Conclusions

- EW global fits stress-test the SM and provide a very strong indirect constraint on new physics.
- New measurement of M_W (and m_t) taken at face value implies a 6.5σ discrepancy with the SM global fit.
- Oblique corrections can reabsorb it with NP at the electroweak scale if loop-mediated (excluded) and at the TeV scale if tree-level.
- A more conservative averaging procedure greatly reduces the tension and the need for a NP explanation.

New independent measurements of M_W (and m_t) become crucial!