M_W in the Context of Global Fits in the SM and Beyond

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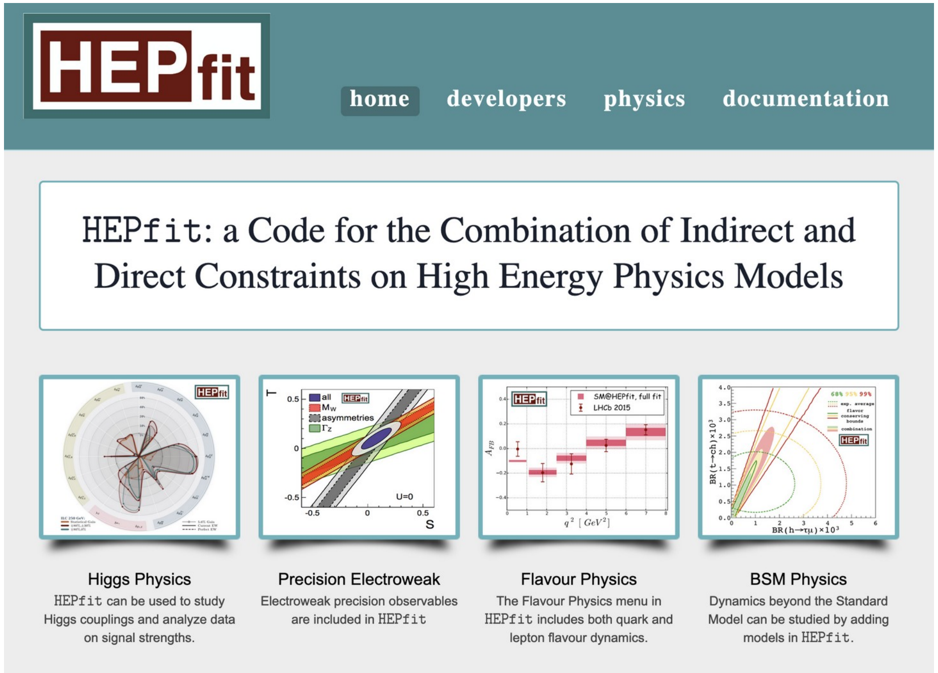
- Introduction
- HEPfit
- M_W and the fit to EWPO in the SM
- M_W and the fit to EWPO beyond the SM:
  - Oblique NP
  - SMEFT
- Summary and outlook

Based on J. de Blas, M. Pierini, L. Reina & L.S., arXiv:2204.04204

INTRODUCTION

- $SU(2)_L \times U(1)_Y$ symmetry hidden at low energies, but restored in the UV
  - tree-level relations among weak couplings and masses corrected by finite and calculable loop corrections
- Accidental custodial symmetry of the SM Higgs potential ensures $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$ at tree level, dominant corrections of $O(G_F m_t^2)$
- precision measurements of masses and couplings
  - test the quantum structure of the SM
  - probe NP through its virtual effects

THE HEPfit FRAMEWORK



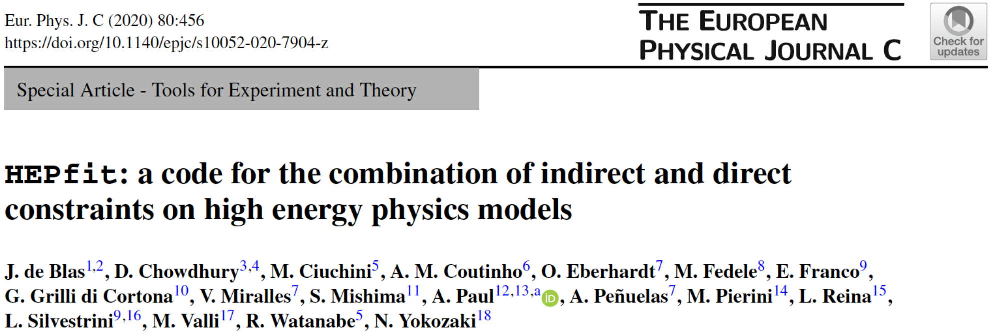
HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models

Higgs Physics
`HEPfit` can be used to study Higgs couplings and analyze data on signal strengths.

Precision Electroweak
Electroweak precision observables are included in `HEPfit`

Flavour Physics
The Flavour Physics menu in `HEPfit` includes both quark and lepton flavour dynamics.

BSM Physics
Dynamics beyond the Standard Model can be studied by adding models in `HEPfit`.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Special Article - Tools for Experiment and Theory

`HEPfit`: a code for the combination of indirect and direct constraints on high energy physics models

J. de Blas[1,2], D. Chowdhury[3,4], M. Ciuchini[5], A. M. Coutinho[6], O. Eberhardt[7], M. Fedele[8], E. Franco[9], G. Grilli di Cortona[10], V. Miralles[7], S. Mishima[11], A. Paul[12,13,a], A. Peñuelas[7], M. Pierini[14], L. Reina[15], L. Silvestrini[9,16], M. Valli[17], R. Watanabe[5], N. Yokozaki[18]

- HEPfit web page
- HEPfit documentation
- GitHub repository

GENERAL STRUCTURE

- Basic building blocks:
  - Models, defined by a set of parameters (possibly correlated) and complemented by model-specific contributions to observables;
  - Observables, defined by a theoretical prediction and possibly by an experimental likelihood which can be binned, multi-dimensional w. correlation, numerical…
  - A parallel MCMC engine based on BAT and ROOT
  - Everything coded from scratch and validated against other public codes

Terminology

- **Full Fit/Posterior:** use all available information on both SM parameters and EWPOs. Gives our current best knowledge.
- **Prediction/Indirect:** remove experimental information on one EWPO (**prediction**) or on one SM parameter (**indirect determination**). Allows to compute pulls and local compatibility, using the output predictive pdf for the observable/parameter removed from the fit.

Terminology

- **Full Prediction:** use only exp info on SM parameters. Using the output pdf (including correlations) for EWPOs and the exp results allows to compute global p-value.
- **Full Indirect:** use only exp info on EWPO. Useful to identify tensions in data that cannot be relaxed in the SM irrespective of the values of SM parameters.

EXPERIMENTAL INPUTS

- SM input parameters:
  - G_F, α, M_Z, M_H, m_t, $\alpha_s(M_Z)$, $\Delta\alpha_{had}^{(5)}$
- For $\Delta\alpha_{had}^{(5)}$ we use lattice QCD in the Euclidean + perturbative running
- For m_t, "standard" average completely dominated by very recent CMS l+jets measurement: m_t=171.77±0.38 GeV. However, there is a 3.5σ tension with the TeVatron average m_t=174.34±0.64 GeV, so consider also "conservative" average with error inflated to 1 GeV. Notice: PDG recipe would give a "ultra-conservative" 1.7 GeV error.

M_W: New Exp. Average

- Also for M_W, “standard” average completely dominated by recent CDF measurement.
- Updating the ATLAS measurement, and taking QED and PDF uncertainties fully correlated between TeVatron and LHC experiments, we obtain M_W=80409.3±7.9 MeV (previous average was M_W=80413.3±8.0 MeV.) Assuming no correlation moves the central value by half σ to M_W=80406.4±7.3 MeV; I will not present results for this choice.
- Also in this case there are tensions between LHC, TeVatron and LEP measurements, so consider also “conservative” average with error inflated à la PDG to 18 MeV

M_W: SM vs EXPERIMENT

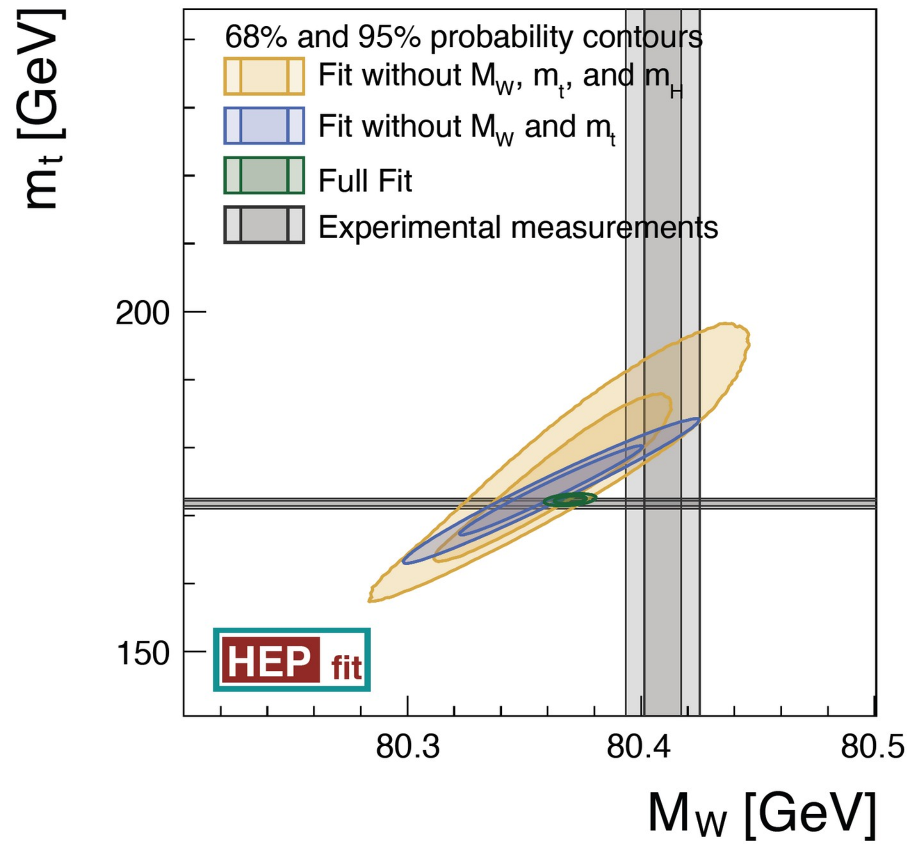
Model	Pred. M_W [GeV]	Pull	Pred. M_W [GeV]	Pull
	standard average		*conservative average*	
SM	80.3499 ± 0.0056	$6.1\,\sigma$	80.3505 ± 0.0077	$3.0\,\sigma$

- The SM prediction is obtained omitting the experimental information on M_W. Before the CDF update, the tension was 1.8σ. Current theory error on M_W in the SM is 4 MeV.

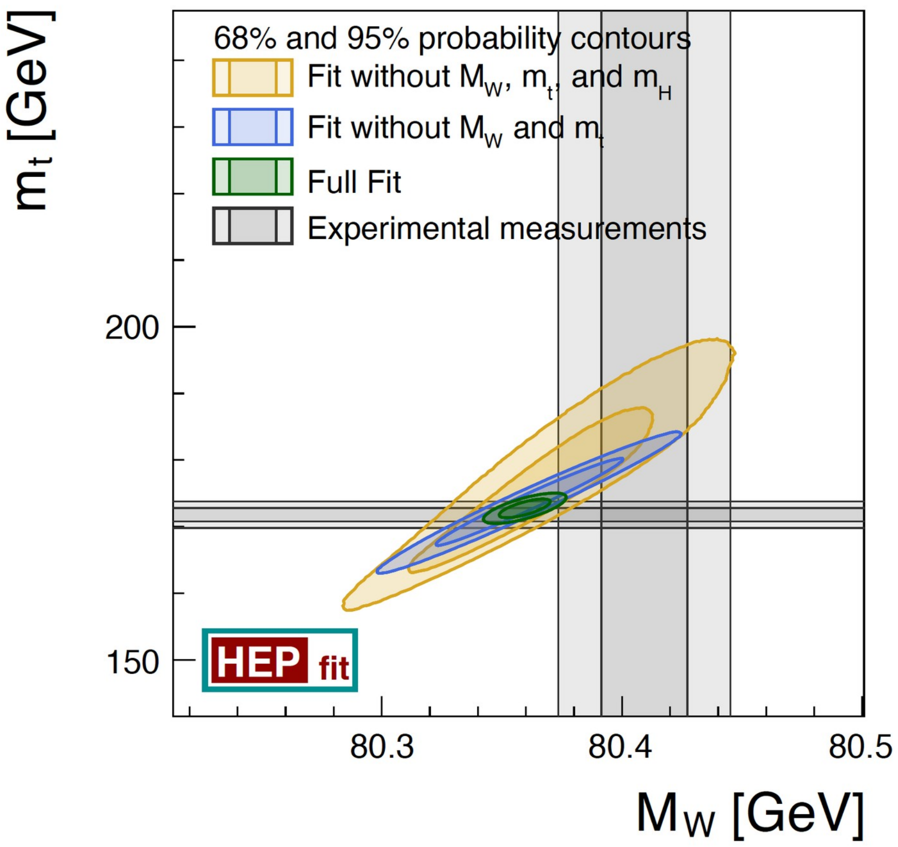
Awramik et al, '03

INTERPLAY OF M_W WITH OTHER OBSERVABLES

standard

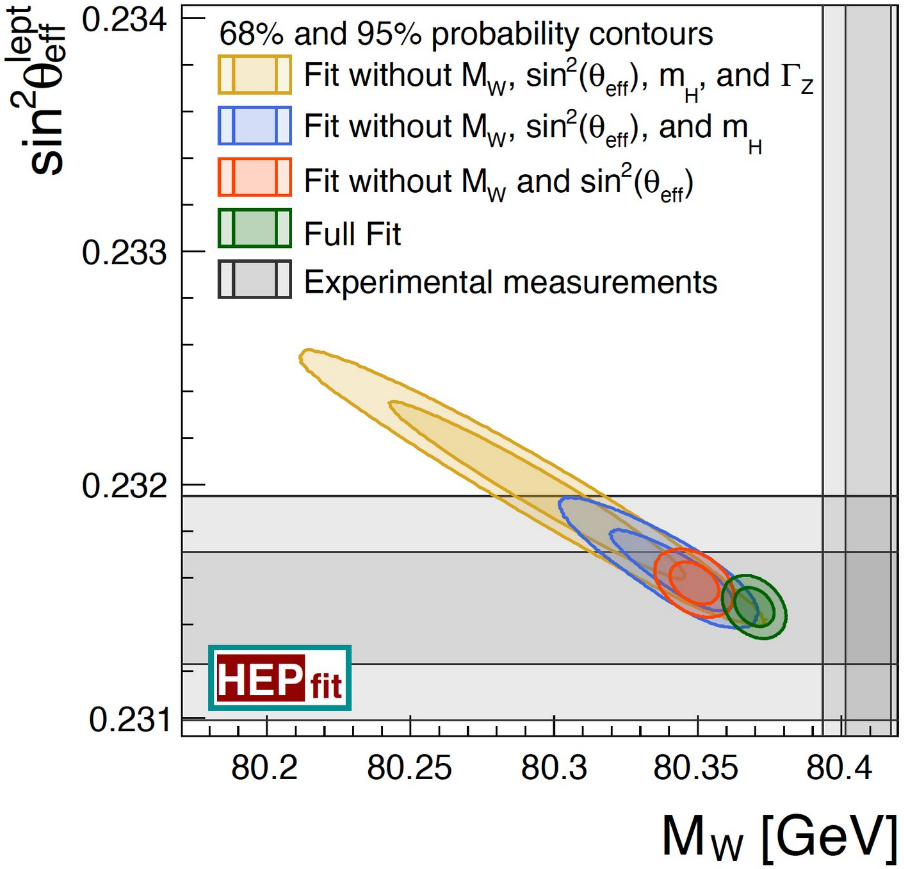


conservative

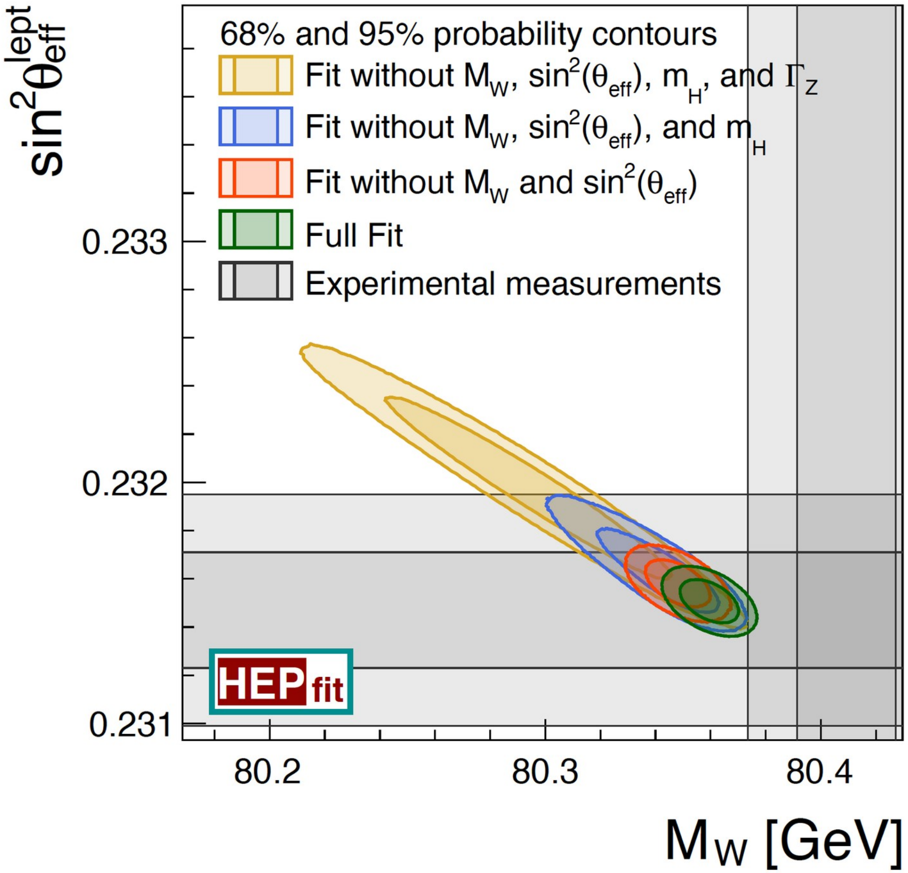


INTERPLAY OF M_W WITH OTHER OBSERVABLES

standard



conservative



	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11763 ± 0.00095 $[0.11577, 0.11946]$	0.1170 ± 0.0028 $[0.1116, 0.1225]$	0.2	0.1217 ± 0.0047 $[0.1126, 0.1310]$	−0.8	0.1177 ± 0.0010 $[0.1157, 0.1197]$	0.0
$\delta\alpha^5_{\rm had}$	0.02766 ± 0.00010	0.027541 ± 0.000096 $[0.027352, 0.027730]$	0.02624 ± 0.00033 $[0.02559, 0.02689]$	4.1	0.02793 ± 0.00068 $[0.02661, 0.02926]$	−0.4	0.02766 ± 0.00010 $[0.02746, 0.02786]$	0.0
M_Z [GeV]	91.1875 ± 0.0021	91.1910 ± 0.0020 $[91.1870, 91.1949]$	91.2287 ± 0.0068 $[91.2154, 91.2421]$	−5.8	91.210 ± 0.039 $[91.134, 91.287]$	−0.6	91.1875 ± 0.0021 $[91.1834, 91.1916]$	0.0
m_t [GeV]	171.79 ± 0.38	172.34 ± 0.37 $[171.61, 173.06]$	180.9 ± 1.5 $[178.0, 183.8]$	−5.9	186.7 ± 9.5 $[168.0, 205.1]$	−1.6	171.80 ± 0.38 $[171.05, 172.54]$	0.0
m_H [GeV]	125.21 ± 0.12	125.21 ± 0.12 $[124.97, 125.44]$	94.0 ± 5.0 $[83.3, 104.3]$	4.1	241.2 ± 121.3 $[100.8, 626.8]$	−0.8	125.21 ± 0.12 $[124.97, 125.45]$	0.0
M_W [GeV]	80.4093 ± 0.0079	80.3696 ± 0.0045 $[80.3608, 80.3786]$	80.3499 ± 0.0056 $[80.3390, 80.3609]$	6.1	80.4089 ± 0.0078 $[80.3934, 80.4241]$	0.0	80.3496 ± 0.0057 $[80.3386, 80.3608]$	6.1
Γ_W [GeV]	2.085 ± 0.042	2.08896 ± 0.00052 $[2.08793, 2.08999]$	2.08896 ± 0.00052 $[2.08793, 2.08998]$	−0.1	2.0940 ± 0.0023 $[2.0896, 2.0984]$	−0.2	2.08744 ± 0.00059 $[2.08627, 2.08859]$	0.0
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.231474 ± 0.000055 $[0.231366, 0.231583]$	0.231473 ± 0.000055 $[0.231364, 0.231581]$	0.8	0.23146 ± 0.00014 $[0.23119, 0.23173]$	0.8	0.231558 ± 0.000062 $[0.231436, 0.231679]$	0.7
$P^{\rm pol}_\tau = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14739 ± 0.00044 $[0.14654, 0.14825]$	0.14741 ± 0.00044 $[0.14655, 0.14827]$	−0.3	0.1475 ± 0.0011 $[0.1454, 0.1496]$	−0.3	0.14675 ± 0.00049 $[0.14580, 0.14770]$	−0.1
Γ_Z [GeV]	2.4955 ± 0.0023	2.49454 ± 0.00064 $[2.49328, 2.49580]$	2.49434 ± 0.00068 $[2.49300, 2.49567]$	0.5	2.4953 ± 0.0020 $[2.4912, 2.4993]$	0.1	2.49397 ± 0.00068 $[2.49262, 2.49531]$	0.6
σ^0_h [nb]	41.480 ± 0.033	41.4892 ± 0.0077 $[41.4742, 41.5042]$	41.4914 ± 0.0080 $[41.4758, 41.5072]$	−0.3	41.462 ± 0.030 $[41.403, 41.522]$	0.4	41.4923 ± 0.0080 $[41.4766, 41.5081]$	−0.4
R^0_ℓ	20.767 ± 0.025	20.7487 ± 0.0080 $[20.7329, 20.7645]$	20.7451 ± 0.0086 $[20.7281, 20.7621]$	0.8	20.760 ± 0.022 $[20.717, 20.802]$	0.2	20.7468 ± 0.0087 $[20.7298, 20.7637]$	0.7
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	0.016293 ± 0.000096 $[0.016106, 0.016482]$	0.016284 ± 0.000096 $[0.016097, 0.016476]$	0.8	0.01631 ± 0.00024 $[0.01585, 0.01679]$	0.8	0.01615 ± 0.00011 $[0.01594, 0.01636]$	1.0
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14739 ± 0.00044 $[0.14654, 0.14825]$	0.14742 ± 0.00045 $[0.14654, 0.14832]$	1.8	0.1475 ± 0.0011 $[0.1454, 0.1496]$	1.6	0.14675 ± 0.00049 $[0.14580, 0.14770]$	2.1
R^0_b	0.21629 ± 0.00066	0.215894 ± 0.000100 $[0.215697, 0.216090]$	0.21589 ± 0.00010 $[0.21569, 0.21609]$	0.6	0.21543 ± 0.00036 $[0.21472, 0.21614]$	1.1	0.21591 ± 0.00010 $[0.21571, 0.21611]$	0.6
R^0_c	0.1721 ± 0.0030	0.172198 ± 0.000054 $[0.172093, 0.172302]$	0.172199 ± 0.000054 $[0.172094, 0.172304]$	−0.1	0.17240 ± 0.00018 $[0.17205, 0.17277]$	−0.1	0.172189 ± 0.000054 $[0.172084, 0.172295]$	−0.1
$A^{0,b}_{\rm FB}$	0.0996 ± 0.0016	0.10334 ± 0.00031 $[0.10273, 0.10393]$	0.10335 ± 0.00032 $[0.10273, 0.10398]$	−2.3	0.10338 ± 0.00077 $[0.10189, 0.10489]$	−2.1	0.10288 ± 0.00034 $[0.10220, 0.10354]$	−2.0
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	0.07384 ± 0.00023 $[0.07339, 0.07428]$	0.07385 ± 0.00024 $[0.07339, 0.07432]$	−0.9	0.07391 ± 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	0.934768 ± 0.000040 $[0.934690, 0.934845]$	0.934769 ± 0.000040 $[0.934691, 0.934846]$	−0.6	0.93460 ± 0.00016 $[0.93428, 0.93492]$	−0.6	0.934721 ± 0.000041 $[0.934642, 0.934801]$	−0.6
$\mathcal{A}_c$	0.670 ± 0.027	0.66795 ± 0.00021 $[0.66753, 0.66837]$	0.66795 ± 0.00022 $[0.66753, 0.66838]$	0.1	0.66817 ± 0.00054 $[0.66711, 0.66921]$	0.1	0.66766 ± 0.00022 $[0.66722, 0.66810]$	0.1
$\mathcal{A}_s$	0.895 ± 0.091	0.935675 ± 0.000039 $[0.935597, 0.935752]$	0.935674 ± 0.000040 $[0.935597, 0.935752]$	−0.4	0.935714 ± 0.000099 $[0.935523, 0.935907]$	−0.5	0.935621 ± 0.000041 $[0.935541, 0.935702]$	−0.5
${\rm BR}_{W\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108388 ± 0.000022 $[0.108345, 0.108431]$	0.108388 ± 0.000022 $[0.108344, 0.108431]$	0.2	0.10829 ± 0.00011 $[0.10807, 0.10850]$	0.3	0.108386 ± 0.000023 $[0.108340, 0.108432]$	0.2
$\sin^2\theta^{ll}_{\rm eff}$ (HC)	0.23143 ± 0.00025	0.231474 ± 0.000055 $[0.231366, 0.231583]$	0.231477 ± 0.000056 $[0.231366, 0.231588]$	−0.2	0.23146 ± 0.00014 $[0.23119, 0.23173]$	−0.1	0.231558 ± 0.000062 $[0.231436, 0.231679]$	−0.5
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000031 $[0.172158, 0.172282]$	0.172220 ± 0.000031 $[0.172158, 0.172281]$	−0.7	0.17242 ± 0.00018 $[0.17208, 0.17278]$	−0.7	0.172212 ± 0.000032 $[0.172149, 0.172275]$	−0.7

“standard” scenario

	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11791 ± 0.00094 $[0.11606, 0.11976]$	0.1197 ± 0.0028 $[0.1142, 0.1253]$	-0.7	0.1218 ± 0.0047 $[0.1126, 0.1310]$	-0.8	0.1177 ± 0.0010 $[0.1157, 0.1197]$	0.0
$\delta\alpha^5_{\text{had}}$	0.02766 ± 0.00010	0.027624 ± 0.000097 $[0.027432, 0.027814]$	0.02703 ± 0.00040 $[0.02624, 0.02781]$	1.5	0.02792 ± 0.00071 $[0.02653, 0.02932]$	-0.4	0.02766 ± 0.00010 $[0.02747, 0.02786]$	-0.1
M_Z [GeV]	91.1875 ± 0.0021	91.1883 ± 0.0021 $[91.1843, 91.1924]$	91.218 ± 0.011 $[91.196, 91.240]$	-2.7	91.209 ± 0.039 $[91.134, 91.287]$	-0.5	91.1875 ± 0.0021 $[91.1834, 91.1916]$	-0.1
m_t [GeV]	171.8 ± 1.0	172.75 ± 0.93 $[170.92, 174.59]$	179.1 ± 2.5 $[174.0, 184.0]$	-2.6	186.5 ± 10.1 $[166.7, 205.8]$	-1.4	171.8 ± 1.0 $[169.8, 173.8]$	0.0
m_H [GeV]	125.21 ± 0.12	125.21 ± 0.12 $[124.97, 125.44]$	105.0 ± 11.3 $[87.7, 134.1]$	1.5	238.4 ± 121.3 $[98.1, 629.5]$	-0.8	125.21 ± 0.12 $[124.97, 125.45]$	0.1
M_W [GeV]	80.409 ± 0.018	80.3595 ± 0.0070 $[80.3456, 80.3733]$	80.3505 ± 0.0077 $[80.3355, 80.3656]$	3.0	80.407 ± 0.017 $[80.373, 80.441]$	0.1	80.3497 ± 0.0079 $[80.3342, 80.3653]$	3.1
Γ_W [GeV]	2.085 ± 0.042	2.08831 ± 0.00067 $[2.08700, 2.08963]$	2.08830 ± 0.00067 $[2.08700, 2.08961]$	-0.1	2.0939 ± 0.0026 $[2.0888, 2.0989]$	-0.2	2.08743 ± 0.00073 $[2.08601, 2.08889]$	0.0
$\sin^2\theta^{\text{lept}}_{\text{eff}}(Q^{\text{had}}_{\text{FB}})$	0.2324 ± 0.0012	0.231507 ± 0.000060 $[0.231389, 0.231623]$	0.231505 ± 0.000059 $[0.231388, 0.231622]$	0.7	0.23146 ± 0.00014 $[0.23119, 0.23173]$	0.8	0.231558 ± 0.000068 $[0.231426, 0.231691]$	0.7
$P^{\text{pol}}_\tau = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14713 ± 0.00047 $[0.14622, 0.14806]$	0.14716 ± 0.00047 $[0.14622, 0.14808]$	-0.2	0.1475 ± 0.0011 $[0.1454, 0.1496]$	-0.3	0.14674 ± 0.00053 $[0.14570, 0.14779]$	-0.1
Γ_Z [GeV]	2.4955 ± 0.0023	2.49444 ± 0.00067 $[2.49313, 2.49574]$	2.49423 ± 0.00071 $[2.49285, 2.49562]$	0.5	2.4952 ± 0.0021 $[2.4911, 2.4993]$	0.1	2.49396 ± 0.00072 $[2.49257, 2.49538]$	0.6
σ^0_h [nb]	41.480 ± 0.033	41.4907 ± 0.0076 $[41.4756, 41.5057]$	41.4928 ± 0.0080 $[41.4771, 41.5086]$	-0.4	41.462 ± 0.030 $[41.403, 41.522]$	0.4	41.4924 ± 0.0080 $[41.4767, 41.5083]$	-0.4
R^0_ℓ	20.767 ± 0.025	20.7495 ± 0.0080 $[20.7337, 20.7652]$	20.7460 ± 0.0087 $[20.7291, 20.7630]$	0.8	20.760 ± 0.022 $[20.717, 20.803]$	0.2	20.7470 ± 0.0087 $[20.7297, 20.7638]$	0.8
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	0.01624 ± 0.00010 $[0.01604, 0.01644]$	0.01623 ± 0.00010 $[0.01602, 0.01643]$	0.9	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	0.14713 ± 0.00047 $[0.14622, 0.14806]$	0.14715 ± 0.00049 $[0.14619, 0.14811]$	1.9	0.1475 ± 0.0011 $[0.1454, 0.1496]$	1.6	0.14674 ± 0.00053 $[0.14570, 0.14779]$	2.1
R^0_b	0.21629 ± 0.00066	0.21588 ± 0.00010 $[0.21567, 0.21608]$	0.21587 ± 0.00011 $[0.21566, 0.21608]$	0.6	0.21545 ± 0.00038 $[0.21470, 0.21617]$	1.1	0.21591 ± 0.00011 $[0.21570, 0.21611]$	0.6
R^0_c	0.1721 ± 0.0030	0.172206 ± 0.000054 $[0.172100, 0.172313]$	0.172206 ± 0.000054 $[0.172099, 0.172312]$	0.0	0.17239 ± 0.00019 $[0.17204, 0.17277]$	-0.1	0.172190 ± 0.000055 $[0.172082, 0.172297]$	-0.1
$A^{0,b}_{\text{FB}}$	0.0996 ± 0.0016	0.10315 ± 0.00033 $[0.10250, 0.10380]$	0.10316 ± 0.00034 $[0.10248, 0.10384]$	-2.2	0.10338 ± 0.00076 $[0.10187, 0.10488]$	-2.1	0.10287 ± 0.00037 $[0.10214, 0.10361]$	-2.0
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	0.07370 ± 0.00025 $[0.07321, 0.07418]$	0.07370 ± 0.00026 $[0.07319, 0.07421]$	-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	0.934739 ± 0.000040 $[0.934661, 0.934819]$	0.934740 ± 0.000040 $[0.934661, 0.934820]$	-0.6	0.93461 ± 0.00017 $[0.93427, 0.93494]$	-0.6	0.934721 ± 0.000041 $[0.934640, 0.934802]$	-0.6
$\mathcal{A}_c$	0.670 ± 0.027	0.66783 ± 0.00023 $[0.66737, 0.66828]$	0.66783 ± 0.00023 $[0.66737, 0.66829]$	0.1	0.66815 ± 0.00054 $[0.66711, 0.66922]$	0.1	0.66766 ± 0.00024 $[0.66718, 0.66814]$	0.1
$\mathcal{A}_s$	0.895 ± 0.091	0.935652 ± 0.000043 $[0.935568, 0.935736]$	0.935653 ± 0.000043 $[0.935568, 0.935736]$	-0.4	0.935713 ± 0.000099 $[0.935518, 0.935906]$	-0.5	0.935622 ± 0.000045 $[0.935533, 0.935709]$	-0.5
$\text{BR}_{W\ell\bar{\nu}_\ell}$	0.10860 ± 0.00090	0.108381 ± 0.000022 $[0.108338, 0.108424]$	0.108381 ± 0.000022 $[0.108338, 0.108424]$	0.2	0.10829 ± 0.00011 $[0.10808, 0.10851]$	0.3	0.108386 ± 0.000023 $[0.108340, 0.108432]$	0.2
$\sin^2\theta^{ll}_{\text{eff}}$ (HC)	0.23143 ± 0.00025	0.231507 ± 0.000060 $[0.231389, 0.231623]$	0.231511 ± 0.000061 $[0.231392, 0.231632]$	-0.3	0.23146 ± 0.00014 $[0.23119, 0.23173]$	-0.1	0.231558 ± 0.000068 $[0.231426, 0.231691]$	-0.5
R_{uc}	0.1660 ± 0.0090	0.172227 ± 0.000033 $[0.172163, 0.172292]$	0.172227 ± 0.000033 $[0.172164, 0.172292]$	-0.7	0.17242 ± 0.00018 $[0.17207, 0.17278]$	-0.7	0.172211 ± 0.000034 $[0.172145, 0.172277]$	-0.7

"conservative" scenario

LOCAL vs GLOBAL SIGNIFICANCE

- Considering the whole set of EWPO, what is the global agreement with the SM?
- Compute global p-value of the "full prediction", taking into account experimental and theoretical correlations:
  - $p=1.2\ 10^{-4}$, i.e. 3.9σ (standard scenario)
  - $p=0.27$, i.e. 1.1σ (conservative scenario)

M_W BEYOND THE SM

- Add heavy NP that decouples, leaving its virtual footprints:
  - dominantly in gauge Boson propagators: "oblique" NP
  - in the complete set of gauge-invariant dimension six operators (SMEFT)
- For explicit models (Z', composite Higgs, etc.) see e.g. Strumia '22

OBLIQUE NP

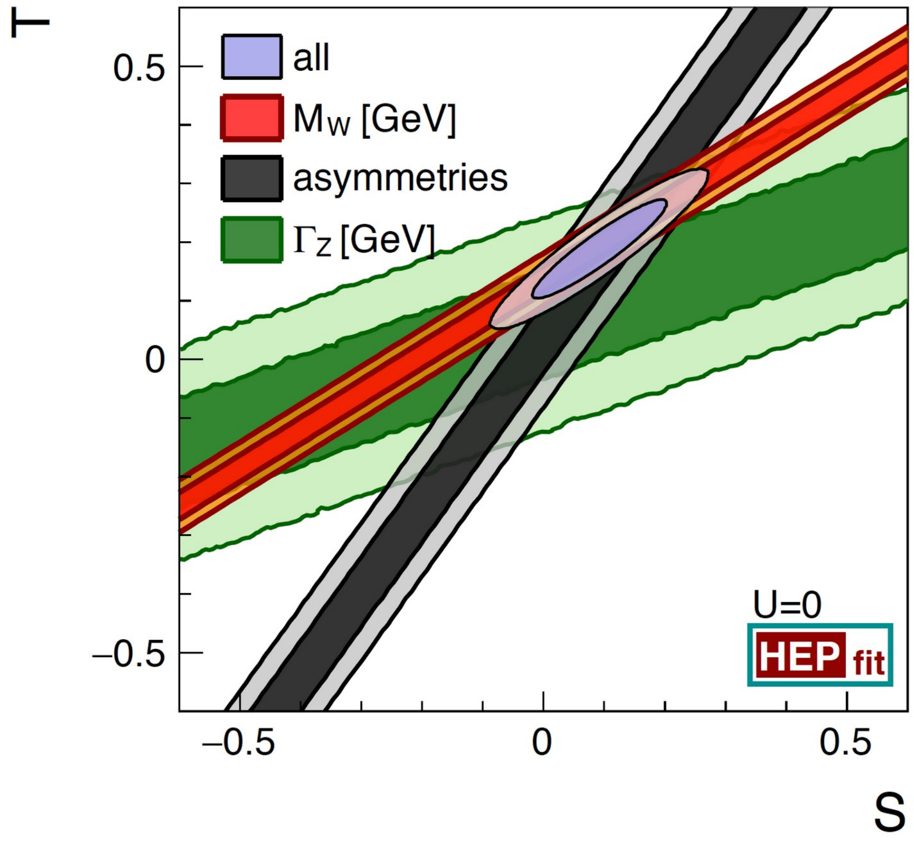
- Assume NP dominant contribution is in gauge Boson propagators:

$$
\begin{aligned}
S &= -16\pi \Pi_{30}^{\mathrm{NP}\prime}(0) = 16\pi \left[\Pi_{33}^{\mathrm{NP}\prime}(0) - \Pi_{3Q}^{\mathrm{NP}\prime}(0)\right], \\
T &= \frac{4\pi}{s_W^2 c_W^2 M_Z^2}\left[\Pi_{11}^{\mathrm{NP}}(0) - \Pi_{33}^{\mathrm{NP}}(0)\right], \\
U &= 16\pi \left[\Pi_{11}^{\mathrm{NP}\prime}(0) - \Pi_{33}^{\mathrm{NP}\prime}(0)\right]
\end{aligned}
$$

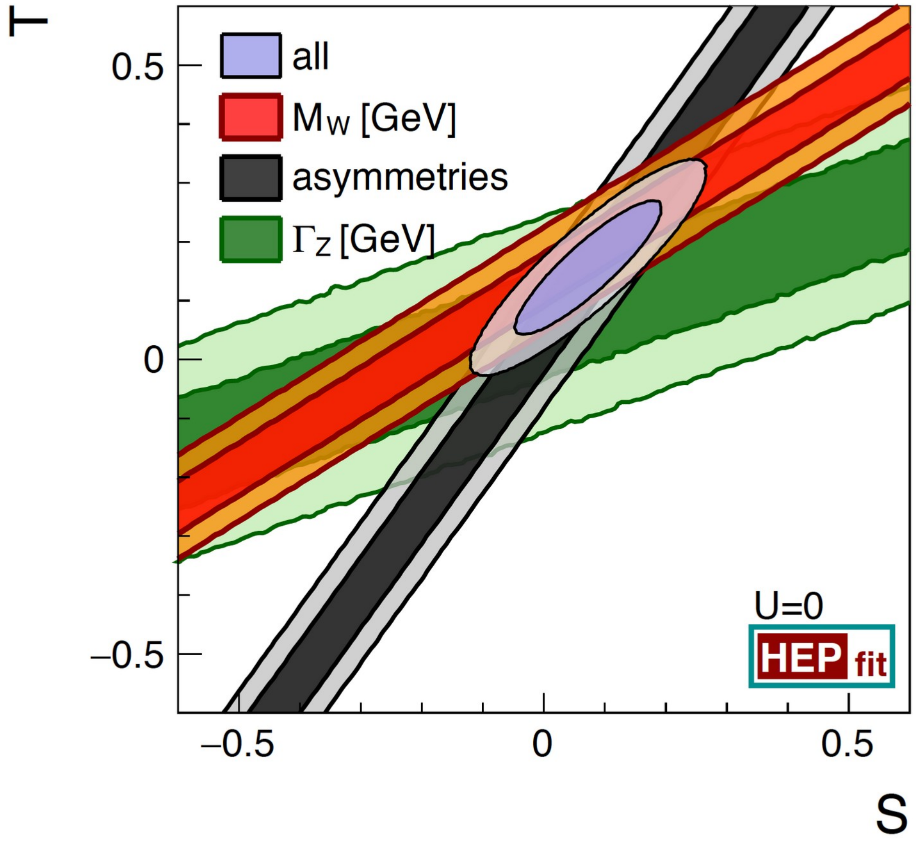
- EWPO are modified as follows:
  - $\delta\Gamma_Z \propto \quad -10(3-8s_W^2)\,S + (63-126s_W^2-40s_W^4)\,T$
  - δM_W, $\delta\Gamma_W \propto \quad S - 2c_W^2\,T - \dfrac{(c_W^2-s_W^2)\,U}{2s_W^2}$
  - all other observables: $S - 4c_W^2 s_W^2\,T$

OBLIQUE NP: U=0

standard



conservative



OBLIQUE NP: RESULTS

- Compare models using the Information Criterion:

$$IC \equiv -2\overline{\log \mathcal{L}} + 4\sigma^2_{\log \mathcal{L}}$$

	Result	Correlation		Result	Correlation		
	$(\mathrm{IC}_{\mathrm{ST}}/\mathrm{IC}_{\mathrm{SM}} = 24.5/73.9)$			$(\mathrm{IC}_{\mathrm{STU}}/\mathrm{IC}_{\mathrm{SM}} = 25.3/73.9)$			
S	0.092 ± 0.073	1.00		0.004 ± 0.096	1.00		
T	0.188 ± 0.056	0.93	1.00	0.04 ± 0.12	0.91	1.00	
U	–	–	–	0.122 ± 0.087	−0.65	−0.88	1.00

- No significant gain in IC for U≠0

Model	Pred. M_W [GeV]	Pull	Pred. M_W [GeV]	Pull
	standard average		*conservative average*	
SM	80.3499 ± 0.0056	$6.1\,\sigma$	80.3505 ± 0.0077	$3.0\,\sigma$
ST	80.366 ± 0.029	$1.4\,\sigma$	80.367 ± 0.029	$1.2\,\sigma$
STU	80.32 ± 0.54	$0.2\,\sigma$	80.32 ± 0.54	$0.2\,\sigma$

THE SMEFT

- Most general gauge-invariant Lagrangian built with SM fields up to dimension d (here d=6)
- Some relevant operators in the "Warsaw basis":

$$\mathcal{O}_{\phi WB} = (\phi^\dagger \sigma_i \phi)\, W^i_{\mu\nu} B^{\mu\nu}\ , \quad \rightarrow \mathrm{S}$$

$$\mathcal{O}_{\phi D} = (\phi^\dagger D^\mu \phi)^* \, (\phi^\dagger D_\mu \phi)\ , \quad \rightarrow \mathrm{T}$$

$$\mathcal{O}_{ll} = (\overline{l_L} \gamma^\mu l_L)(\overline{l_L} \gamma^\mu l_L)$$

$$\mathcal{O}^{(1)}_{\phi l} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{l}_L \gamma^\mu l_L)\ ,$$

$$\mathcal{O}^{(3)}_{\phi l} = (\phi^\dagger i \overleftrightarrow{D}^i_\mu \phi)(\bar{l}_L\, \sigma_i \gamma^\mu l_L)\ ,$$

$$\mathcal{O}_{\phi e} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{e}_R \gamma^\mu e_R)\ ,$$

$$\mathcal{O}^{(1)}_{\phi q} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_L \gamma^\mu q_L)\ ,$$

$$\mathcal{O}^{(3)}_{\phi q} = (\phi^\dagger i \overleftrightarrow{D}^i_\mu \phi)(\bar{q}_L\, \sigma_i \gamma^\mu q_L)\ ,$$

$$\mathcal{O}_{\phi u} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}_R \gamma^\mu u_R)\ ,$$

$$\mathcal{O}_{\phi d} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{d}_R \gamma^\mu d_R)\ ,$$

M_W IN THE SMEFT

- Eight independent combinations of dim. 6 operators contribute to EWPO. In the Warsaw basis:

$$\hat{C}^{(1)}_{\varphi f} = C^{(1)}_{\varphi f} - \frac{Y_f}{2} C_{\varphi D}, \quad f = l, q, e, u, d, \tag{6}$$

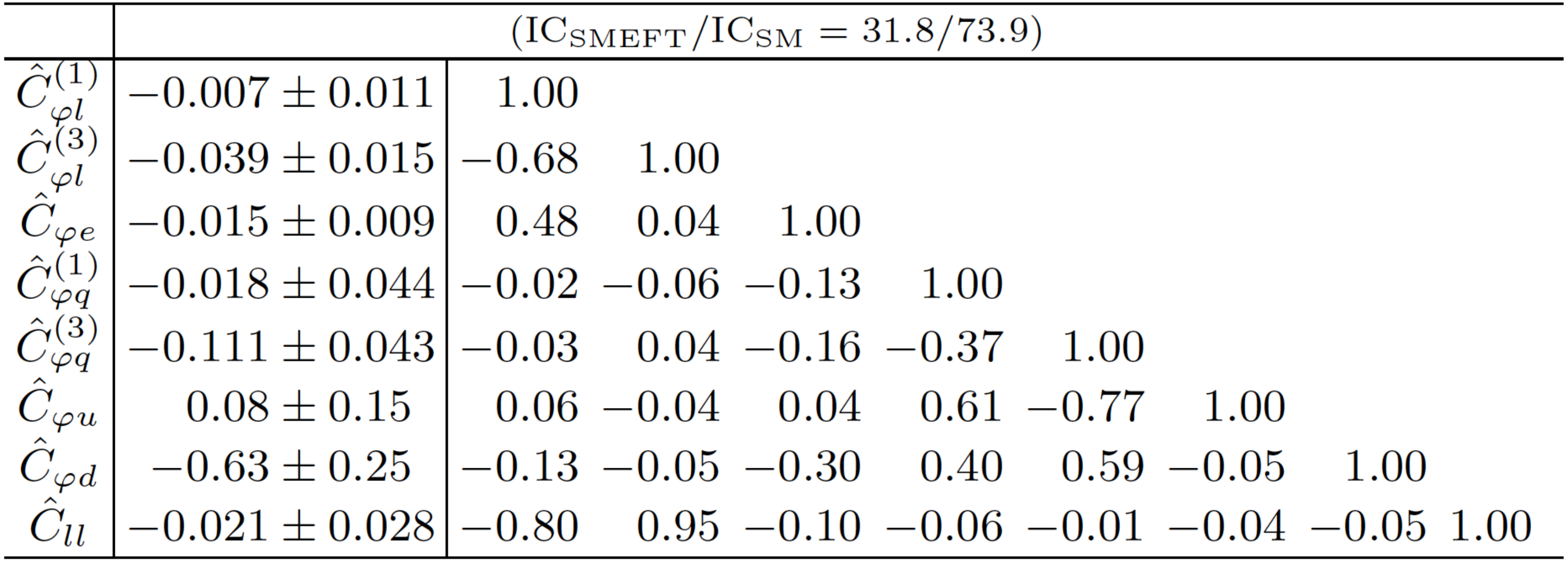
$$\hat{C}^{(3)}_{\varphi f} = C^{(3)}_{\varphi f} + \frac{c_w^2}{4 s_w^2} C_{\varphi D} + \frac{c_w}{s_w} C_{\varphi WB}, \quad f = l, q, \tag{7}$$

$$\hat{C}_{ll} = \frac{1}{2}\left((C_{ll})_{1221} + (C_{ll})_{2112}\right) = (C_{ll})_{1221}, \tag{8}$$

- Again, one independent combination enters only M_W and Γ_W, namely: $\hat{C}^{(3)}_{\varphi l} - \hat{C}_{ll}/2$; very loose prediction for M_W from Γ_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	$-0.1\,\sigma$

SMEFT: FIT RESULTS



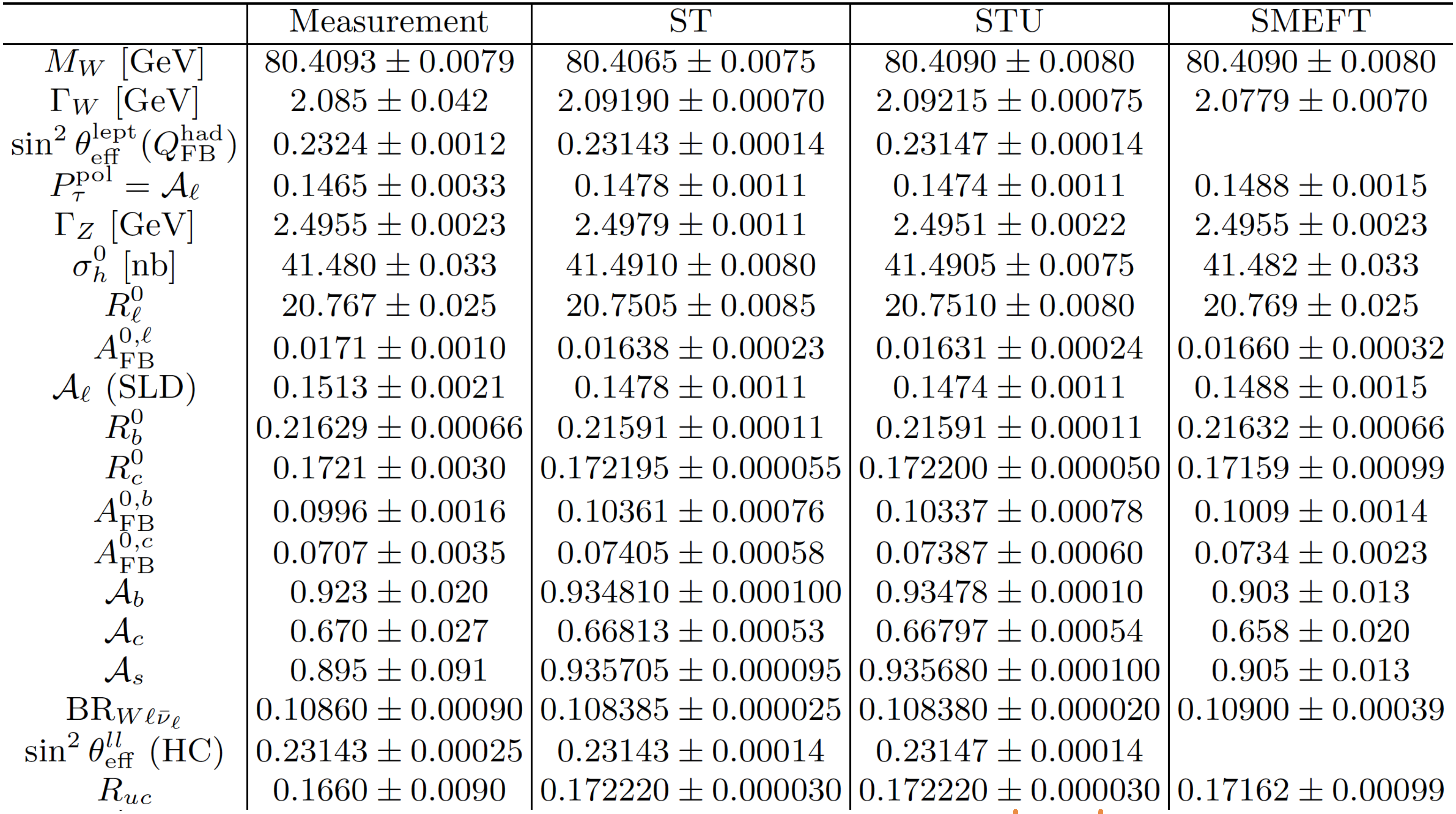
	$(\mathrm{IC}_{\mathrm{SMEFT}}/\mathrm{IC}_{\mathrm{SM}} = 31.8/73.9)$								
$\hat{C}^{(1)}_{\varphi l}$	-0.007 ± 0.011	1.00							
$\hat{C}^{(3)}_{\varphi l}$	-0.039 ± 0.015	−0.68	1.00						
$\hat{C}_{\varphi e}$	-0.015 ± 0.009	0.48	0.04	1.00					
$\hat{C}^{(1)}_{\varphi q}$	-0.018 ± 0.044	−0.02	−0.06	−0.13	1.00				
$\hat{C}^{(3)}_{\varphi q}$	-0.111 ± 0.043	−0.03	0.04	−0.16	−0.37	1.00			
$\hat{C}_{\varphi u}$	0.08 ± 0.15	0.06	−0.04	0.04	0.61	−0.77	1.00		
$\hat{C}_{\varphi d}$	-0.63 ± 0.25	−0.13	−0.05	−0.30	0.40	0.59	−0.05	1.00	
$\hat{C}_{ll}$	-0.021 ± 0.028	−0.80	0.95	−0.10	−0.06	−0.01	−0.04	−0.05	1.00

TeV^{-2}

standard averages

- Cirigliano et al. noted that a combination of these operators also contributes to first-row CKM unitarity violation. This effect can be compensated by $C^{(3)}_{lq}$ which does not enter EWPO. However, $C^{(3)}_{lq}$ can be constrained by LHC e.g. in pp→ll.

EWPO BEYOND THE SM



	Measurement	ST	STU	SMEFT
M_W [GeV]	80.4093 ± 0.0079	80.4065 ± 0.0075	80.4090 ± 0.0080	80.4090 ± 0.0080
Γ_W [GeV]	2.085 ± 0.042	2.09190 ± 0.00070	2.09215 ± 0.00075	2.0779 ± 0.0070
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23143 ± 0.00014	0.23147 ± 0.00014	
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.1478 ± 0.0011	0.1474 ± 0.0011	0.1488 ± 0.0015
Γ_Z [GeV]	2.4955 ± 0.0023	2.4979 ± 0.0011	2.4951 ± 0.0022	2.4955 ± 0.0023
σ_h^0 [nb]	41.480 ± 0.033	41.4910 ± 0.0080	41.4905 ± 0.0075	41.482 ± 0.033
R_ℓ^0	20.767 ± 0.025	20.7505 ± 0.0085	20.7510 ± 0.0080	20.769 ± 0.025
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.01638 ± 0.00023	0.01631 ± 0.00024	0.01660 ± 0.00032
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1478 ± 0.0011	0.1474 ± 0.0011	0.1488 ± 0.0015
R_b^0	0.21629 ± 0.00066	0.21591 ± 0.00011	0.21591 ± 0.00011	0.21632 ± 0.00066
R_c^0	0.1721 ± 0.0030	0.172195 ± 0.000055	0.172200 ± 0.000050	0.17159 ± 0.00099
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016	0.10361 ± 0.00076	0.10337 ± 0.00078	0.1009 ± 0.0014
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07405 ± 0.00058	0.07387 ± 0.00060	0.0734 ± 0.0023
$\mathcal{A}_b$	0.923 ± 0.020	0.934810 ± 0.000100	0.93478 ± 0.00010	0.903 ± 0.013
$\mathcal{A}_c$	0.670 ± 0.027	0.66813 ± 0.00053	0.66797 ± 0.00054	0.658 ± 0.020
$\mathcal{A}_s$	0.895 ± 0.091	0.935705 ± 0.000095	0.935680 ± 0.000100	0.905 ± 0.013
${\rm BR}_{W\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108385 ± 0.000025	0.108380 ± 0.000020	0.10900 ± 0.00039
$\sin^2\theta_{\rm eff}^{ll}$ (HC)	0.23143 ± 0.00025	0.23143 ± 0.00014	0.23147 ± 0.00014	
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000030	0.172220 ± 0.000030	0.17162 ± 0.00099

standard averages

Conclusions

- Remarkable experimental progress in m_t and M_W, but tensions among measurements present in both cases: outcome of M_W and m_t averaging group badly needed!
- Taken at face value, M_W implies a local (global) discrepancy at the 6.1σ (3.9σ) level, calling for NP
- Oblique/decoupling NP can accommodate the tension for scales close to the EW scale if loop-mediated, or at the TeV scale if tree-level/strongly interacting.
- If a more conservative averaging procedure is followed, the tension becomes much milder and the implications on NP much softer.
- More measurements of M_W (and m_t) crucial!

BACKUP

NP fits in the conservative scenario

	Result	Correlation		Result	Correlation		
	$(\mathrm{IC_{ST}}/\mathrm{IC_{SM}} = 24.0/29.7)$			$(\mathrm{IC_{STU}}/\mathrm{IC_{SM}} = 25.3/29.7)$			
S	0.073 ± 0.079	1.00		0.004 ± 0.096	1.00		
T	0.156 ± 0.075	0.88	1.00	0.04 ± 0.12	0.90	1.00	
U	–	–	–	0.122 ± 0.098	−0.57	−0.77	1.00

TeV^{-2}

	Result	Correlation Matrix							
	$(\mathrm{IC_{SMEFT}}/\mathrm{IC_{SM}} = 31.8/29.7)$								
$\hat{C}_{\varphi l}^{(1)}$	-0.007 ± 0.011	1.00							
$\hat{C}_{\varphi l}^{(3)}$	-0.039 ± 0.018	−0.34	1.00						
$\hat{C}_{\varphi e}$	-0.015 ± 0.011	0.54	0.40	1.00					
$\hat{C}_{\varphi q}^{(1)}$	-0.019 ± 0.044	−0.02	−0.06	−0.11	1.00				
$\hat{C}_{\varphi q}^{(3)}$	-0.111 ± 0.044	0.04	0.18	0.04	−0.36	1.00			
$\hat{C}_{\varphi u}$	0.08 ± 0.15	0.05	−0.05	0.01	0.61	−0.76	1.00		
$\hat{C}_{\varphi d}$	-0.63 ± 0.25	−0.12	−0.04	−0.23	0.40	0.57	−0.05	1.00	
$\hat{C}_{ll}$	-0.021 ± 0.028	−0.67	0.88	0.06	−0.06	0.05	−0.04	−0.05	1.00

NP fits in the conservative scenario

	Measurement	ST	STU	SMEFT
M_W [GeV]	80.409 ± 0.018	80.398 ± 0.016	80.409 ± 0.018	80.409 ± 0.018
Γ_W [GeV]	2.085 ± 0.042	2.0912 ± 0.0012	2.0922 ± 0.0015	2.0778 ± 0.0070
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23144 ± 0.00014	0.23147 ± 0.00014	
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.1477 ± 0.0011	0.1474 ± 0.0011	0.1488 ± 0.0015
Γ_Z [GeV]	2.4955 ± 0.0023	2.4973 ± 0.0014	2.4951 ± 0.0022	2.4955 ± 0.0023
σ_h^0 [nb]	41.480 ± 0.033	41.4910 ± 0.0080	41.4905 ± 0.0075	41.482 ± 0.033
R_ℓ^0	20.767 ± 0.025	20.7505 ± 0.0085	20.7515 ± 0.0085	20.769 ± 0.025
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.01636 ± 0.00024	0.01630 ± 0.00024	0.01660 ± 0.00032
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1477 ± 0.0011	0.1474 ± 0.0011	0.1488 ± 0.0015
R_b^0	0.21629 ± 0.00066	0.21591 ± 0.00011	0.21591 ± 0.00011	0.21633 ± 0.00066
R_c^0	0.1721 ± 0.0030	0.172195 ± 0.000055	0.172195 ± 0.000055	0.17160 ± 0.00100
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016	0.10355 ± 0.00076	0.10336 ± 0.00078	0.1009 ± 0.0014
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07400 ± 0.00059	0.07387 ± 0.00060	0.0735 ± 0.0023
$\mathcal{A}_b$	0.923 ± 0.020	0.934800 ± 0.000100	0.93478 ± 0.00010	0.903 ± 0.013
$\mathcal{A}_c$	0.670 ± 0.027	0.66810 ± 0.00053	0.66797 ± 0.00053	0.658 ± 0.020
$\mathcal{A}_s$	0.895 ± 0.091	0.935700 ± 0.000100	0.935680 ± 0.000100	0.905 ± 0.013
${\rm BR}_{W\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108385 ± 0.000025	0.108380 ± 0.000020	0.10900 ± 0.00039
$\sin^2\theta_{\rm eff}^{ll}$ (HC)	0.23143 ± 0.00025	0.23144 ± 0.00014	0.23147 ± 0.00014	
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000030	0.172220 ± 0.000030	0.17161 ± 0.00099

Theory Errors in the Fit

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

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

$$\delta_{\mathrm{th}} R^0_\ell = 0.006, \quad \delta_{\mathrm{th}} R^0_c = 0.00005, \quad \delta_{\mathrm{th}} R^0_b = 0.0001.$$

SYMMETRIES OF THE SM HIGGS SECTOR

In the SM, one Higgs doublet φ w. potential

$$V(\varphi) = -\frac{\mu^2}{2}|\varphi|^2 + \frac{\lambda}{4}|\varphi|^4 = -\frac{\mu^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\lambda}{4}\mathrm{Tr}(\Phi^\dagger\Phi)^2$$

with $\Phi \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} \varphi_0^* & \varphi_+ \\ -\varphi_+^* & \varphi_0 \end{pmatrix}$, invariant under $\Phi \to U_L \Phi U_R^\dagger$

where SU(2)$_L$ coincides with gauge SU(2), while Y with the third component of SU(2)$_R$. The charge-conserving

$\langle\Phi\rangle \equiv \frac{1}{2}\begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix}$ leaves the diagonal SU(2)$_V$ unbroken,

ensuring $M_{W_1} = M_{W_2} = M_{W_3}$ and $\rho \equiv \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$

SYMMETRIES OF THE SM HIGGS SECTOR

- Promoting right-handed quarks to $SU(2)_R$ doublets, one can write Yukawa couplings in the form

$$\bar{Q}_L \Phi \begin{pmatrix} Y_u & 0 \\ 0 & Y_d \end{pmatrix} Q_R$$

which would be $SU(2)_R$-invariant for $Y_u=Y_d$. Therefore, the tree-level prediction $\rho=1$ gets loop corrections proportional to $G_F m_t^2$.