Precision Electroweak Physics in the SM and Beyond

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- Introduction
- m_t, M_W and the fit to EWPO in the SM
- m_t, 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

HEPfit

INFN Istituto Nazionale di Fisica Nucleare

INTRODUCTION

- $SU(2)_L$ X $U(1)_Y$ gauge 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
  - precision measurements of masses and couplings
    - test the quantum structure of the SM
    - probe NP through its virtual effects

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 $G_F m_t^2$.

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 recent CMS l+jets measurement: m_t=171.77±0.37 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

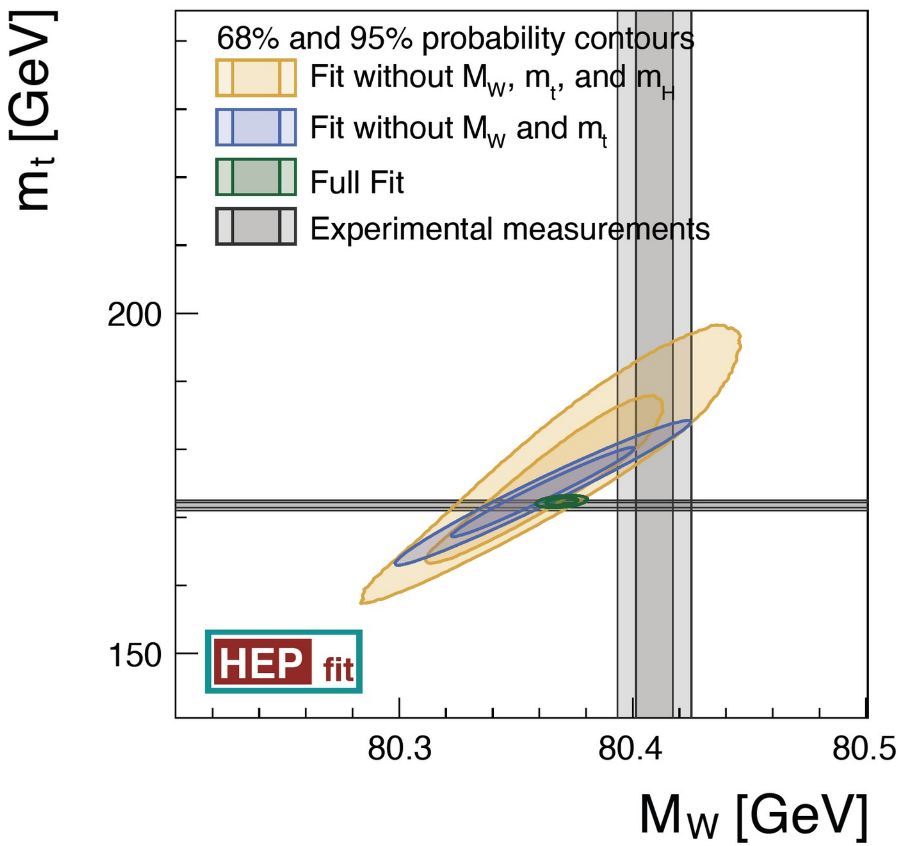
Model	Pred. M_W [GeV]	Pull	Pred. M_W [GeV]	Pull
	standard average		*conservative average*	
SM	80.3499 ± 0.0056	$6.1\,\sigma$	80.3505 ± 0.0077	$3.0\,\sigma$

- 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.

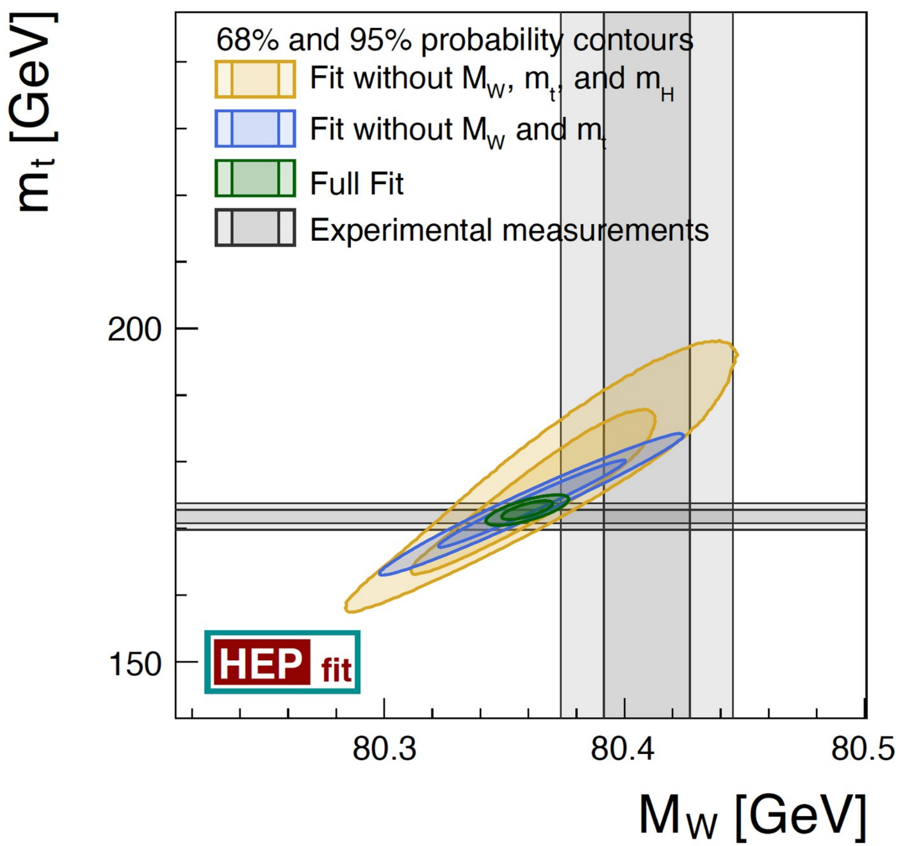
Awramik et al, '03

INTERPLAY OF M_W WITH OTHER OBSERVABLES

standard

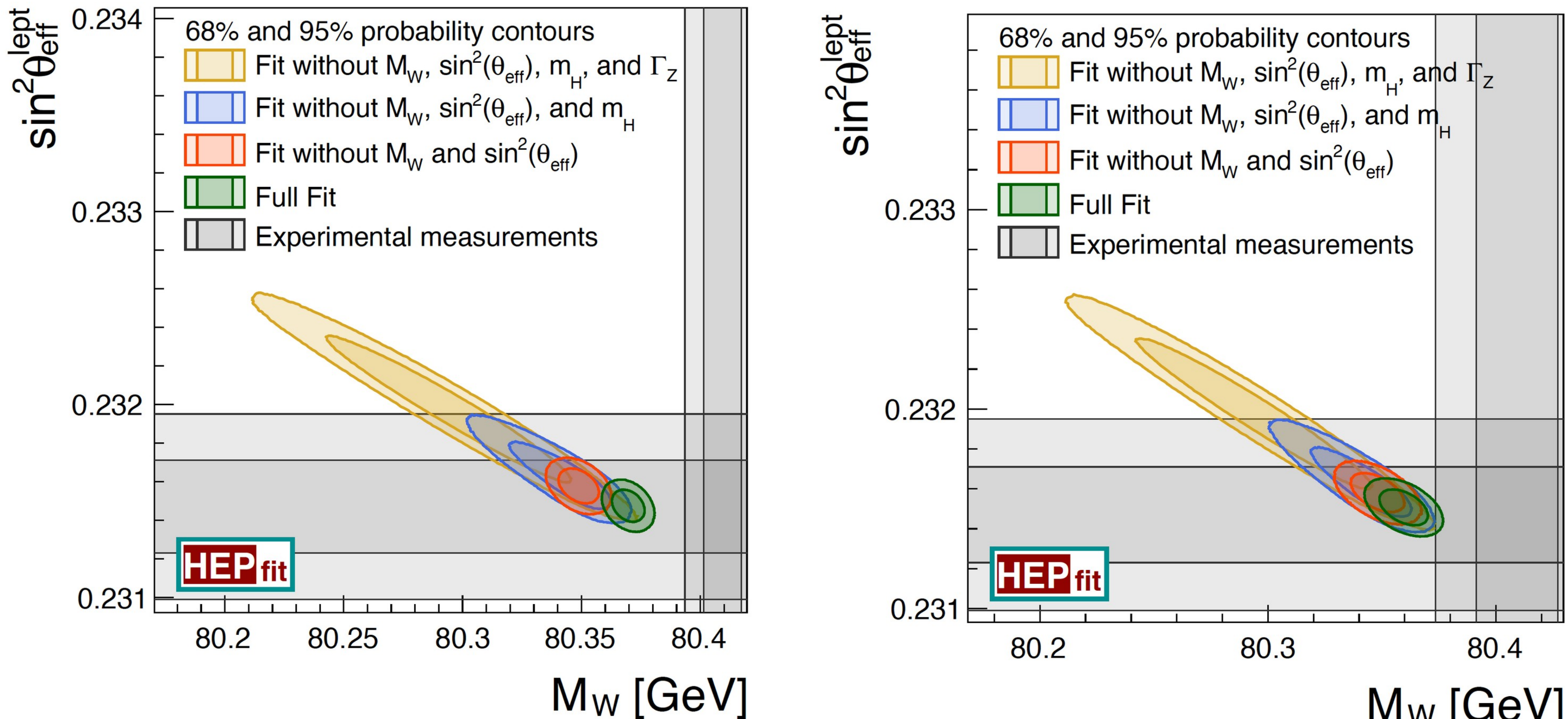


conservative



INTERPLAY OF M_W WITH OTHER OBSERVABLES

standard | conservative



Terminology

- Full Fit/Posterior: use all available information on both SM parameters and EWPOs. Gives our current best knowledge, assuming the validity of the SM
- 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.

	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11763 ± 0.00095	0.1170 ± 0.0028	0.2	0.1217 ± 0.0047	−0.8	0.1177 ± 0.0010	0.0
		[0.11577, 0.11946]	[0.1116, 0.1225]		[0.1126, 0.1310]		[0.1157, 0.1197]	
$\delta\alpha^5_{\rm had}$	0.02766 ± 0.00010	0.027541 ± 0.000096	0.02624 ± 0.00033	4.1	0.02793 ± 0.00068	−0.4	0.02766 ± 0.00010	0.0
		[0.027352, 0.027730]	[0.02559, 0.02689]		[0.02661, 0.02926]		[0.02746, 0.02786]	
M_Z [GeV]	91.1875 ± 0.0021	91.1910 ± 0.0020	91.2287 ± 0.0068	−5.8	91.210 ± 0.039	−0.6	91.1875 ± 0.0021	0.0
		[91.1870, 91.1949]	[91.2154, 91.2421]		[91.134, 91.287]		[91.1834, 91.1916]	
m_t [GeV]	171.79 ± 0.38	172.34 ± 0.37	180.9 ± 1.5	−5.9	186.7 ± 9.5	−1.6	171.80 ± 0.38	0.0
		[171.61, 173.06]	[178.0, 183.8]		[168.0, 205.1]		[171.05, 172.54]	
m_H [GeV]	125.21 ± 0.12	125.21 ± 0.12	94.0 ± 5.0	4.1	241.2 ± 121.3	−0.8	125.21 ± 0.12	0.0
		[124.97, 125.44]	[83.3, 104.3]		[100.8, 626.8]		[124.97, 125.45]	
M_W [GeV]	80.4093 ± 0.0079	80.3696 ± 0.0045	80.3499 ± 0.0056	6.1	80.4089 ± 0.0078	0.0	80.3496 ± 0.0057	6.1
		[80.3608, 80.3786]	[80.3390, 80.3609]		[80.3934, 80.4241]		[80.3386, 80.3608]	
Γ_W [GeV]	2.085 ± 0.042	2.08896 ± 0.00052	2.08896 ± 0.00052	−0.1	2.0940 ± 0.0023	−0.2	2.08744 ± 0.00059	0.0
		[2.08793, 2.08999]	[2.08793, 2.08998]		[2.0896, 2.0984]		[2.08627, 2.08859]	
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.231474 ± 0.000055	0.231473 ± 0.000055	0.8	0.23146 ± 0.00014	0.8	0.231558 ± 0.000062	0.7
		[0.231366, 0.231583]	[0.231364, 0.231581]		[0.23119, 0.23173]		[0.231436, 0.231679]	
$P^{\rm pol}_\tau = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14739 ± 0.00044	0.14741 ± 0.00044	−0.3	0.1475 ± 0.0011	−0.3	0.14675 ± 0.00049	−0.1
		[0.14654, 0.14825]	[0.14655, 0.14827]		[0.1454, 0.1496]		[0.14580, 0.14770]	
Γ_Z [GeV]	2.4955 ± 0.0023	2.49454 ± 0.00064	2.49434 ± 0.00068	0.5	2.4953 ± 0.0020	0.1	2.49397 ± 0.00068	0.6
		[2.49328, 2.49580]	[2.49300, 2.49567]		[2.4912, 2.4993]		[2.49262, 2.49531]	
σ^0_h [nb]	41.480 ± 0.033	41.4892 ± 0.0077	41.4914 ± 0.0080	−0.3	41.462 ± 0.030	0.4	41.4923 ± 0.0080	−0.4
		[41.4742, 41.5042]	[41.4758, 41.5072]		[41.403, 41.522]		[41.4766, 41.5081]	
R^0_ℓ	20.767 ± 0.025	20.7487 ± 0.0080	20.7451 ± 0.0086	0.8	20.760 ± 0.022	0.2	20.7468 ± 0.0087	0.7
		[20.7329, 20.7645]	[20.7281, 20.7621]		[20.717, 20.802]		[20.7298, 20.7637]	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	0.016293 ± 0.000096	0.016284 ± 0.000096	0.8	0.01631 ± 0.00024	0.8	0.01615 ± 0.00011	1.0
		[0.016106, 0.016482]	[0.016097, 0.016476]		[0.01585, 0.01679]		[0.01594, 0.01636]	
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14739 ± 0.00044	0.14742 ± 0.00045	1.8	0.1475 ± 0.0011	1.6	0.14675 ± 0.00049	2.1
		[0.14654, 0.14825]	[0.14654, 0.14832]		[0.1454, 0.1496]		[0.14580, 0.14770]	
R^0_b	0.21629 ± 0.00066	0.215894 ± 0.000100	0.21589 ± 0.00010	0.6	0.21543 ± 0.00036	1.1	0.21591 ± 0.00010	0.6
		[0.215697, 0.216090]	[0.21569, 0.21609]		[0.21472, 0.21614]		[0.21571, 0.21611]	
R^0_c	0.1721 ± 0.0030	0.172198 ± 0.000054	0.172199 ± 0.000054	−0.1	0.17240 ± 0.00018	−0.1	0.172189 ± 0.000054	−0.1
		[0.172093, 0.172302]	[0.172094, 0.172304]		[0.17205, 0.17277]		[0.172084, 0.172295]	
$A^{0,b}_{\rm FB}$	0.0996 ± 0.0016	0.10334 ± 0.00031	0.10335 ± 0.00032	−2.3	0.10338 ± 0.00077	−2.1	0.10288 ± 0.00034	−2.0
		[0.10273, 0.10393]	[0.10273, 0.10398]		[0.10189, 0.10489]		[0.10220, 0.10354]	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	0.07384 ± 0.00023	0.07385 ± 0.00024	−0.9	0.07391 ± 0.00059	−0.9	0.07348 ± 0.00025	−0.8
		[0.07339, 0.07428]	[0.07339, 0.07432]		[0.07275, 0.07507]		[0.07298, 0.07398]	
$\mathcal{A}_b$	0.923 ± 0.020	0.934768 ± 0.000040	0.934769 ± 0.000040	−0.6	0.93460 ± 0.00016	−0.6	0.934721 ± 0.000041	−0.6
		[0.934690, 0.934845]	[0.934691, 0.934846]		[0.93428, 0.93492]		[0.934642, 0.934801]	
$\mathcal{A}_c$	0.670 ± 0.027	0.66795 ± 0.00021	0.66795 ± 0.00022	0.1	0.66817 ± 0.00054	0.1	0.66766 ± 0.00022	0.1
		[0.66753, 0.66837]	[0.66753, 0.66838]		[0.66711, 0.66921]		[0.66722, 0.66810]	
$\mathcal{A}_s$	0.895 ± 0.091	0.935675 ± 0.000039	0.935674 ± 0.000040	−0.4	0.935714 ± 0.000099	−0.5	0.935621 ± 0.000041	−0.5
		[0.935597, 0.935752]	[0.935597, 0.935752]		[0.935523, 0.935907]		[0.935541, 0.935702]	
${\rm BR}_{W\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108388 ± 0.000022	0.108388 ± 0.000022	0.2	0.10829 ± 0.00011	0.3	0.108386 ± 0.000023	0.2
		[0.108345, 0.108431]	[0.108344, 0.108431]		[0.10807, 0.10850]		[0.108340, 0.108432]	
$\sin^2\theta^{ll}_{\rm eff}$ (HC)	0.23143 ± 0.00025	0.231474 ± 0.000055	0.231477 ± 0.000056	−0.2	0.23146 ± 0.00014	−0.1	0.231558 ± 0.000062	−0.5
		[0.231366, 0.231583]	[0.231366, 0.231588]		[0.23119, 0.23173]		[0.231436, 0.231679]	
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000031	0.172220 ± 0.000031	−0.7	0.17242 ± 0.00018	−0.7	0.172212 ± 0.000032	−0.7
		[0.172158, 0.172282]	[0.172158, 0.172281]		[0.17208, 0.17278]		[0.172149, 0.172275]	

"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	0.1197 ± 0.0028	-0.7	0.1218 ± 0.0047	-0.8	0.1177 ± 0.0010	0.0
		$[0.11606, 0.11976]$	$[0.1142, 0.1253]$		$[0.1126, 0.1310]$		$[0.1157, 0.1197]$	
$\delta\alpha^5_{\rm had}$	0.02766 ± 0.00010	0.027624 ± 0.000097	0.02703 ± 0.00040	1.5	0.02792 ± 0.00071	-0.4	0.02766 ± 0.00010	-0.1
		$[0.027432, 0.027814]$	$[0.02624, 0.02781]$		$[0.02653, 0.02932]$		$[0.02747, 0.02786]$	
M_Z [GeV]	91.1875 ± 0.0021	91.1883 ± 0.0021	91.218 ± 0.011	-2.7	91.209 ± 0.039	-0.5	91.1875 ± 0.0021	-0.1
		$[91.1843, 91.1924]$	$[91.196, 91.240]$		$[91.134, 91.287]$		$[91.1834, 91.1916]$	
m_t [GeV]	171.8 ± 1.0	172.75 ± 0.93	179.1 ± 2.5	-2.6	186.5 ± 10.1	-1.4	171.8 ± 1.0	0.0
		$[170.92, 174.59]$	$[174.0, 184.0]$		$[166.7, 205.8]$		$[169.8, 173.8]$	
m_H [GeV]	125.21 ± 0.12	125.21 ± 0.12	105.0 ± 11.3	1.5	238.4 ± 121.3	-0.8	125.21 ± 0.12	0.1
		$[124.97, 125.44]$	$[87.7, 134.1]$		$[98.1, 629.5]$		$[124.97, 125.45]$	
M_W [GeV]	80.409 ± 0.018	80.3595 ± 0.0070	80.3505 ± 0.0077	3.0	80.407 ± 0.017	0.1	80.3497 ± 0.0079	3.1
		$[80.3456, 80.3733]$	$[80.3355, 80.3656]$		$[80.373, 80.441]$		$[80.3342, 80.3653]$	
Γ_W [GeV]	2.085 ± 0.042	2.08831 ± 0.00067	2.08830 ± 0.00067	-0.1	2.0939 ± 0.0026	-0.2	2.08743 ± 0.00073	0.0
		$[2.08700, 2.08963]$	$[2.08700, 2.08961]$		$[2.0888, 2.0989]$		$[2.08601, 2.08889]$	
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.231507 ± 0.000060	0.231505 ± 0.000059	0.7	0.23146 ± 0.00014	0.8	0.231558 ± 0.000068	0.7
		$[0.231389, 0.231623]$	$[0.231388, 0.231622]$		$[0.23119, 0.23173]$		$[0.231426, 0.231691]$	
$P^{\rm pol}_\tau = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14713 ± 0.00047	0.14716 ± 0.00047	-0.2	0.1475 ± 0.0011	-0.3	0.14674 ± 0.00053	-0.1
		$[0.14622, 0.14806]$	$[0.14622, 0.14808]$		$[0.1454, 0.1496]$		$[0.14570, 0.14779]$	
Γ_Z [GeV]	2.4955 ± 0.0023	2.49444 ± 0.00067	2.49423 ± 0.00071	0.5	2.4952 ± 0.0021	0.1	2.49396 ± 0.00072	0.6
		$[2.49313, 2.49574]$	$[2.49285, 2.49562]$		$[2.4911, 2.4993]$		$[2.49257, 2.49538]$	
σ^0_h [nb]	41.480 ± 0.033	41.4907 ± 0.0076	41.4928 ± 0.0080	-0.4	41.462 ± 0.030	0.4	41.4924 ± 0.0080	-0.4
		$[41.4756, 41.5057]$	$[41.4771, 41.5086]$		$[41.403, 41.522]$		$[41.4767, 41.5083]$	
R^0_ℓ	20.767 ± 0.025	20.7495 ± 0.0080	20.7460 ± 0.0087	0.8	20.760 ± 0.022	0.2	20.7470 ± 0.0087	0.8
		$[20.7337, 20.7652]$	$[20.7291, 20.7630]$		$[20.717, 20.803]$		$[20.7297, 20.7638]$	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	0.01624 ± 0.00010	0.01623 ± 0.00010	0.9	0.01631 ± 0.00024	0.8	0.01615 ± 0.00012	1.0
		$[0.01604, 0.01644]$	$[0.01602, 0.01643]$		$[0.01585, 0.01679]$		$[0.01592, 0.01638]$	
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14713 ± 0.00047	0.14715 ± 0.00049	1.9	0.1475 ± 0.0011	1.6	0.14674 ± 0.00053	2.1
		$[0.14622, 0.14806]$	$[0.14619, 0.14811]$		$[0.1454, 0.1496]$		$[0.14570, 0.14779]$	
R^0_b	0.21629 ± 0.00066	0.21588 ± 0.00010	0.21587 ± 0.00011	0.6	0.21545 ± 0.00038	1.1	0.21591 ± 0.00011	0.6
		$[0.21567, 0.21608]$	$[0.21566, 0.21608]$		$[0.21470, 0.21617]$		$[0.21570, 0.21611]$	
R^0_c	0.1721 ± 0.0030	0.172206 ± 0.000054	0.172206 ± 0.000054	0.0	0.17239 ± 0.00019	-0.1	0.172190 ± 0.000055	-0.1
		$[0.172100, 0.172313]$	$[0.172099, 0.172312]$		$[0.17204, 0.17277]$		$[0.172082, 0.172297]$	
$A^{0,b}_{\rm FB}$	0.0996 ± 0.0016	0.10315 ± 0.00033	0.10316 ± 0.00034	-2.2	0.10338 ± 0.00076	-2.1	0.10287 ± 0.00037	-2.0
		$[0.10250, 0.10380]$	$[0.10248, 0.10384]$		$[0.10187, 0.10488]$		$[0.10214, 0.10361]$	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	0.07370 ± 0.00025	0.07370 ± 0.00026	-0.9	0.07391 ± 0.00059	-0.9	0.07348 ± 0.00028	-0.8
		$[0.07321, 0.07418]$	$[0.07319, 0.07421]$		$[0.07275, 0.07507]$		$[0.07293, 0.07403]$	
$\mathcal{A}_b$	0.923 ± 0.020	0.934739 ± 0.000040	0.934740 ± 0.000040	-0.6	0.93461 ± 0.00017	-0.6	0.934721 ± 0.000041	-0.6
		$[0.934661, 0.934819]$	$[0.934661, 0.934820]$		$[0.93427, 0.93494]$		$[0.934640, 0.934802]$	
$\mathcal{A}_c$	0.670 ± 0.027	0.66783 ± 0.00023	0.66783 ± 0.00023	0.1	0.66815 ± 0.00054	0.1	0.66766 ± 0.00024	0.1
		$[0.66737, 0.66828]$	$[0.66737, 0.66829]$		$[0.66711, 0.66922]$		$[0.66718, 0.66814]$	
$\mathcal{A}_s$	0.895 ± 0.091	0.935652 ± 0.000043	0.935653 ± 0.000043	-0.4	0.935713 ± 0.000099	-0.5	0.935622 ± 0.000045	-0.5
		$[0.935568, 0.935736]$	$[0.935568, 0.935736]$		$[0.935518, 0.935906]$		$[0.935533, 0.935709]$	
${\rm BR}_{W\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108381 ± 0.000022	0.108381 ± 0.000022	0.2	0.10829 ± 0.00011	0.3	0.108386 ± 0.000023	0.2
		$[0.108338, 0.108424]$	$[0.108338, 0.108424]$		$[0.10808, 0.10851]$		$[0.108340, 0.108432]$	
$\sin^2\theta^{ll}_{\rm eff}$ (HC)	0.23143 ± 0.00025	0.231507 ± 0.000060	0.231511 ± 0.000061	-0.3	0.23146 ± 0.00014	-0.1	0.231558 ± 0.000068	-0.5
		$[0.231389, 0.231623]$	$[0.231392, 0.231632]$		$[0.23119, 0.23173]$		$[0.231426, 0.231691]$	
R_{uc}	0.1660 ± 0.0090	0.172227 ± 0.000033	0.172227 ± 0.000033	-0.7	0.17242 ± 0.00018	-0.7	0.172211 ± 0.000034	-0.7
		$[0.172163, 0.172292]$	$[0.172164, 0.172292]$		$[0.17207, 0.17278]$		$[0.172145, 0.172277]$	

"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:

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

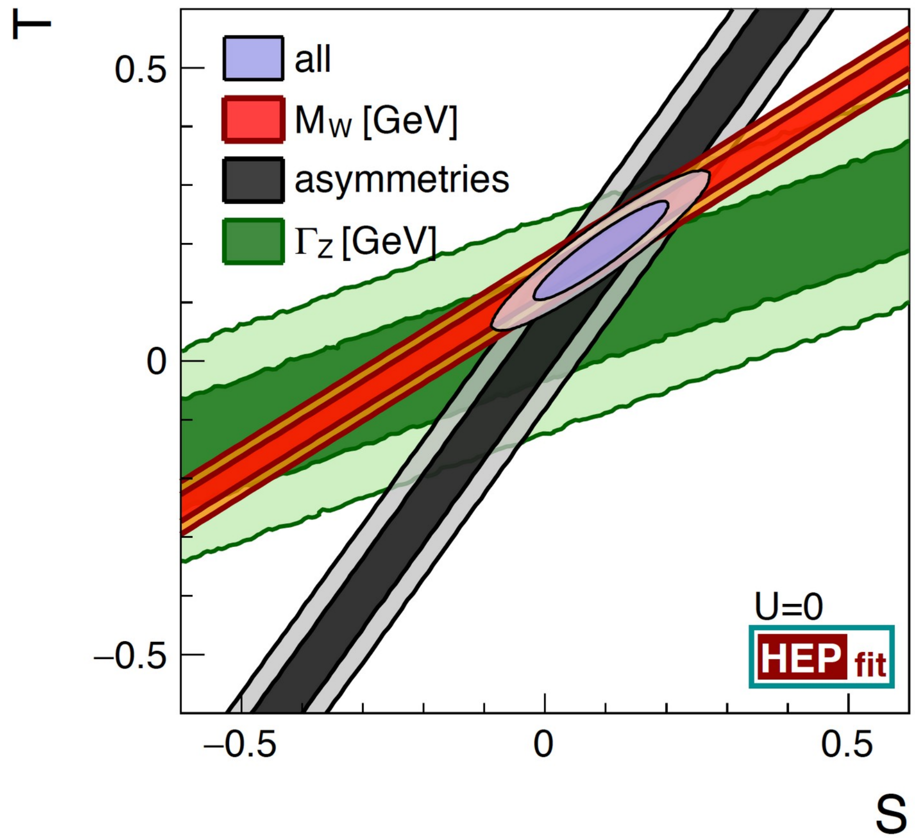
$$T = \frac{4\pi}{s_W^2 c_W^2 M_Z^2}\left[\Pi_{11}^{\mathrm{NP}}(0) - \Pi_{33}^{\mathrm{NP}}(0)\right],$$

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

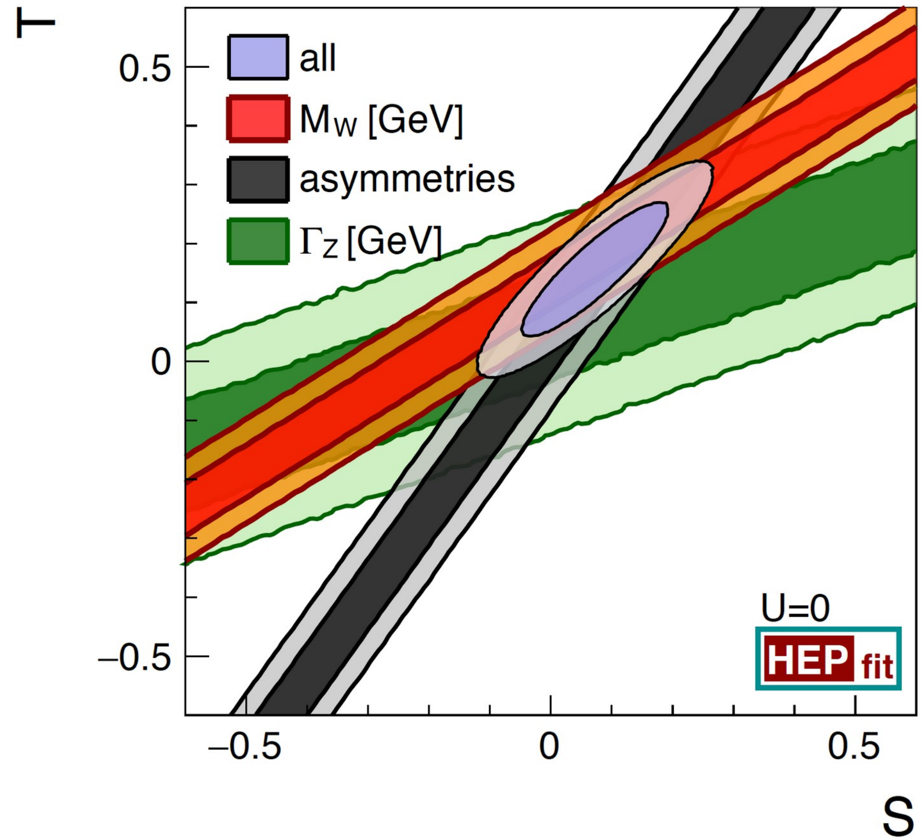
- EWPO are modified as follows:
  - $\delta\Gamma_Z \propto \quad -10(3-8s_W^2)\,S + (63-126s_W^2-40s_W^4)\,T$
  - $\delta M_W, \delta\Gamma_W \propto \quad S - 2c_W^2\,T - \frac{(c_W^2 - s_W^2)\,U}{2s_W^2}$
  - all other observables: $S - 4c_W^2 s_W^2\,T$

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		
	$(IC_{ST}/IC_{SM} = 24.5/73.9)$				$(IC_{STU}/IC_{SM} = 25.3/73.9)$			
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":

$$\mathcal{O}_{\phi WB} = (\phi^\dagger \sigma_i \phi)\, W^i_{\mu\nu} B^{\mu\nu} \;, \quad \rightarrow S$$
$$\mathcal{O}_{\phi D} = (\phi^\dagger D^\mu \phi)^* \,(\phi^\dagger D_\mu \phi) \;, \quad \rightarrow T$$
$$\mathcal{O}_{ll} = (\overline{l_L}\gamma^\mu l_L)(\overline{l_L}\gamma^\mu l_L)$$

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

M_W IN THE SMEFT

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

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

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

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

- 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

	$(\mathrm{IC_{SMEFT}}/\mathrm{IC_{SM}} = 31.8/73.9)$								
$\hat{C}^{(1)}_{\varphi l}$	-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 $pp \to ll$.

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
$\mathrm{BR}_{W\ell\bar{\nu}_\ell}$	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!