High-precision measurement of the W boson mass: theory context and implications

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- Introduction
- 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
See also ~100 more papers...

HEPfit

INFN Istituto Nazionale di Fisica Nucleare

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
  - 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 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.

M_W: SM vs EXPERIMENT

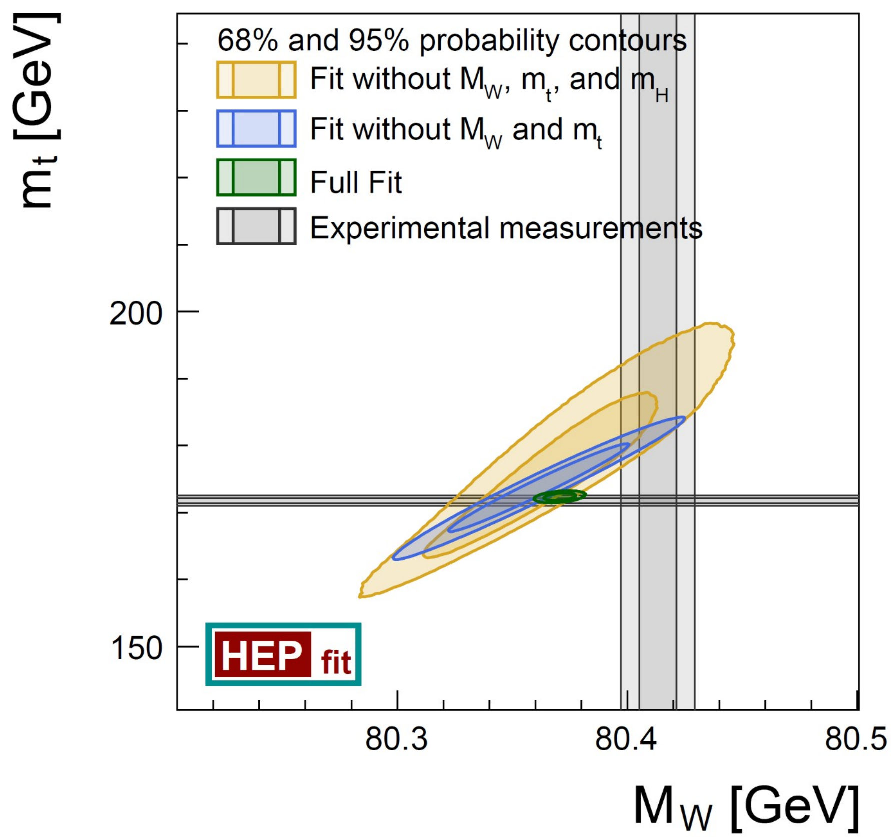
- Also for M_W, "standard" average completely dominated by very recent CDF measurement. Taking systematic errors fully correlated, we obtain M_W=80413.3±8.0 MeV. However, there are tensions between LHC, TeVatron and LEP measurements, so consider also "conservative" average with error inflated à la PDG to 15 MeV

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

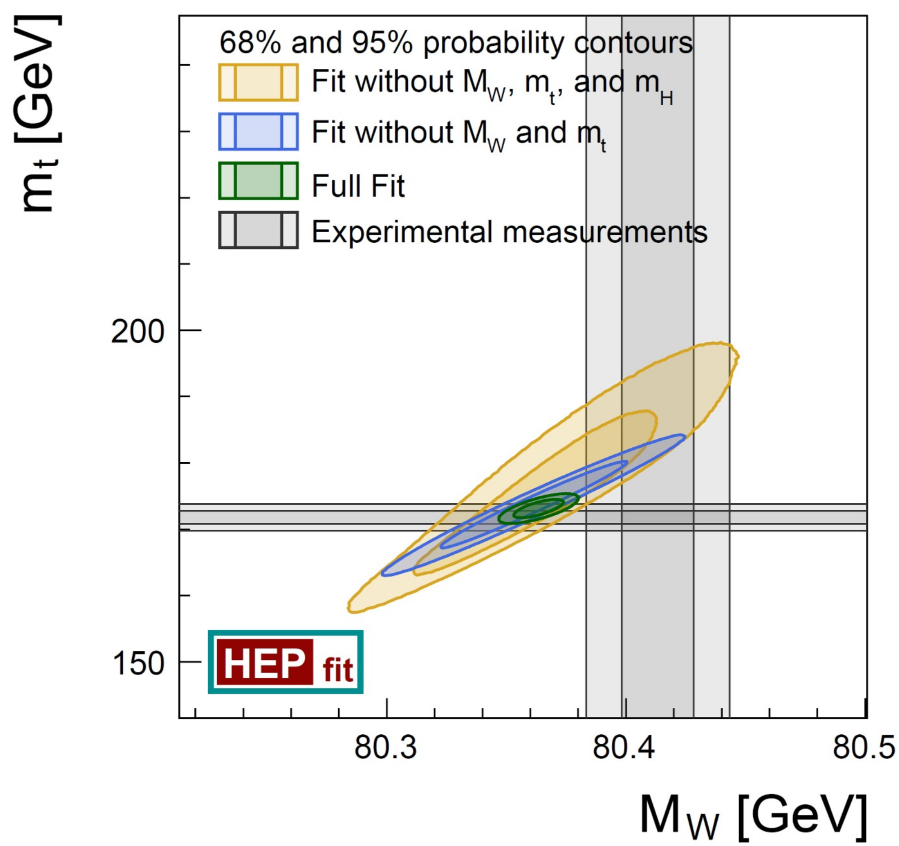
The SM prediction is obtained omitting the experimental information on M_W. Previously, the tension was 1.8σ. Current theory error on M_W in the SM is 4 MeV Awramik et al, '03

INTERPLAY OF M_W WITH OTHER OBSERVABLES

standard

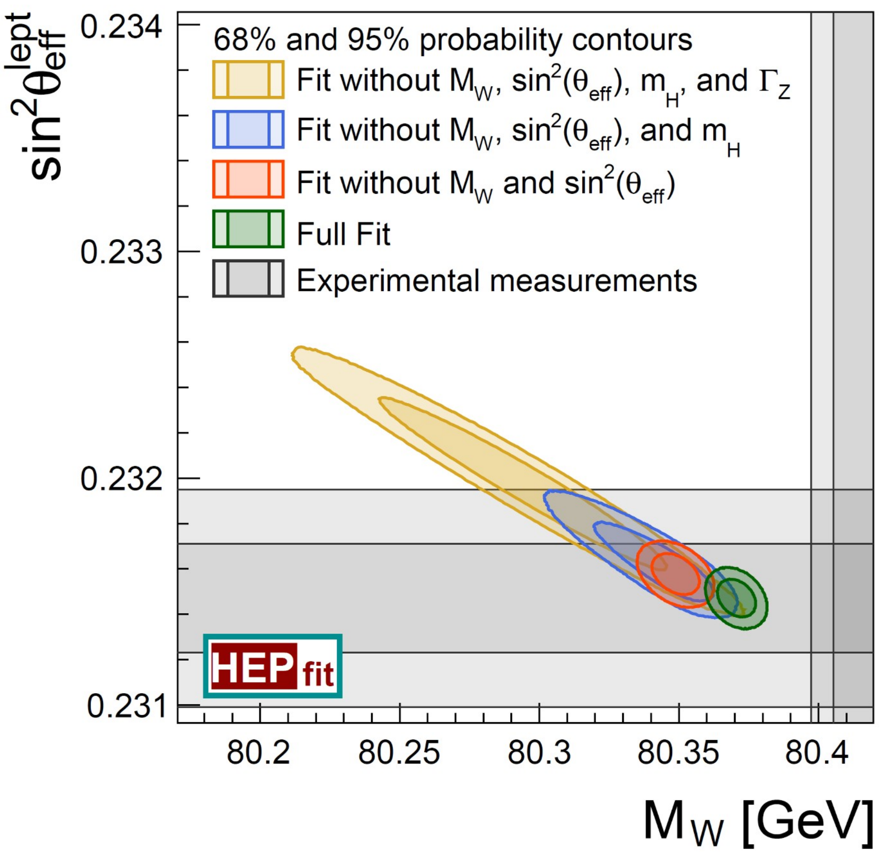


conservative

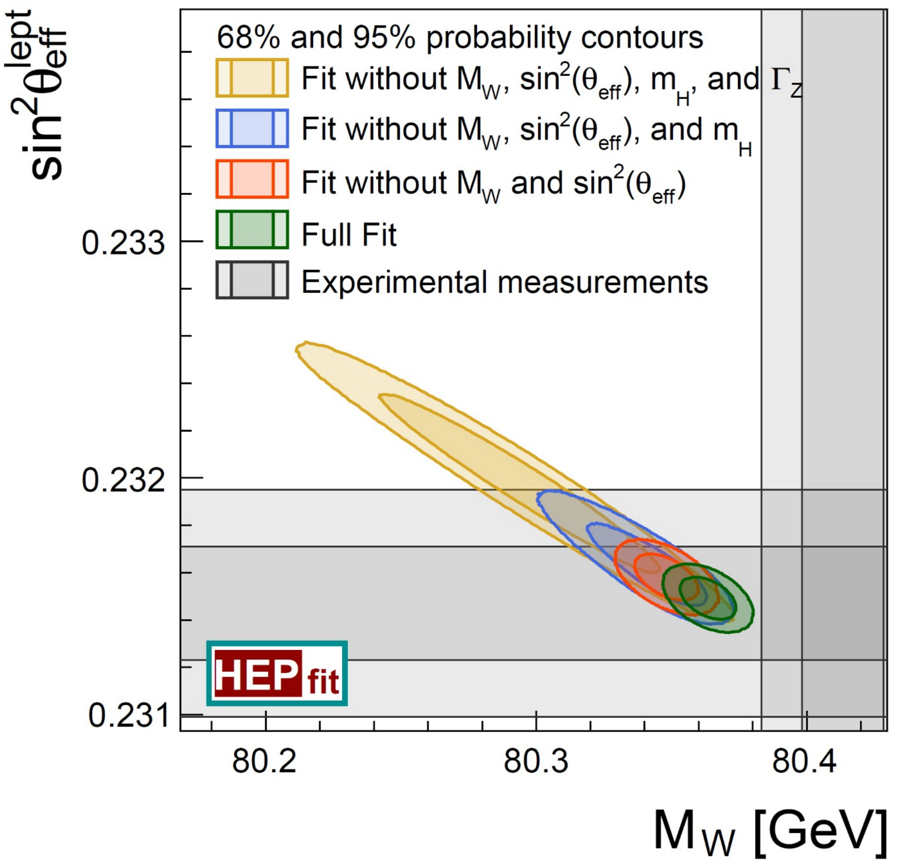


INTERPLAY OF M_W WITH OTHER OBSERVABLES

standard



conservative



	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11762 ± 0.00095 [0.11576, 0.11946]	0.11685 ± 0.00278 [0.11145, 0.1[illegible]33]	0.3	0.12181 ± 0.00470 [0.1126, [illegible]1310]	−0.8	0.1177 ± 0.0010 [0.1157, 0.11[illegible]]	–
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	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, 17[illegible]]	181.45 ± 1.49 [illegible]	6.3	187.58 ± 9.52 [169.1, 206.1]	−1.7	171.80 ± 0.3[illegible]	[illegible]
m_H [GeV]	[illegible]	$125.20 \pm$ [illegible] [124.97, 12[illegible]]	[illegible]	[illegible]	247.98 ± 125.35 [100.8, 640.4]	−0.9	[illegible]	[illegible]
M_W [GeV]	[illegible]	[illegible].3706 ± [illegible] [illegible].3617, [illegible]	[illegible]	[illegible]	80.4129 ± 0.0080 [80.3973, 80.4284]	0.1	[illegible]	[illegible]
Γ_W [GeV]	[illegible]	[illegible]8903 ± 0[illegible] [illegible]08800, 2.[illegible]	[illegible]	[illegible]	2.09430 ± 0.00224 [2.0900, 2.0988]	−0.2	[illegible]	[illegible]
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.231471 ± 0[illegible] [0.231362, 0.231580]	[illegible] [0.231361, 0.231578]	[illegible]	0.231460 ± 0.000138 [0.23119, 0.23173]	0.8	0.231558 ± 0.000062 [0.231436, 0.231679]	0.7
$P^{\rm pol}_\tau = \mathcal{A}_\ell$	$0.1465 \pm 0.$[illegible]	[illegible]	0.14744 ± 0.00044 [0.14657, 0.14830]	[illegible]	[illegible]	[illegible]	0.14675 ± 0.00049 [0.14580, 0.14770]	−0.1
Γ_Z [GeV]	$2.4955 \pm 0.$[illegible]	[illegible]	2.49437 ± 0.00068 [2.49301, 2.49569]	[illegible]	[illegible]	[illegible]	2.49397 ± 0.00068 [2.49262, 2.49531]	0.6
σ^0_h [nb]	$41.480 \pm 0.$[illegible]	[illegible] [41.4741, 41.5041]	41.4914 ± 0.0080 [41.4757, 41.5070]	[illegible]	[illegible]	[illegible]	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 ± 0.0087 [20.7281, 20.7621]	[illegible]	[illegible]	[illegible]	20.7468 ± 0.0087 [20.7298, 20.7637]	0.7
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	0.016300 ± 0.000095 [0.016111, 0.016487]	0.016291 ± 0.000096 [0.016102, 0.016480]	0.8	0.016316 ± 0.000240 [0.01585, 0.01679]	0.8	0.01615 ± 0.00011 [0.01594, 0.01636]	1.0
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14742 ± 0.00044 [0.14656, 0.14827]	0.14745 ± 0.00045 [0.14656, 0.14834]	1.8	0.14750 ± 0.00108 [0.1454, 0.1496]	1.6	0.14675 ± 0.00049 [0.14580, 0.14770]	2.1
R^0_b	0.21629 ± 0.00066	0.215892 ± 0.000100 [0.215696, 0.216089]	0.215886 ± 0.000102 [0.215688, 0.216086]	0.6	0.215413 ± 0.000364 [0.21469, 0.21611]	1.2	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]	0.172197 ± 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
$A^{0,b}_{\rm FB}$	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
$A^{0,c}_{\rm FB}$	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
${\rm BR}_{W\to\ell\bar\nu_\ell}$	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
$\sin^2\theta^{\rm lept}_{\rm eff}$ (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 value used as input

Result of the global fit

Result of the fit not using the corresponding measurement

Result of the fit not using any info on SM parameters

Prediction using only info on SM parameters

"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	0.11685 ± 0.00278	0.3	0.12181 ± 0.00470	-0.8	0.1177 ± 0.0010	–
		$[0.11576, 0.11946]$	$[0.11145, 0.12233]$		$[0.1126, 0.1310]$		$[0.1157, 0.1197]$	
$\Delta\alpha^{(5)}_{\text{had}}(M_Z)$	0.02766 ± 0.00010	0.027535 ± 0.000096	0.026174 ± 0.000334	4.3	0.028005 ± 0.000675	-0.5	0.02766 ± 0.00010	–
		$[0.027349, 0.027726]$	$[0.025522, 0.026826]$		$[0.02667, 0.02932]$		$[0.02746, 0.02786]$	
M_Z [GeV]	91.1875 ± 0.0021	91.1911 ± 0.0020	91.2314 ± 0.0069	-6.1	91.2108 ± 0.0390	-0.6	91.1875 ± 0.0021	–
		$[91.1872, 91.1950]$	$[91.2178, 91.2447]$		$[91.136, 91.288]$		$[91.1834, 91.1916]$	
m_t [GeV]	171.79 ± 0.38	172.36 ± 0.37	181.45 ± 1.49	-6.3	187.58 ± 9.52	-1.7	171.80 ± 0.38	–
		$[171.64, 173.09]$	$[178.53, 184.42]$		$[169.1, 206.1]$		$[171.05, 172.54]$	
m_H [GeV]	125.21 ± 0.12	125.20 ± 0.12	93.36 ± 4.99	4.3	247.98 ± 125.35	-0.9	125.21 ± 0.12	–
		$[124.97, 125.44]$	$[82.92, 102.89]$		$[100.8, 640.4]$		$[124.97, 125.45]$	
M_W [GeV]	80.4133 ± 0.0080	80.3706 ± 0.0045	80.3499 ± 0.0056	6.5	80.4129 ± 0.0080	0.1	80.3496 ± 0.0057	6.5
		$[80.3617, 80.3794]$	$[80.3391, 80.3610]$		$[80.3973, 80.4284]$		$[80.3386, 80.3608]$	
Γ_W [GeV]	2.085 ± 0.042	2.08903 ± 0.00053	2.08902 ± 0.00052	-0.1	2.09430 ± 0.00224	-0.2	2.08744 ± 0.00059	0.0
		$[2.08800, 2.09006]$	$[2.08799, 2.09005]$		$[2.0900, 2.0988]$		$[2.08627, 2.08859]$	
$\sin^2\theta^{\text{lept}}_{\text{eff}}(Q^{\text{had}}_{\text{FB}})$	0.2324 ± 0.0012	0.231471 ± 0.000055	0.231469 ± 0.000056	0.8	0.231460 ± 0.000138	0.8	0.231558 ± 0.000062	0.7
		$[0.231362, 0.231580]$	$[0.231361, 0.231578]$		$[0.23119, 0.23173]$		$[0.231436, 0.231679]$	
$P^{\text{pol}}_\tau = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14742 ± 0.00044	0.14744 ± 0.00044	-0.3	0.14750 ± 0.00108	-0.3	0.14675 ± 0.00049	-0.1
		$[0.14656, 0.14827]$	$[0.14657, 0.14830]$		$[0.1454, 0.1496]$		$[0.14580, 0.14770]$	
Γ_Z [GeV]	2.4955 ± 0.0023	2.49455 ± 0.00065	2.49437 ± 0.00068	0.5	2.49530 ± 0.00204	0.0	2.49397 ± 0.00068	0.6
		$[2.49329, 2.49581]$	$[2.49301, 2.49569]$		$[2.4912, 2.4993]$		$[2.49262, 2.49531]$	
σ^0_h [nb]	41.480 ± 0.033	41.4892 ± 0.0077	41.4914 ± 0.0080	-0.3	41.4613 ± 0.0303	0.4	41.4923 ± 0.0080	-0.4
		$[41.4741, 41.5041]$	$[41.4757, 41.5070]$		$[41.402, 41.521]$		$[41.4766, 41.5081]$	
R^0_ℓ	20.767 ± 0.025	20.7487 ± 0.0080	20.7451 ± 0.0087	0.8	20.7587 ± 0.0217	0.2	20.7468 ± 0.0087	0.7
		$[20.7329, 20.7645]$	$[20.7281, 20.7621]$		$[20.716, 20.801]$		$[20.7298, 20.7637]$	
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	0.016300 ± 0.000095	0.016291 ± 0.000096	0.8	0.016316 ± 0.000240	0.8	0.01615 ± 0.00011	1.0
		$[0.016111, 0.016487]$	$[0.016102, 0.016480]$		$[0.01585, 0.01679]$		$[0.01594, 0.01636]$	
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14742 ± 0.00044	0.14745 ± 0.00045	1.8	0.14750 ± 0.00108	1.6	0.14675 ± 0.00049	2.1
		$[0.14656, 0.14827]$	$[0.14656, 0.14834]$		$[0.1454, 0.1496]$		$[0.14580, 0.14770]$	
R^0_b	0.21629 ± 0.00066	0.215892 ± 0.000100	0.215886 ± 0.000102	0.6	0.215413 ± 0.000364	1.2	0.21591 ± 0.00010	0.6
		$[0.215696, 0.216089]$	$[0.215688, 0.216086]$		$[0.21469, 0.21611]$		$[0.21571, 0.21611]$	
R^0_c	0.1721 ± 0.0030	0.172198 ± 0.000054	0.172197 ± 0.000054	-0.1	0.172404 ± 0.000183	-0.1	0.172189 ± 0.000054	-0.1
		$[0.172093, 0.172302]$	$[0.172094, 0.172303]$		$[0.17206, 0.17278]$		$[0.172084, 0.172295]$	
$A^{0,b}_{\text{FB}}$	0.0996 ± 0.0016	0.10335 ± 0.00030	0.10337 ± 0.00032	-2.3	0.10338 ± 0.00077	-2.1	0.10288 ± 0.00034	-2.0
		$[0.10276, 0.10396]$	$[0.10275, 0.10400]$		$[0.10189, 0.10490]$		$[0.10220, 0.10354]$	
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	0.07385 ± 0.00023	0.07387 ± 0.00023	-0.9	0.07392 ± 0.00059	-0.9	0.07348 ± 0.00025	-0.8
		$[0.07341, 0.07430]$	$[0.07341, 0.07434]$		$[0.07275, 0.07507]$		$[0.07298, 0.07398]$	
$\mathcal{A}_b$	0.923 ± 0.020	0.934770 ± 0.000039	0.934772 ± 0.000040	-0.6	0.934593 ± 0.000166	-0.6	0.934721 ± 0.000041	-0.6
		$[0.934693, 0.934847]$	$[0.934693, 0.934849]$		$[0.93426, 0.93491]$		$[0.934642, 0.934801]$	
$\mathcal{A}_c$	0.670 ± 0.027	0.66796 ± 0.00021	0.66797 ± 0.00021	0.1	0.66817 ± 0.00054	0.1	0.66766 ± 0.00022	0.1
		$[0.66754, 0.66838]$	$[0.66755, 0.66839]$		$[0.66712, 0.66922]$		$[0.66722, 0.66810]$	
$\mathcal{A}_s$	0.895 ± 0.091	0.935678 ± 0.000039	0.935677 ± 0.000040	-0.4	0.935716 ± 0.000098	-0.5	0.935621 ± 0.000041	-0.5
		$[0.935600, 0.935755]$	$[0.935599, 0.935754]$		$[0.935523, 0.935909]$		$[0.935541, 0.935702]$	
$\text{BR}_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108388 ± 0.000022	0.108388 ± 0.000022	0.2	0.108291 ± 0.000109	0.3	0.108386 ± 0.000023	0.2
		$[0.108345, 0.108431]$	$[0.108345, 0.108431]$		$[0.10808, 0.10851]$		$[0.108340, 0.108432]$	
$\sin^2\theta^{\text{lept}}_{\text{eff}}$ (HC)	0.23143 ± 0.00025	0.231471 ± 0.000055	0.231474 ± 0.000056	-0.2	0.231460 ± 0.000138	-0.1	0.231558 ± 0.000062	-0.5
		$[0.231362, 0.231580]$	$[0.231363, 0.231584]$		$[0.23119, 0.23173]$		$[0.231436, 0.231679]$	
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000031	0.172220 ± 0.000032	-0.7	0.172424 ± 0.000180	-0.7	0.172212 ± 0.000032	-0.7
		$[0.172159, 0.172282]$	$[0.172159, 0.172282]$		$[0.17209, 0.17279]$		$[0.172149, 0.172275]$	

"standard" scenario

	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11786 ± 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 $[0.1157, 0.1197]$	–
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	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
${\rm BR}_{W\to\ell\bar\nu_\ell}$	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

“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:
  - $p=2.45\ 10^{-5}$, i.e. 4.2σ (standard scenario)
  - $p=0.10$, i.e. 1.6σ (conservative scenario)

M_W BEYOND THE SM

- Two broad options:
  - Add NP that breaks custodial symmetry and allows for $\rho \neq 1$ at tree level $\rightarrow$ not considered here; see for example Strumia, arXiv:2204.04191
  - 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).

OBLIQUE NP

- Assume NP dominant contribution in gauge Boson propagators:

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

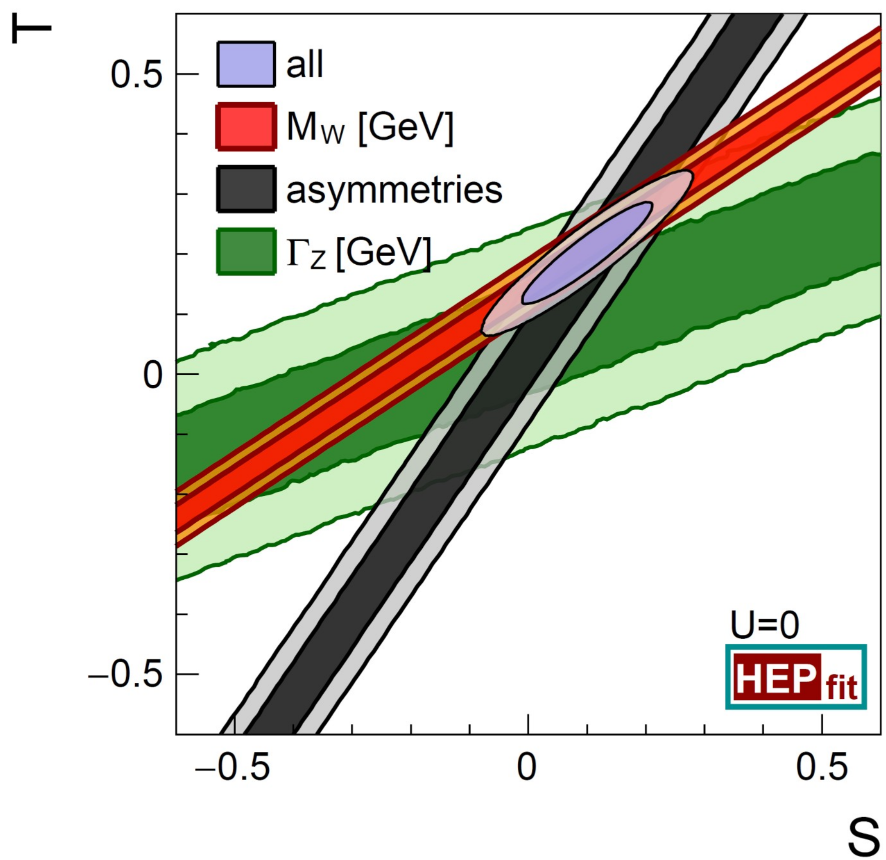
$$T = \frac{4\pi}{s_W^2 c_W^2 M_Z^2}\left[\Pi_{11}^{\mathrm{NP}}(0) - \Pi_{33}^{\mathrm{NP}}(0)\right],$$

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

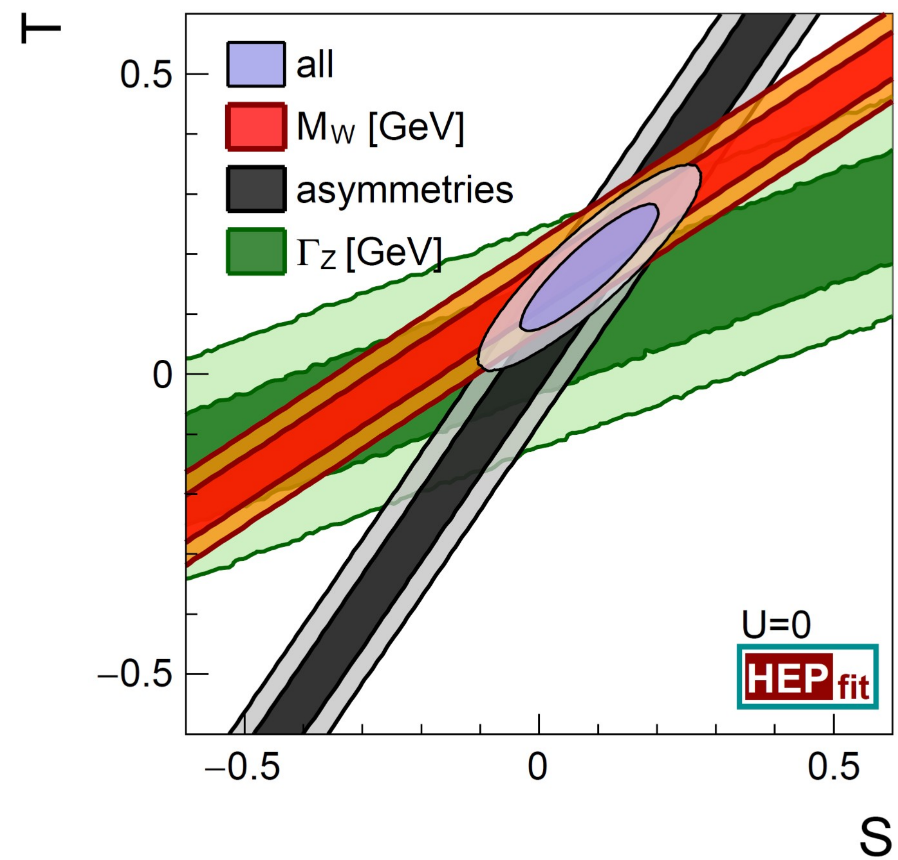
- EWPO are modified as follows:
  - $\delta\Gamma_Z \propto \quad -10(3 - 8s_W^2)\,S + (63 - 126s_W^2 - 40s_W^4)\,T$
  - $\delta M_W,\ \delta\Gamma_W \propto \quad S - 2c_W^2\,T - \frac{(c_W^2 - s_W^2)\,U}{2s_W^2}$
  - all other observables: $S - 4c_W^2 s_W^2\,T$

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		
	($IC_{ST}/IC_{SM} = 25.0/80.2$)			($IC_{STU}/IC_{SM} = 25.3/80.2$)			
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

- No significant gain in IC for U≠0

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	$0.2\,\sigma$

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":

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

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

M_W IN THE SMEFT

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

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

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

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

- 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

$\hat{C}_{\varphi l}^{(1)}$	-0.007 ± 0.011	1.00							
$\hat{C}_{\varphi l}^{(3)}$	-0.042 ± 0.015	-0.68	1.00						
$\hat{C}_{\varphi e}$	-0.017 ± 0.009	0.48	0.04	1.00					
$\hat{C}_{\varphi q}^{(1)}$	-0.018 ± 0.044	-0.02	-0.06	-0.13	1.00				
$\hat{C}_{\varphi q}^{(3)}$	-0.113 ± 0.043	-0.03	0.04	-0.16	-0.37	1.00			
$\hat{C}_{\varphi u}$	0.090 ± 0.150	0.06	-0.04	0.04	0.61	-0.77	1.00		
$\hat{C}_{\varphi d}$	-0.630 ± 0.250	-0.13	-0.05	-0.30	0.40	0.58	-0.04	1.00	
$\hat{C}_{ll}$	-0.022 ± 0.028	-0.80	0.95	-0.10	-0.06	-0.01	-0.04	-0.05	1.00

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]	80.413 ± 0.015	80.403 ± 0.013	80.413 ± 0.015	80.413 ± 0.015
Γ_W [GeV]	2.085 ± 0.042	2.0916 ± 0.0011	2.0925 ± 0.0012	2.0778 ± 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 ± 0.0014
Γ_Z [GeV]	2.4955 ± 0.0023	2.4976 ± 0.0012	2.4951 ± 0.0022	2.4955 ± 0.0023
σ_h^0 [nb]	41.480 ± 0.033	41.4909 ± 0.0077	41.4905 ± 0.0077	41.482 ± 0.033
R_ℓ^0	20.767 ± 0.025	20.7507 ± 0.0084	20.7512 ± 0.0084	20.769 ± 0.025
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.01637 ± 0.00023	0.01630 ± 0.00024	0.01660 ± 0.00032
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1478 ± 0.0011	0.1474 ± 0.0011	0.1488 ± 0.0014
R_b^0	0.21629 ± 0.00066	0.21591 ± 0.00011	0.21591 ± 0.00011	0.21632 ± 0.00065
R_c^0	0.1721 ± 0.0030	0.172199 ± 0.000055	0.172199 ± 0.000055	0.17160 ± 0.00099
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016	0.10359 ± 0.00075	0.10337 ± 0.00077	0.1009 ± 0.0014
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07403 ± 0.00059	0.07385 ± 0.00059	0.0735 ± 0.0022
$\mathcal{A}_b$	0.923 ± 0.020	0.934807 ± 0.000097	0.934779 ± 0.000100	0.903 ± 0.013
$\mathcal{A}_c$	0.670 ± 0.027	0.66811 ± 0.00052	0.66797 ± 0.00053	0.658 ± 0.020
$\mathcal{A}_s$	0.895 ± 0.091	0.935705 ± 0.000096	0.935677 ± 0.000097	0.905 ± 0.012
${\rm BR}_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108385 ± 0.000022	0.108380 ± 0.000022	0.10900 ± 0.00038
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025	0.23143 ± 0.00014	0.23147 ± 0.00014	–
R_{uc}	0.1660 ± 0.0090	0.172221 ± 0.000034	0.172221 ± 0.000034	0.17162 ± 0.00099

standard averages

Conclusions

- Remarkable experimental progress in m_t and M_W, but tensions among measurements present in both cases
- Taken at face value, M_W implies a local (global) discrepancy at the 6.5σ (4.2σ) 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.
- Independent measurements of M_W (and m_t) crucial!

BACKUP

NP fits in the conservative scenario

	Result	Correlation		Result	Correlation		
	($IC_{ST}/IC_{SM} = 24.5/37.1$)			($IC_{STU}/IC_{SM} = 25.3/37.1$)			
S	0.086 ± 0.077	1.00		0.004 ± 0.096	1.00		
T	0.177 ± 0.070	0.89	1.00	0.040 ± 0.120	0.90	1.00	
U	–	–	–	0.134 ± 0.095	−0.60	−0.81	1.00

	Result	Correlation Matrix							
$\hat{C}_{\varphi l}^{(1)}$	-0.007 ± 0.012	1.00							
$\hat{C}_{\varphi l}^{(3)}$	-0.042 ± 0.018	−0.44	1.00						
$\hat{C}_{\varphi e}$	-0.017 ± 0.010	0.52	0.31	1.00					
$\hat{C}_{\varphi q}^{(1)}$	-0.018 ± 0.045	−0.02	−0.05	−0.12	1.00				
$\hat{C}_{\varphi q}^{(3)}$	-0.114 ± 0.044	0.02	0.14	−0.02	−0.36	1.00			
$\hat{C}_{\varphi u}$	0.090 ± 0.150	0.05	−0.04	0.02	0.61	−0.76	1.00		
$\hat{C}_{\varphi d}$	-0.630 ± 0.250	−0.13	−0.04	−0.25	0.40	0.57	−0.04	1.00	
$\hat{C}_{ll}$	-0.022 ± 0.028	−0.72	0.89	0.01	−0.06	0.03	−0.04	−0.05	1.00

NP fits in the conservative scenario

	Measurement	ST	STU	SMEFT
M_W [GeV]	80.413 ± 0.015	80.403 ± 0.013	80.413 ± 0.015	80.413 ± 0.015
Γ_W [GeV]	2.085 ± 0.042	2.0916 ± 0.0011	2.0925 ± 0.0012	2.0778 ± 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 ± 0.0014
Γ_Z [GeV]	2.4955 ± 0.0023	2.4976 ± 0.0012	2.4951 ± 0.0022	2.4955 ± 0.0023
σ_h^0 [nb]	41.480 ± 0.033	41.4909 ± 0.0077	41.4905 ± 0.0077	41.482 ± 0.033
R_ℓ^0	20.767 ± 0.025	20.7507 ± 0.0084	20.7512 ± 0.0084	20.769 ± 0.025
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.01637 ± 0.00023	0.01630 ± 0.00024	0.01660 ± 0.00032
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1478 ± 0.0011	0.1474 ± 0.0011	0.1488 ± 0.0014
R_b^0	0.21629 ± 0.00066	0.21591 ± 0.00011	0.21591 ± 0.00011	0.21632 ± 0.00065
R_c^0	0.1721 ± 0.0030	0.172199 ± 0.000055	0.172199 ± 0.000055	0.17160 ± 0.00099
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016	0.10359 ± 0.00075	0.10337 ± 0.00077	0.1009 ± 0.0014
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07403 ± 0.00059	0.07385 ± 0.00059	0.0735 ± 0.0022
$\mathcal{A}_b$	0.923 ± 0.020	0.934807 ± 0.000097	0.934779 ± 0.000100	0.903 ± 0.013
$\mathcal{A}_c$	0.670 ± 0.027	0.66811 ± 0.00052	0.66797 ± 0.00053	0.658 ± 0.020
$\mathcal{A}_s$	0.895 ± 0.091	0.935705 ± 0.000096	0.935677 ± 0.000097	0.905 ± 0.012
${\rm BR}_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108385 ± 0.000022	0.108380 ± 0.000022	0.10900 ± 0.00038
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025	0.23143 ± 0.00014	0.23147 ± 0.00014	–
R_{uc}	0.1660 ± 0.0090	0.172221 ± 0.000034	0.172221 ± 0.000034	0.17162 ± 0.00099