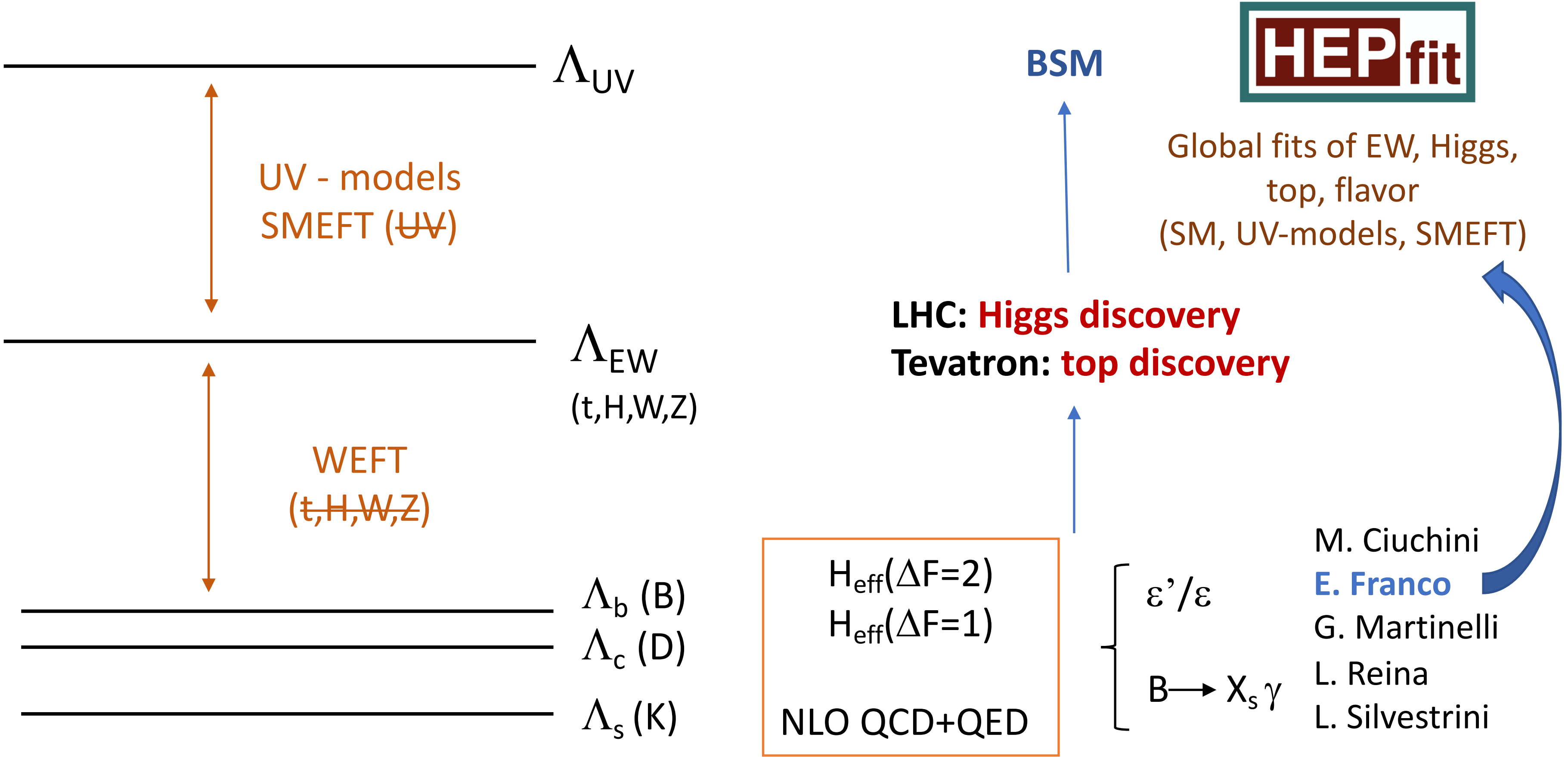
HEPfit e la fisica elettrodebole

Un pomeriggio dedicato a Enrico Franco
ricordando momenti e progetti condivisi nel corso degli anni

Roma – Università La Sapienza
23 Maggio 2023

Laura Reina
(Florida State University)

Exploring new physics via the EW-scale (and below)



Λ_{UV}

UV - models

SMEFT (~~UV~~)

Λ_{EW}

(t,H,W,Z)

WEFT

(~~t,H,W,Z~~)

Λ_b (B)

Λ_c (D)

Λ_s (K)

$H_{eff}(\Delta F=2)$

$H_{eff}(\Delta F=1)$

NLO QCD+QED

ε'/ε

$B \longrightarrow X_s \gamma$

LHC: Higgs discovery

Tevatron: top discovery

BSM

HEPfit

Global fits of EW, Higgs, top, flavor (SM, UV-models, SMEFT)

M. Ciuchini

E. Franco

G. Martinelli

L. Reina

L. Silvestrini

The role of global fits

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

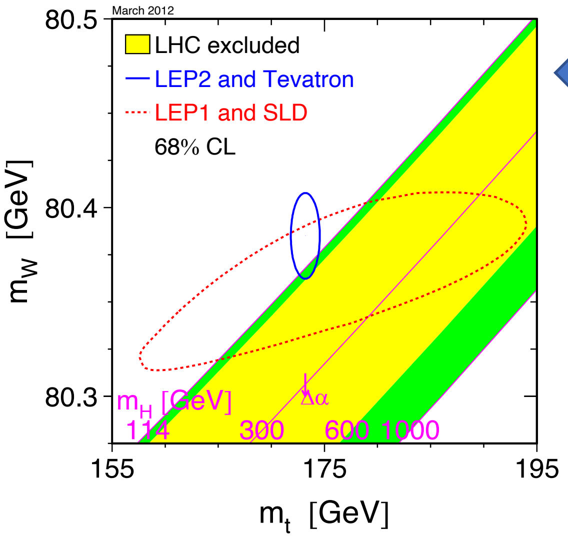
- The renormalizability of the theory assures that tree-level relations are modified by finite calculable corrections.

- **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

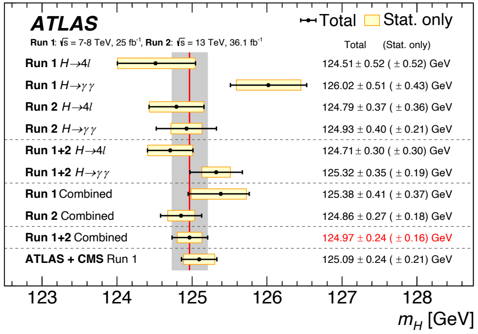
A very successful history

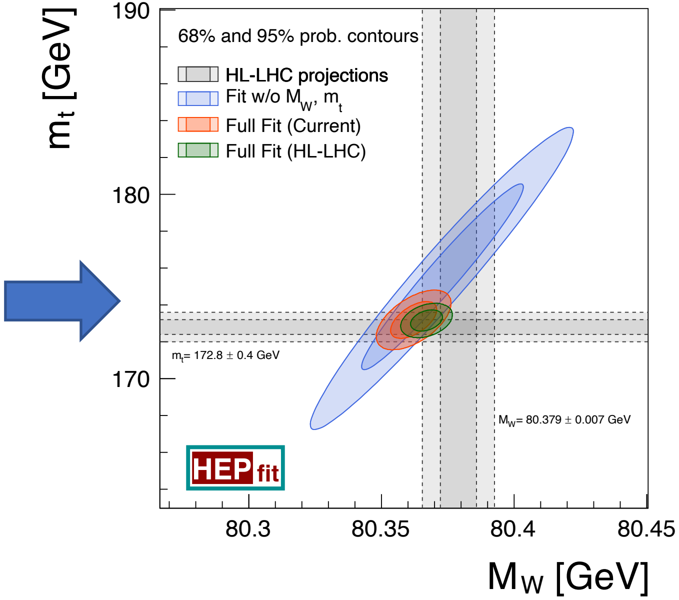
Global fits of precision EW observables gave us strong indications of where to find the SM Higgs boson and we now use its mass as one of the EW precision observables of the EW global fit to constrain new physics.



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

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





EW Global fit: general framework

- Set of input parameters (ex: 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
  - ….

Specific framework: HEPfit

http://hepfit.roma1.infn.it

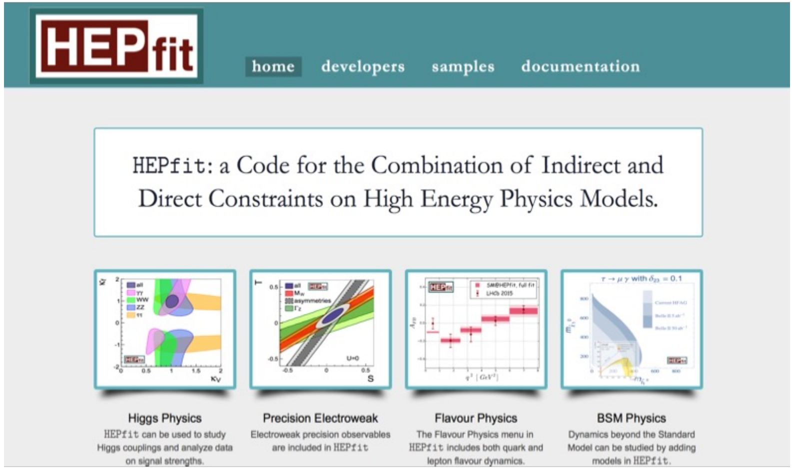
Open-source tool

New code, built from scratch, validated against other public codes.

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



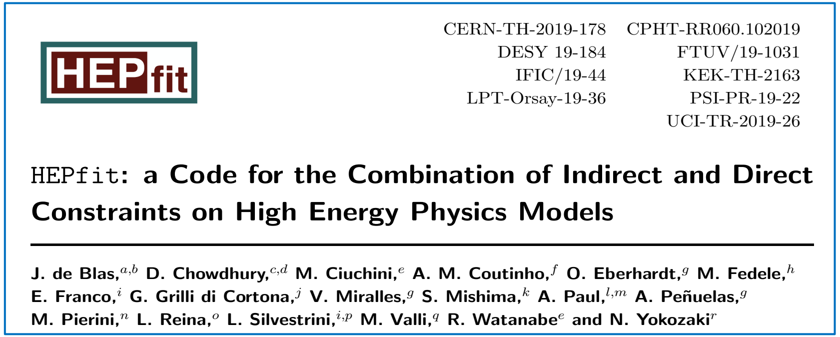
HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.

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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DESY 19-184 FTUV/19-1031
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LPT-Orsay-19-36 PSI-PR-19-22
UCI-TR-2019-26

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

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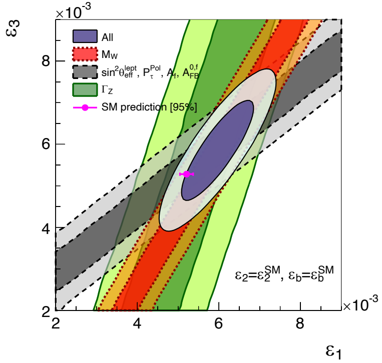

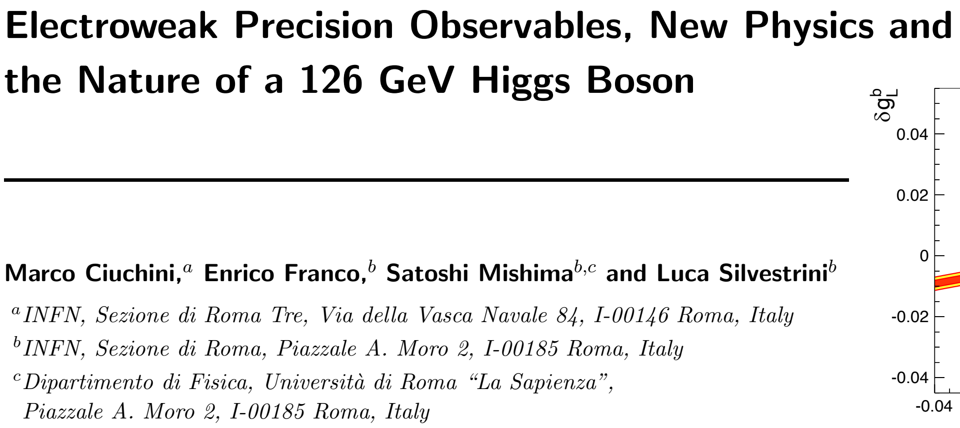

Electroweak Precision Observables, New Physics and the Nature of a 126 GeV Higgs Boson

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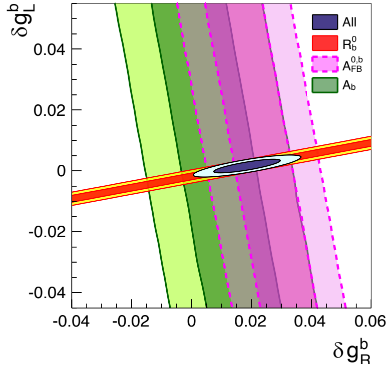
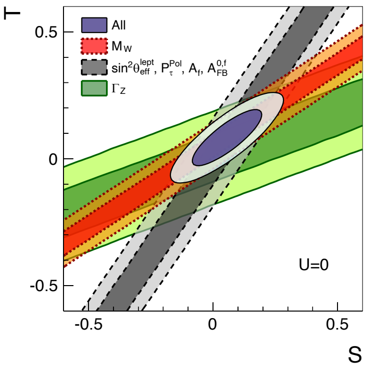
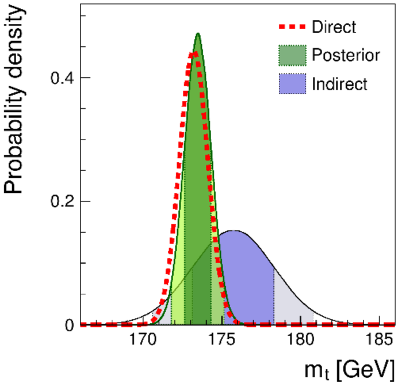


Abstract: We perform the fit of electroweak precision observables within the Standar Model with a 126 GeV Higgs boson, compare the results with the theoretical predictions an discuss the impact of recent experimental and theoretical improvements. We introduce Ne Physics contributions in a model-independent way and fit for the S, T and U parameter for the $\epsilon_{1,2,3,b}$ ones, for modified $Zb\bar{b}$ couplings and for a modified Higgs coupling to vecto bosons. We point out that composite Higgs models are very strongly constrained. Finall we compute the bounds on dimension-six operators relevant for the electroweak fit.





A seminal paper on which the global fit of EW precision observables in HEPfit is currently based.

Experimental inputs

De Blas et al.
arXiv:2112.07274 (**before**)
arXiv:2204.04204 (**after**)

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

- To get $\alpha(M_Z) \longrightarrow \Delta\alpha_{had}^{(5)}$: 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

after

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]
  - Recent ATLAS measurement [M_W=(80.360 ±0.016) GeV]

before

after

previous average

M_W = 80.379 ± 0.012 GeV

→

new average

M_W = (80.4133 ± 0.0088 GeV)
= 80.4093 ± 0.0079 GeV

"standard"

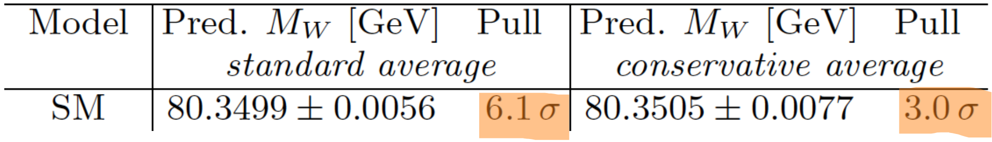
new average

M_W = (80.4133 ± 0.015 GeV)
= 80.4093 ± 0.018 GeV

"conservative"

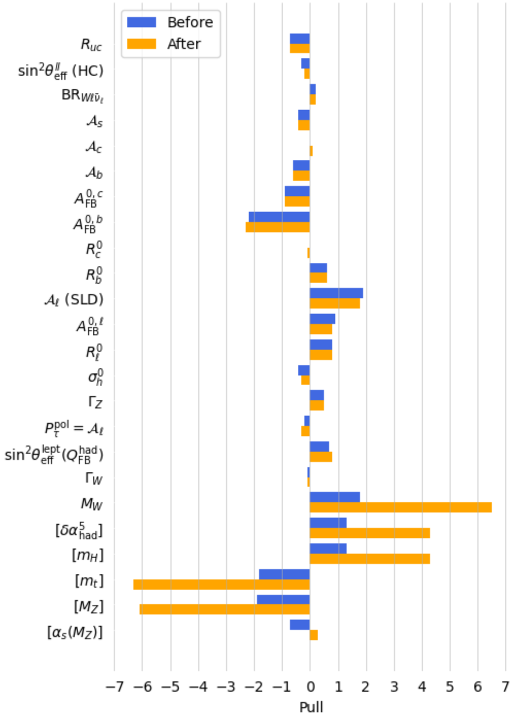
New CDF results dominates standard average but tensions between LEP 2, Tevatron, and LHC results → consider "conservative" scenario

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

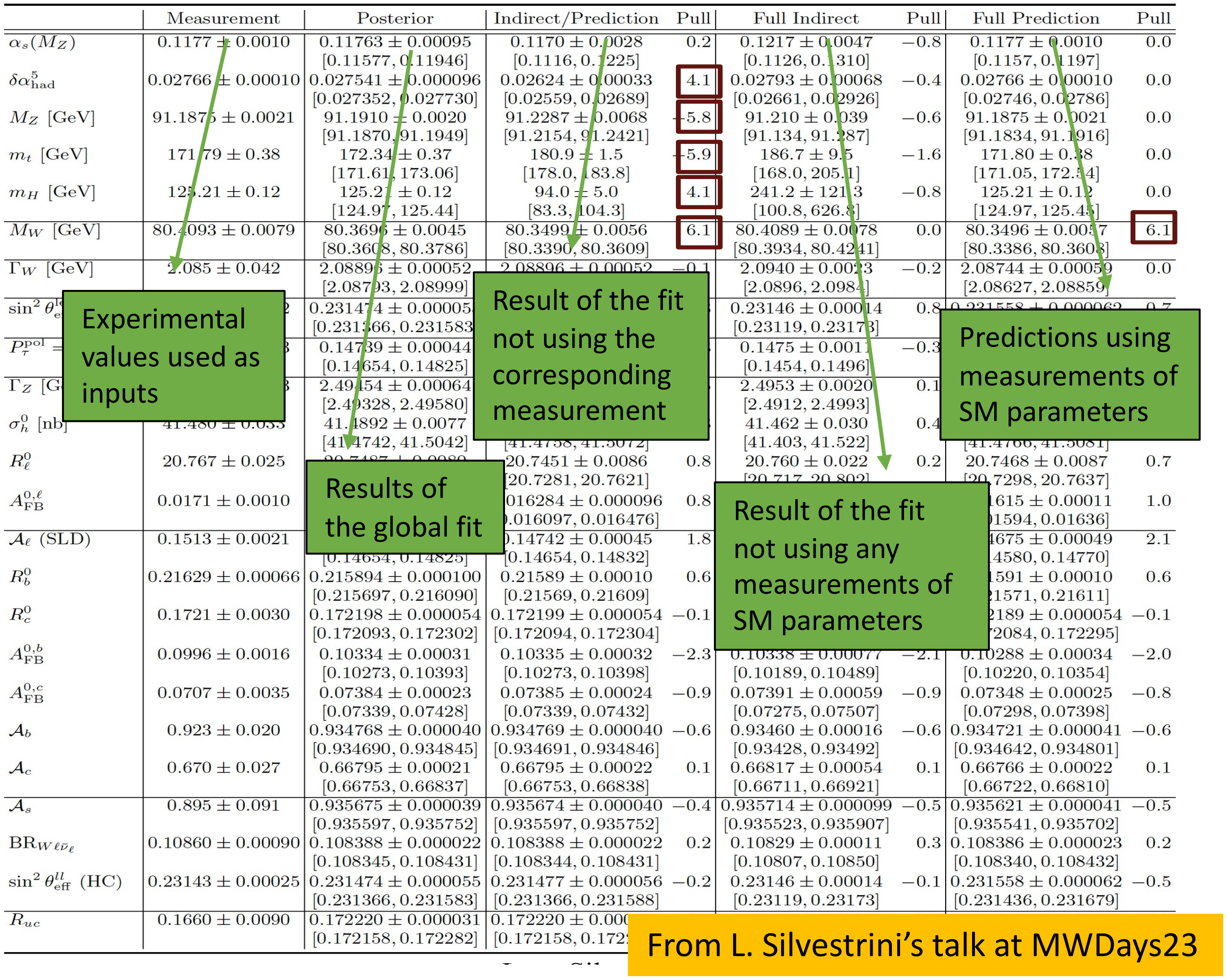


Model	Pred. M_W [GeV] *standard average*	Pull	Pred. M_W [GeV] *conservative average*	Pull
SM	80.3499 ± 0.0056	$6.1\,\sigma$	80.3505 ± 0.0077	$3.0\,\sigma$

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	0.11763 ± 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
$\delta\alpha_{\mathrm{had}}^5$	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 [illegible]	−0.1	2.0940 ± 0.0023 [2.0896, 2.0984]	−0.2	2.08744 ± 0.00059 [2.08627, 2.08859]	0.0
$\sin^2\theta_{\mathrm{e}}^{\mathrm{le}}$ [illegible]	[illegible]	0.231474 ± 0.00005 [illegible] [0.231366, 0.231583 [illegible]	[illegible]	[illegible]	0.23146 ± 0.00014 [0.23119, 0.23173]	0.8	0.231558 ± 0.000062 [illegible]	0.7
P_τ^{pol} = [illegible]	[illegible]	0.14739 ± 0.00044 [0.14654, 0.14825]	[illegible]	[illegible]	0.1475 ± 0.0011 [0.1454, 0.1496]	−0.3	[illegible]	[illegible]
Γ_Z [G [illegible]	[illegible]	2.49454 ± 0.00064 [2.49328, 2.49580]	[illegible]	[illegible]	2.4953 ± 0.0020 [2.4912, 2.4993]	0.1	[illegible]	[illegible]
σ_h^0 [nb]	41.480 ± 0.033	41.4892 ± 0.0077 [41.4742, 41.5042]	[illegible] [41.4758, 41.5072]	[illegible]	41.462 ± 0.030 [41.403, 41.522]	0.4	[illegible] [41.4766, 41.5081]	[illegible]
R_ℓ^0	20.767 ± 0.025	20.7487 ± 0.0080 [illegible]	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
$A_{\mathrm{FB}}^{0,\ell}$	0.0171 ± 0.0010	[illegible]	016284 ± 0.000096 .016097, 0.016476]	0.8	[illegible]	[illegible]	1615 ± 0.00011 1594, 0.01636]	1.0
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	[illegible] [0.14654, 0.14825]	.14742 ± 0.00045 [0.14654, 0.14832]	1.8	[illegible]	[illegible]	4675 ± 0.00049 4580, 0.14770]	2.1
R_b^0	0.21629 ± 0.00066	0.215894 ± 0.000100 [0.215697, 0.216090]	0.21589 ± 0.00010 [0.21569, 0.21609]	0.6	[illegible]	[illegible]	1591 ± 0.00010 21571, 0.21611]	0.6
R_c^0	0.1721 ± 0.0030	0.172198 ± 0.000054 [0.172093, 0.172302]	0.172199 ± 0.000054 [0.172094, 0.172304]	−0.1	[illegible]	[illegible]	2189 ± 0.000054 72084, 0.172295]	−0.1
$A_{\mathrm{FB}}^{0,b}$	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
$A_{\mathrm{FB}}^{0,c}$	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
$\mathrm{BR}_{W\ell\bar{\nu}_\ell}$	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
$\sin^2\theta_{\mathrm{eff}}^{ll}$ (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 ± 0.000 [illegible] [0.172158, 0.172 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Experimental values used as inputs

Results of the global fit

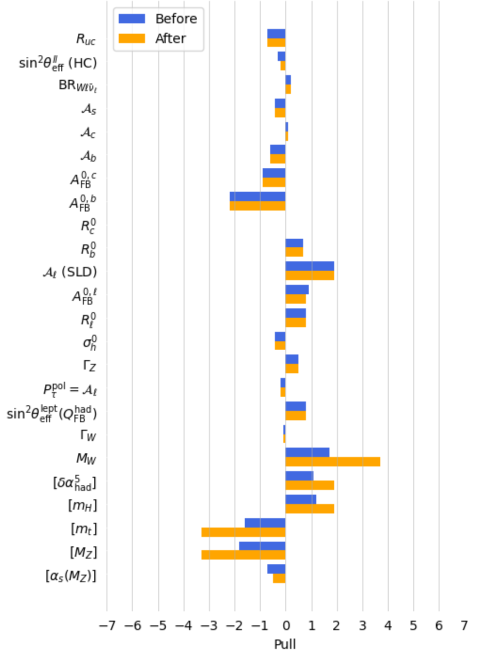
Result of the fit not using the corresponding measurement

Result of the fit not using any measurements of SM parameters

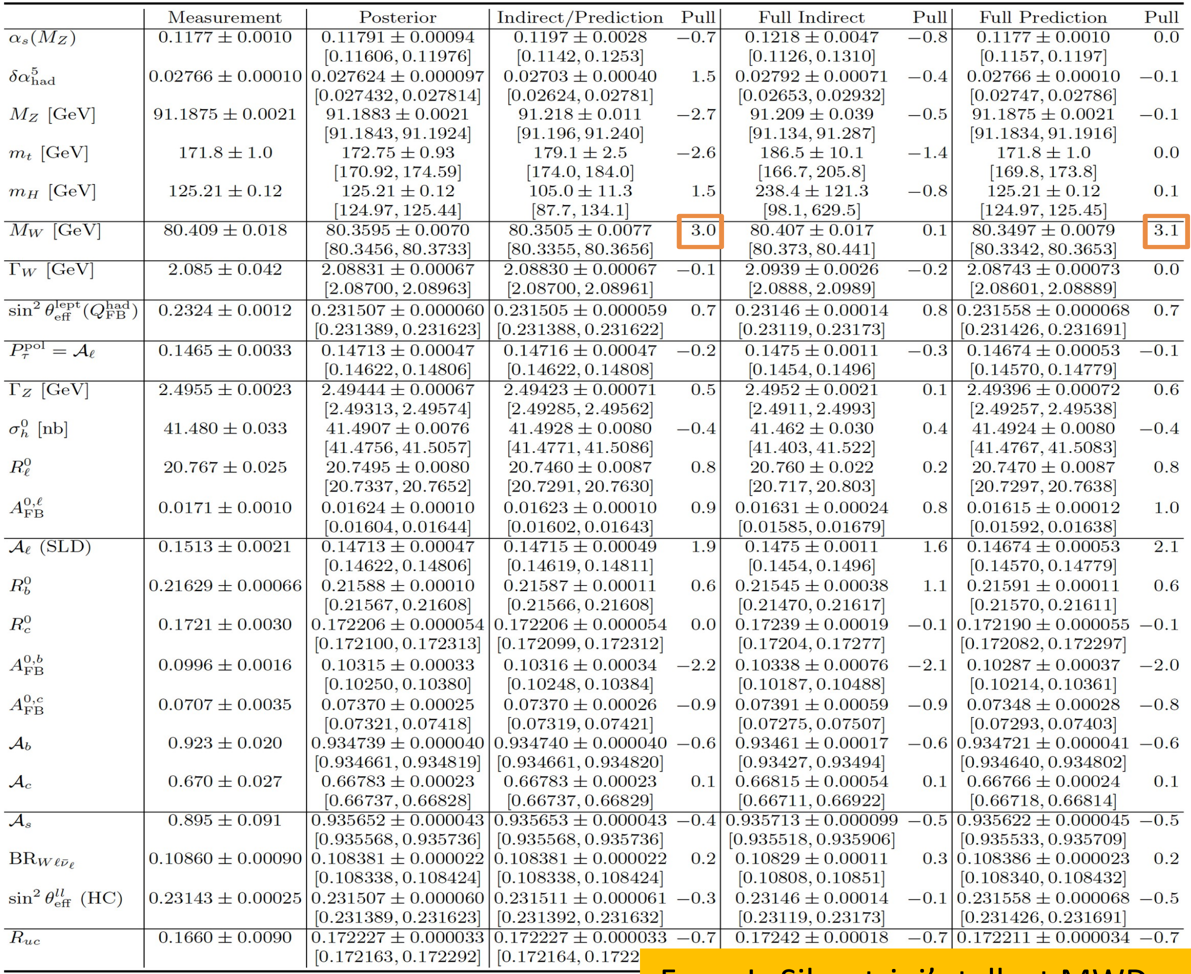
Predictions using measurements of SM parameters

From L. Silvestrini's talk at MWDays23

Results of global fit



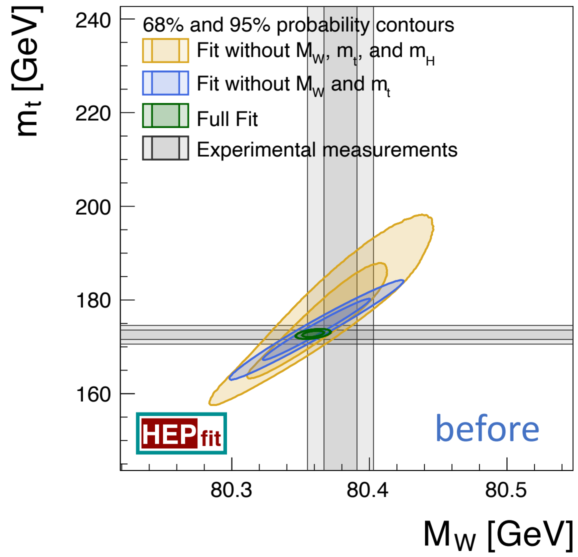
"conservative" scenario

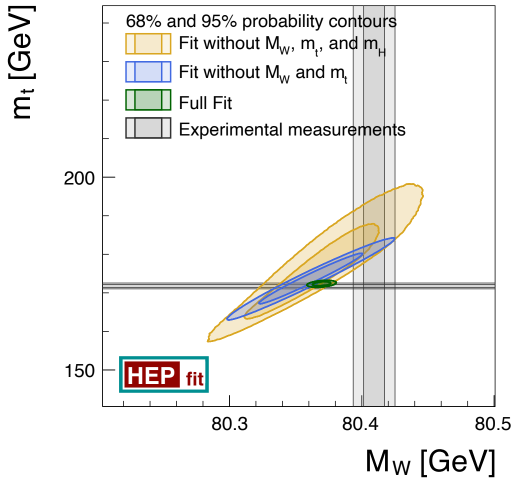


	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11791 ± 0.00094 $[0.11606, 0.11976]$	0.1197 ± 0.0028 $[0.1142, 0.1253]$	−0.7	0.1218 ± 0.0047 $[0.1126, 0.1310]$	−0.8	0.1177 ± 0.0010 $[0.1157, 0.1197]$	0.0
$\delta\alpha^5_{\rm had}$	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
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	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
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	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_h^0 [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_ℓ^0	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
$A_{\rm FB}^{0,\ell}$	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_b^0	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_c^0	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
$A_{\rm FB}^{0,b}$	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
$A_{\rm FB}^{0,c}$	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
$\mathrm{BR}_{W\ell\bar\nu_\ell}$	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
$\sin^2\theta_{\rm eff}^{ll}$ (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 $[0.172164, 0.1722$	−0.7	0.17242 ± 0.00018	−0.7	0.172211 ± 0.000034	−0.7

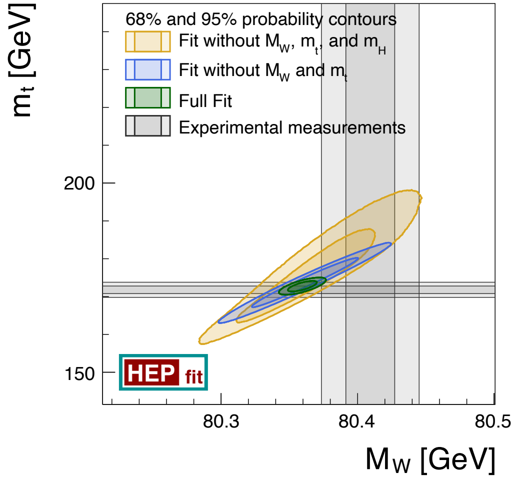
From L. Silvestrini's talk at MWDays23

Interplay between m_t and M_W





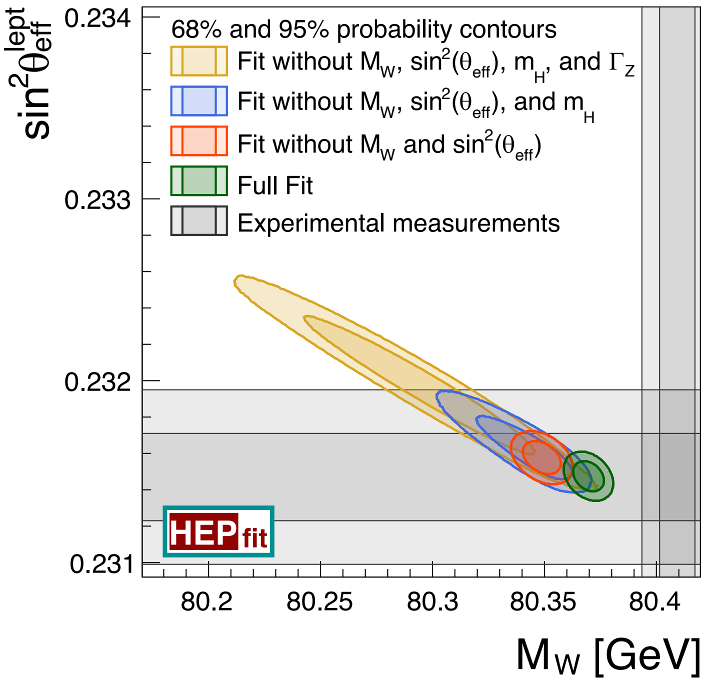
after
“standard”



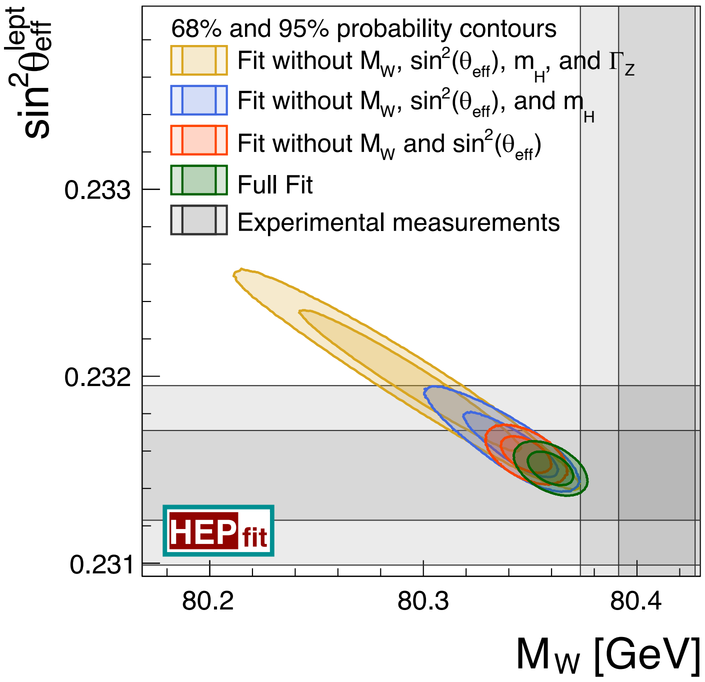
after
“conservative”

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 $\propto G_F m_t^2$.

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



“standard” scenario



“conservative” scenario

Beyond the SM

Very broadly, two main options:

- Add new physics that breaks residual SU(2)$_V$ custodial symmetry and allows ρ≠1 at tree level ⟶ 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}

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

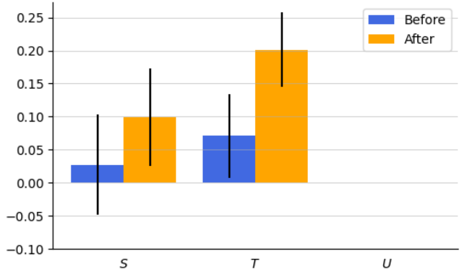
$$T = \frac{4}{s_W^2 c_W^2 M_Z^2}[\Pi_{11}^{\mathrm{NP}}(0) - \Pi_{33}^{\mathrm{NP}}(0)]$$

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

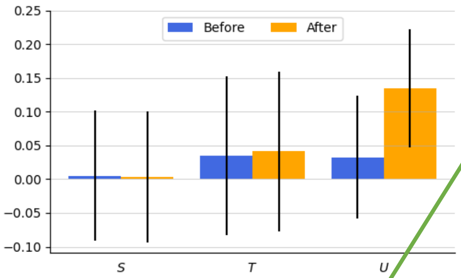
$$g_{\mathrm{SM}} + \Delta g \begin{cases} \Delta g^{Zf\bar{f}} \propto (S,T) \\ \Delta g^{Wf'\bar{f}} \propto (S,T,U) \end{cases}$$

$$\Downarrow$$

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



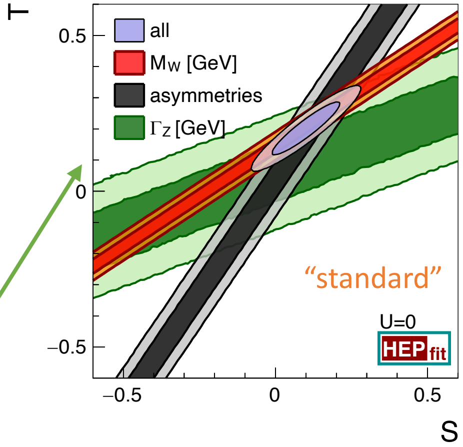
U=0, (S,T) reabsorb impact of M_W



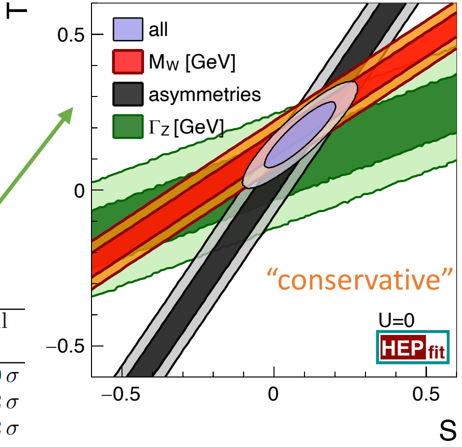
U≠0, U reabsorb impact of M_W

	Result	Correlation		Result	Correlation		
	$(\mathrm{IC_{ST}/IC_{SM}} = 24.5/73.9)$			$(\mathrm{IC_{STU}/IC_{SM}} = 25.3/73.9)$			
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

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	$0.2\,\sigma$



"standard"



"conservative"

Beyond the SM: SMEFT (d=6)

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

Zff/Wff
vertex
corrections

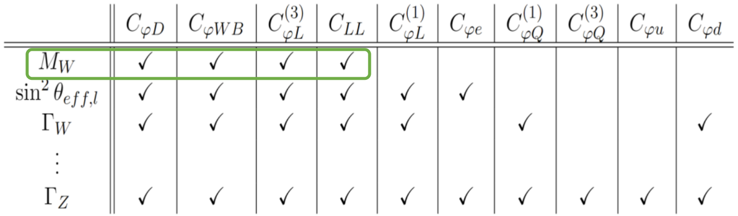
$$\mathcal{O}_{\phi WB} = (\phi^\dagger \sigma_i \phi) \, W^i_{\mu\nu} B^{\mu\nu} \ ,$$
$$\mathcal{O}_{\phi D} = (\phi^\dagger D^\mu \phi)^* \, (\phi^\dagger D_\mu \phi) \ ,$$

W/Z
propagators ↔ S,T

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

Only 8 independent combinations enter EWPO

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

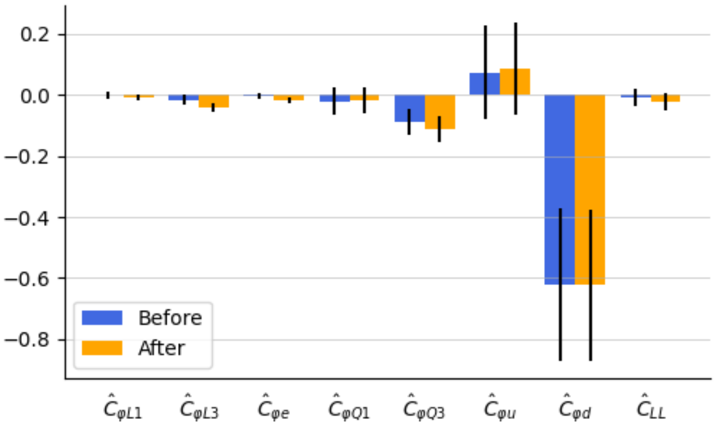


	$C_{\varphi D}$	$C_{\varphi WB}$	$C^{(3)}_{\varphi L}$	C_{LL}	$C^{(1)}_{\varphi L}$	$C_{\varphi e}$	$C^{(1)}_{\varphi Q}$	$C^{(3)}_{\varphi Q}$	$C_{\varphi u}$	$C_{\varphi d}$
M_W	✓	✓	✓	✓						
$\sin^2\theta_{eff,l}$	✓	✓	✓	✓	✓	✓				
Γ_W	✓	✓	✓	✓	✓		✓			✓
⋮										
Γ_Z	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

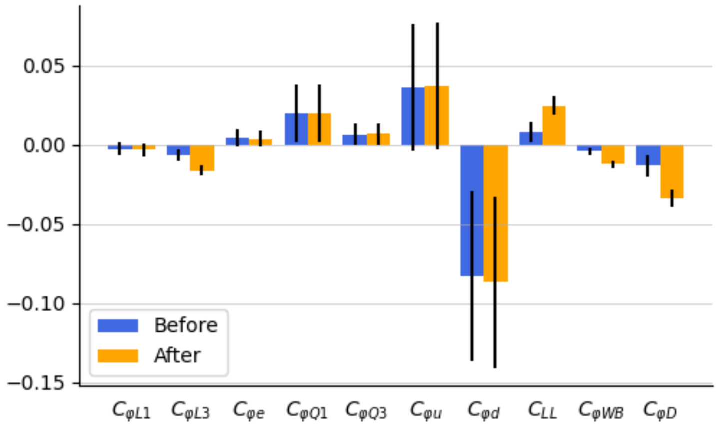
Very loose prediction of M_W from $\Gamma_W(M_W)$

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

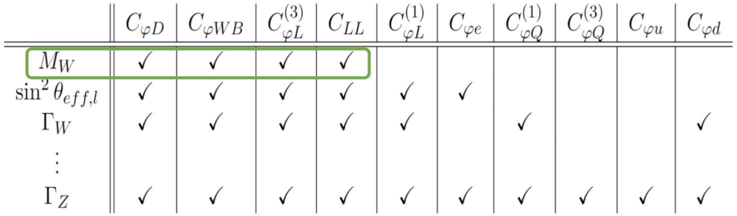


No substantial impact of new mt and MW measurements, within uncertainty of the fit.

Adding Higgs observables lifts the degeneracy

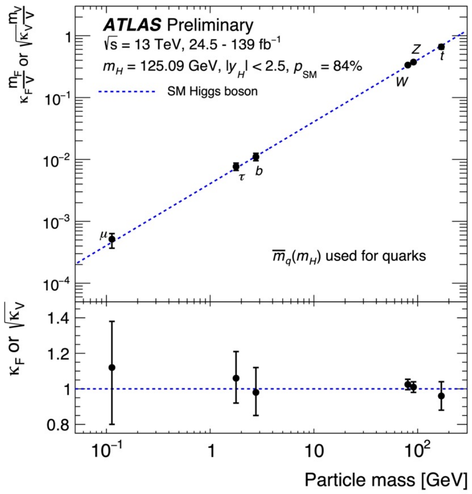
⬇

Extended set of coefficients constrained independently by the global fit



	$C_{\varphi D}$	$C_{\varphi WB}$	$C^{(3)}_{\varphi L}$	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	✓	✓	✓	✓	✓		✓			✓
$\vdots$										
Γ_Z	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Run 2 Zooming in on couplings to probe the TeV scale



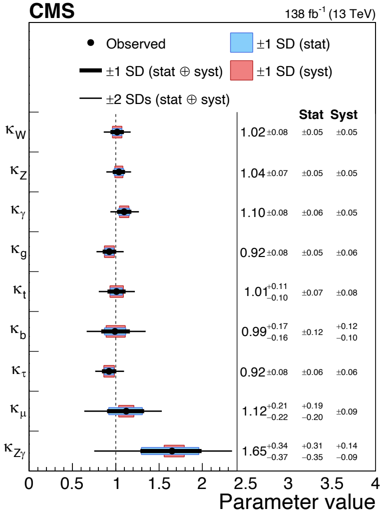
$$\kappa = g_X/g_X^{SM} = 1 + \Delta\kappa$$

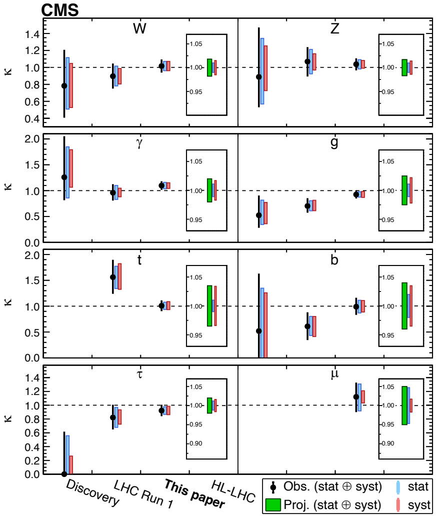
$$\Delta\kappa \propto v^2/\Lambda_{BSM}^2$$

Precision on Δκ

reach for Λ_{BSM}

CMS, arXiv:2207.00043





- ➢ Couplings to **W/Z at 5-10 %**
- ➢ Couplings to **3rd generation to 10-20%**
- ➢ **First measurements of 2nd generation** couplings

- ➢ **HL-LHC projections** from **partial Run 2** data (YR):
  - ➢ **2-5 % on most couplings**
  - ➢ **< 50% on Higgs self-coupling.**
- ➢ **Full Run2** results **drastically improve partial Run 2 results:** better projections expected

Run 2 and beyond

Beyond SM-coupling rescaling

Model new physics by extending the SM Lagrangian by effective interactions (ex. SM EFT)

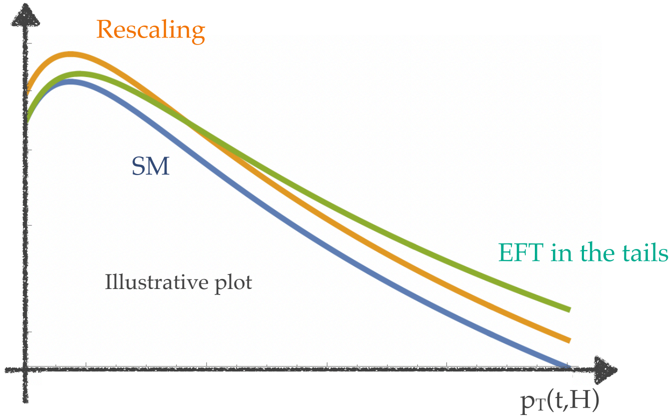
$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$

Under the assumption that new physics leaves at scales $\Lambda > \sqrt{s}$

Expansion in $(v, E)/\Lambda$: **affects all SM observables** at both low and high energy

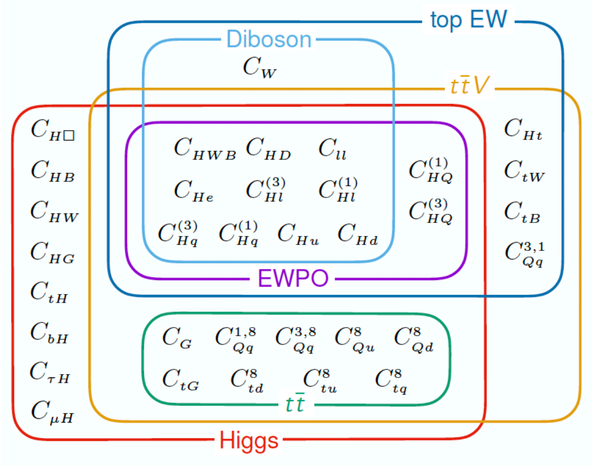
- **SM masses and couplings** → **rescaling**
- **Shapes of distributions** → more visible in **tails of distributions**



Towards SMEFT global fits

EW + Higgs: already in HEPfit

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \left(\frac{1}{\Lambda^2}\sum_i C_i O_i + \text{h.c.}\right) + O(\Lambda^{-4})$$



top EW

Diboson

C_W

$t\bar{t}V$

$C_{H\Box}$ C_{HB} C_{HW} C_{HG} C_{tH} C_{bH} $C_{\tau H}$ $C_{\mu H}$

C_{HWB} C_{HD} C_{ll}

C_{He} $C_{Hl}^{(3)}$ $C_{Hl}^{(1)}$

$C_{Hq}^{(3)}$ $C_{Hq}^{(1)}$ C_{Hu} C_{Hd}

$C_{HQ}^{(1)}$ $C_{HQ}^{(3)}$

C_{Ht} C_{tW} C_{tB} $C_{Qq}^{3,1}$

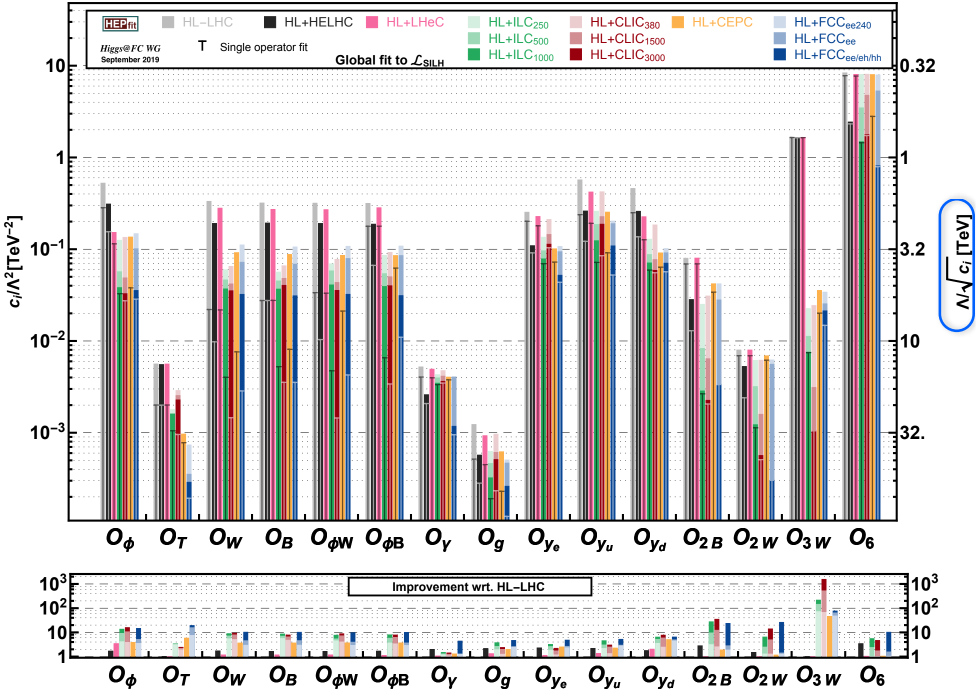
EWPO

C_G $C_{Qq}^{1,8}$ $C_{Qq}^{3,8}$ C_{Qu}^{8} C_{Qd}^{8}

C_{tG} C_{td}^{8} C_{tu}^{8} C_{tq}^{8}

$t\bar{t}$

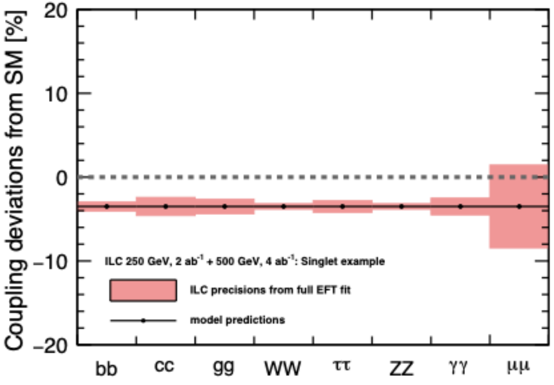
Higgs



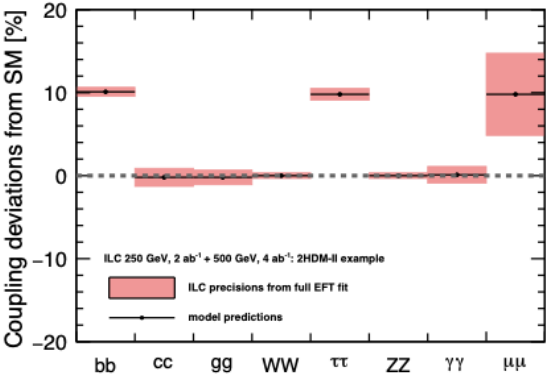
EFT connects different processes with large correlations: pattern of coefficients give insights on underlying BSM model

Disentangling models from EFT patterns

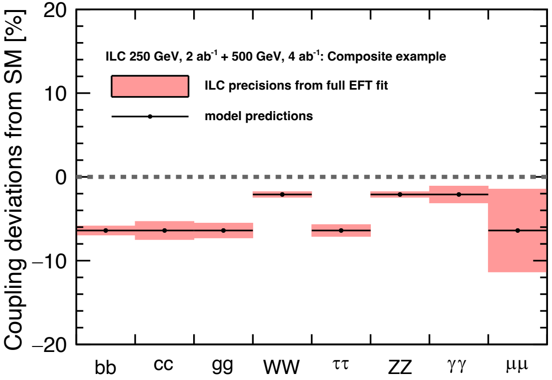
The “inverse Higgs” problem



additional scalar singlet
(m_S=2.8 TeV, max mixing)



2HDM-II
(MH=600 GeV, tanβ=7)



Composite Higgs
(f=1.2 TeV)

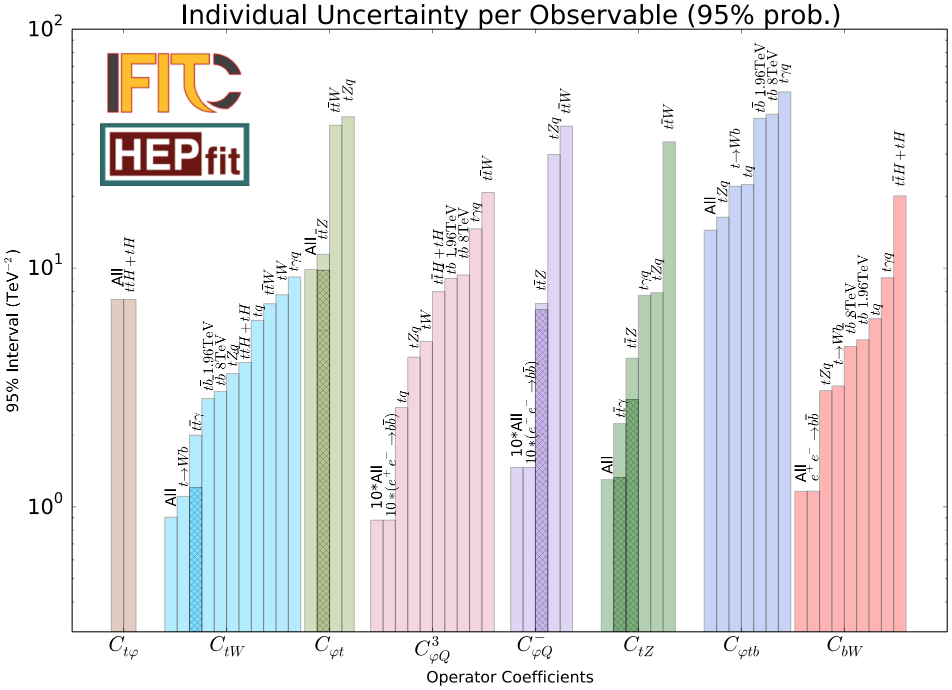
Snowmass 2021: ILC white paper (arXiv: 2203.07622)

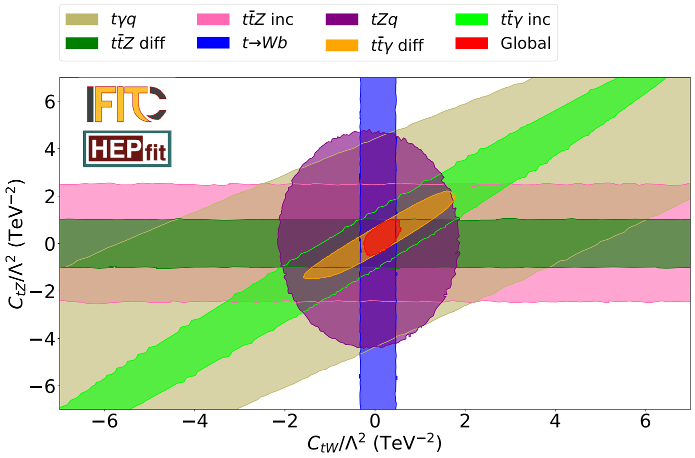
Examples to illustrate the **different patterns of Higgs coupling deviations** from **different BSM models**

Adding top-quark observables

Global fits of top observables

V. Miralles, et al. [arXiv:2107.13917]





Kinematic distributions add substantial constraining power

Now being included into HEPfit global fit of SMEFT

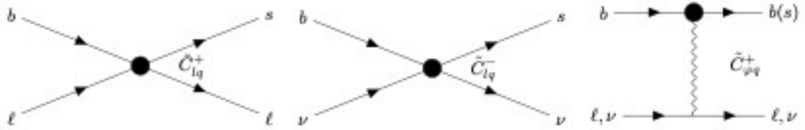
HEPfit: matching EW + Higgs + top with flavor

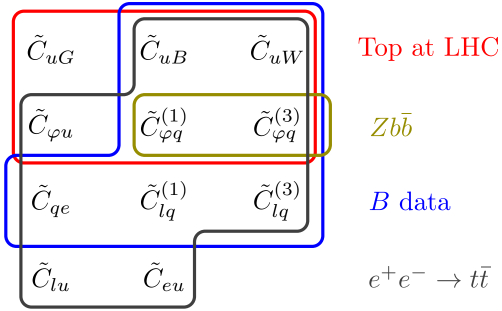
$$\mathcal{L}_{\rm SM}^{\rm EFT} \xrightarrow{\Lambda \ll \Lambda_{EW}} \mathcal{L}_{\rm Weak}^{\rm EFT} = \sum_{i=1}^{10} C_i^{\rm WEFT} \mathcal{O}_i^{\rm WEFT}$$

where

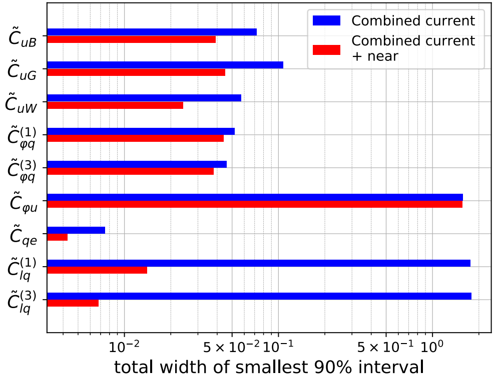
$\mathcal{O}_i^{\rm WEFT}$ → 4-fermion operators of quarks(except t) and leptons

$C_i^{\rm WEFT}$ → depend on $C_i^{\rm SMEFT}$





Strong constraint from B-meson semileptonic decays and intriguing relation with flavor anomalies



near:
including Belle II
and HL-LHC

Bissman et al. [arXiv:2-12.10456]

Comprehensive study of ΔF=2 constraints on SMEFT

Silvestrini and Valli [arXiv:1812.10913]

RGE evolution [RGESolver]

Di Noi and Silvestrini [arXiv:2210.06838]

Concluding remarks

- **EW global fits stress-test the SM and provide a very strong indirect constraint on new physics,** as recent measurements of M_W and m_t have reminded us.
- **Global fits**: **combining EW observables with Higgs and top-quark** total and differential observables will offer many more constraints on interactions beyond the SM by probing patterns of coefficients.
- Ultimately **connecting to flavor physics** will probe further structure.
- **The Roma group has been the core center for the development of HEPfit**, a state-of-the-art framework for global fit of the SM and BSM theories.
- **Enrico** has been part of this effort for many years and **greatly contributed to the work of the group** that created HEPfit.

His legacy lives on!