Electroweak Precision Physics
from Beta Decays to the Z Pole
October 27, 2022

Electroweak Precision Fits with HEPfit

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Based on:
J.B., M. Pierini, L. Reina, L. Silvestrini,
arXiv: 2204.04204 [hep-ph]

Universidad de Granada

Transformación Económica, Industria, Conocimiento y Universidades

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Introduction

- Electroweak precision data: Very precise measurements of the W & Z boson properties

  ✓ The LEP/SLD legacy, Z-pole observables:

$$\frac{d\sigma_{e^+e^-\to Z\to \bar{f}f}}{d\Omega} = \frac{9}{4}\frac{s\Gamma_e\Gamma_f/M_Z^2}{\left(s-M_Z^2\right)^2+s^2\Gamma_Z^2/M_Z^2}\left[\left(1+\cos^2\theta\right)\left(1-P_eA_e\right)+2\cos\theta A_f\left(-P_e+A_e\right)\right]$$

$$M_Z,\ \Gamma_Z,\ \sigma_{\rm had}^0,\ \ \sin^2\theta_{\rm Eff}^{\rm lept},\ P_\tau^{\rm pol},\ A_f,\ A_{FB}^{0,f},\ R_f^0$$

Z-pole obs. (SLD/LEP) 0.002-$O(1)\%$

and W measurements from LEP 2

$$M_W,\ \Gamma_W,\ {\rm BR}_{W\to\ell\nu}$$

W obs. (LEP2) 0.02-$O(1)\%$

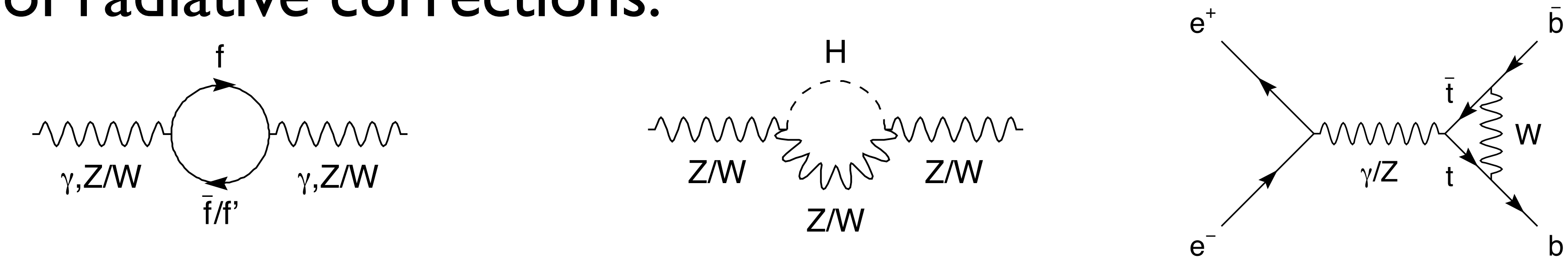
  ✓ But also receive contributions from Hadron colliders:

$M_W,\ \Gamma_W$	m_t	M_H
0.02-$O(1)\%$	0.4%	0.2%

Precision in many cases at per-mille level

Introduction

- This per-mille level precision makes EWPO a powerful test of SM predictions, to the level of radiative corrections:



✓ Test of the validity of the SM description of EW interactions

✓ Sensitive to all SM (or new) particles via loop corrections:

Introduction

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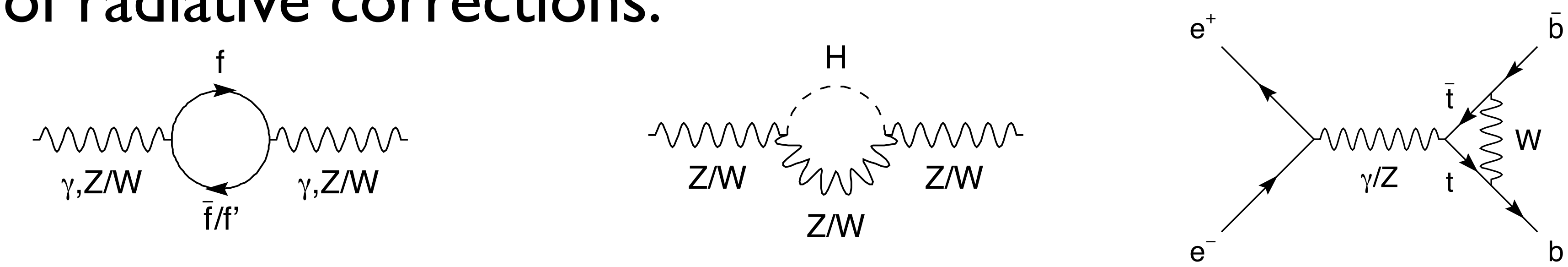
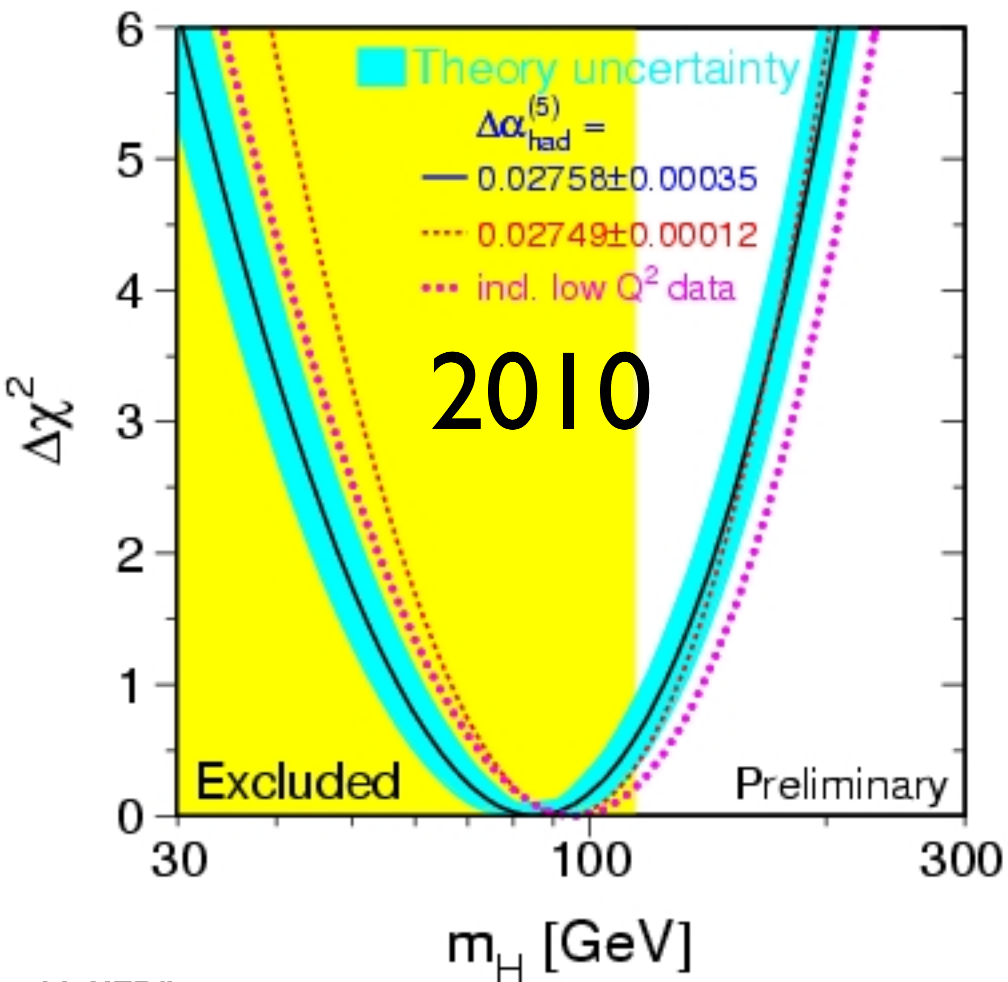


✓ Test of the validity of the SM description of EW interactions

✓ Sensitive to all SM (or new) particles via loop corrections:

Before Higgs discovery:

- Indirect evidence of a light Higgs
- Interplay SM-NP in EWPO



Introduction

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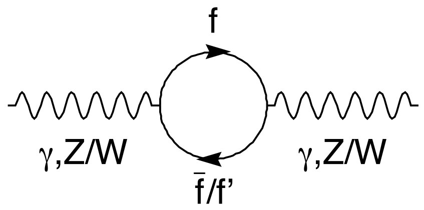
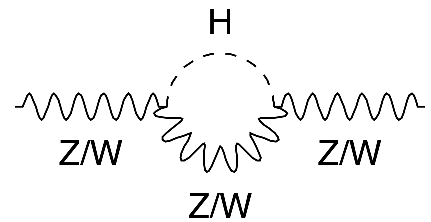
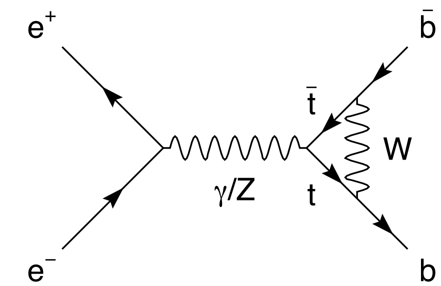






✓ Test of the validity of the SM description of EW interactions

✓ Sensitive to all SM (or new) particles via loop corrections:

After Higgs discovery:

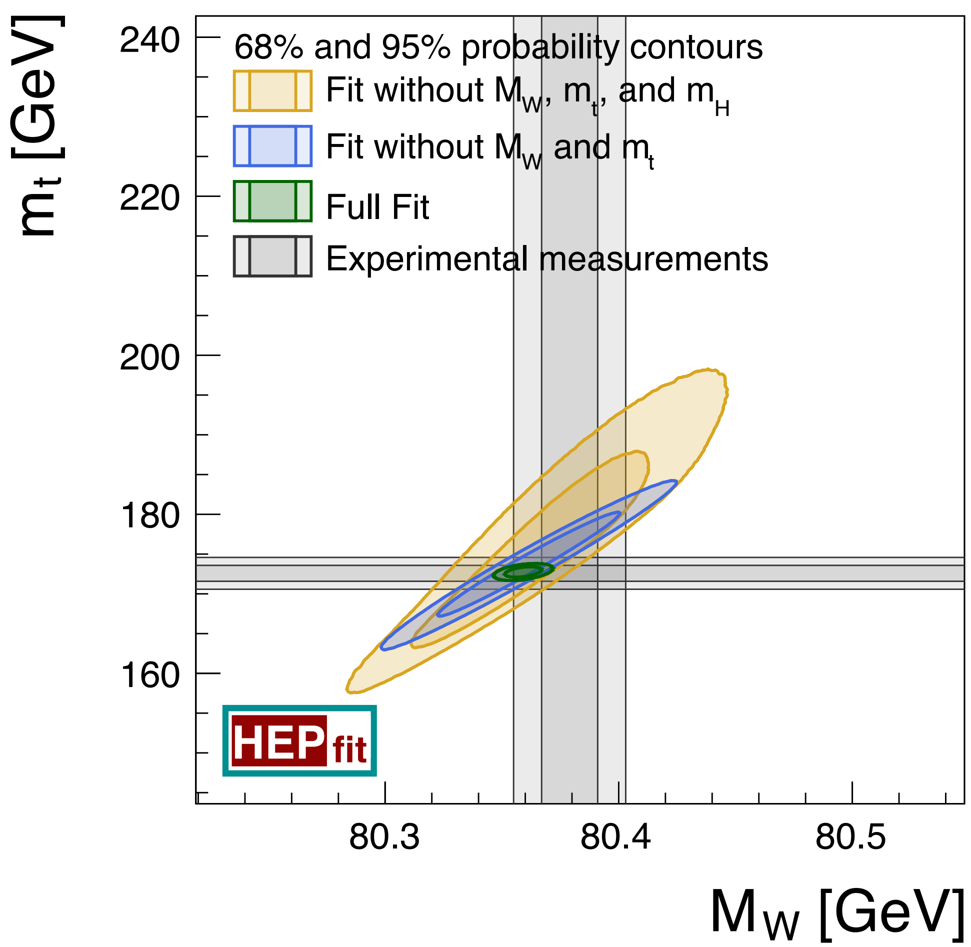
- All inputs of the SM are known
- Observables can be fully predicted in the SM
- Test of new physics (NP): strong (unambiguous) constraints on NP modifying the EW sector (e.g. solutions to the hierarchy problem)

Introduction

Consistency of the SM with Electroweak Precision Tests

(Before April 2022)

J.B. et al., arXiv: 2112.07274 [hep-ph] (Accepted for pub. In PRD)

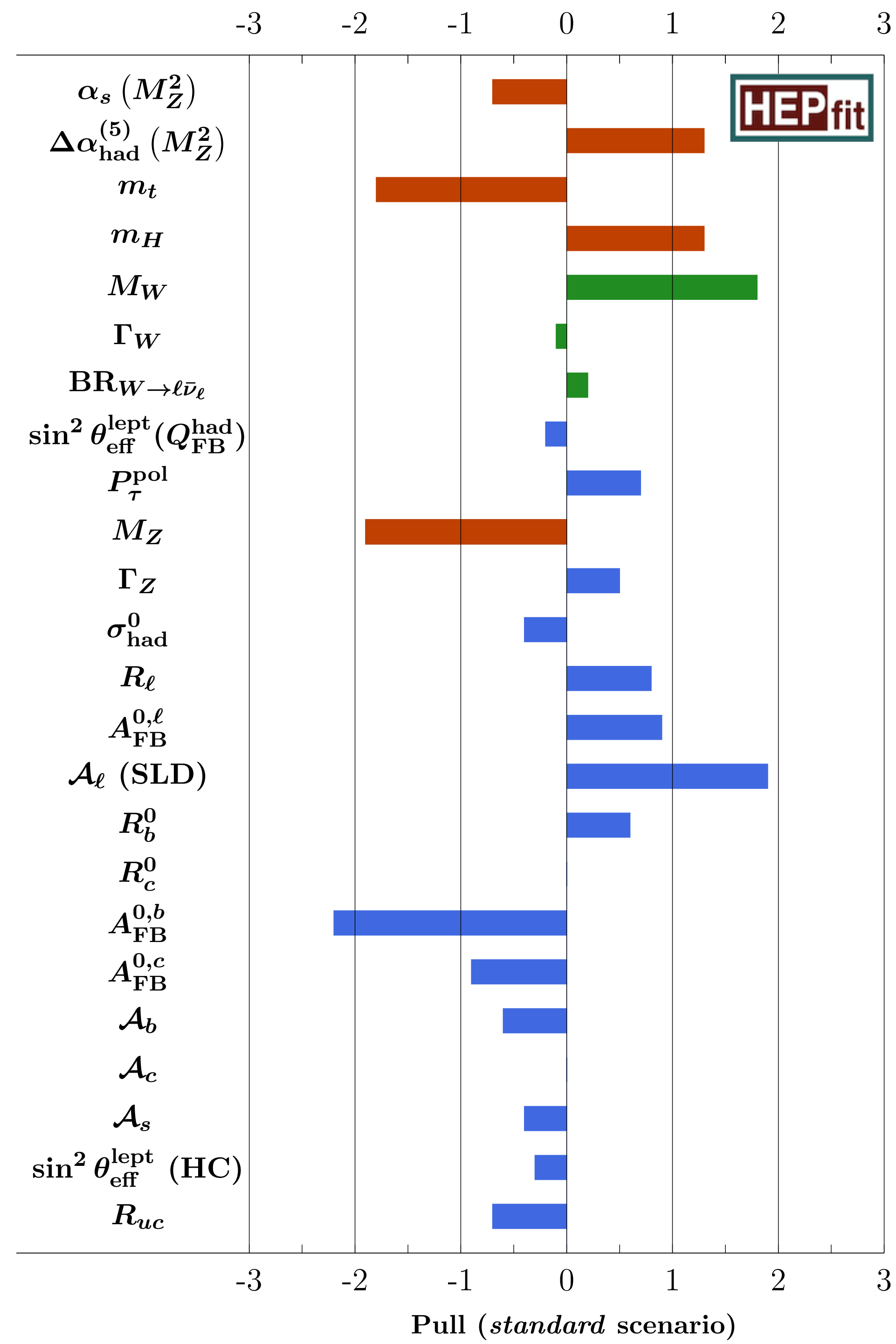


Overall consistency of the SM fit at 1σ

p-value: 0.45

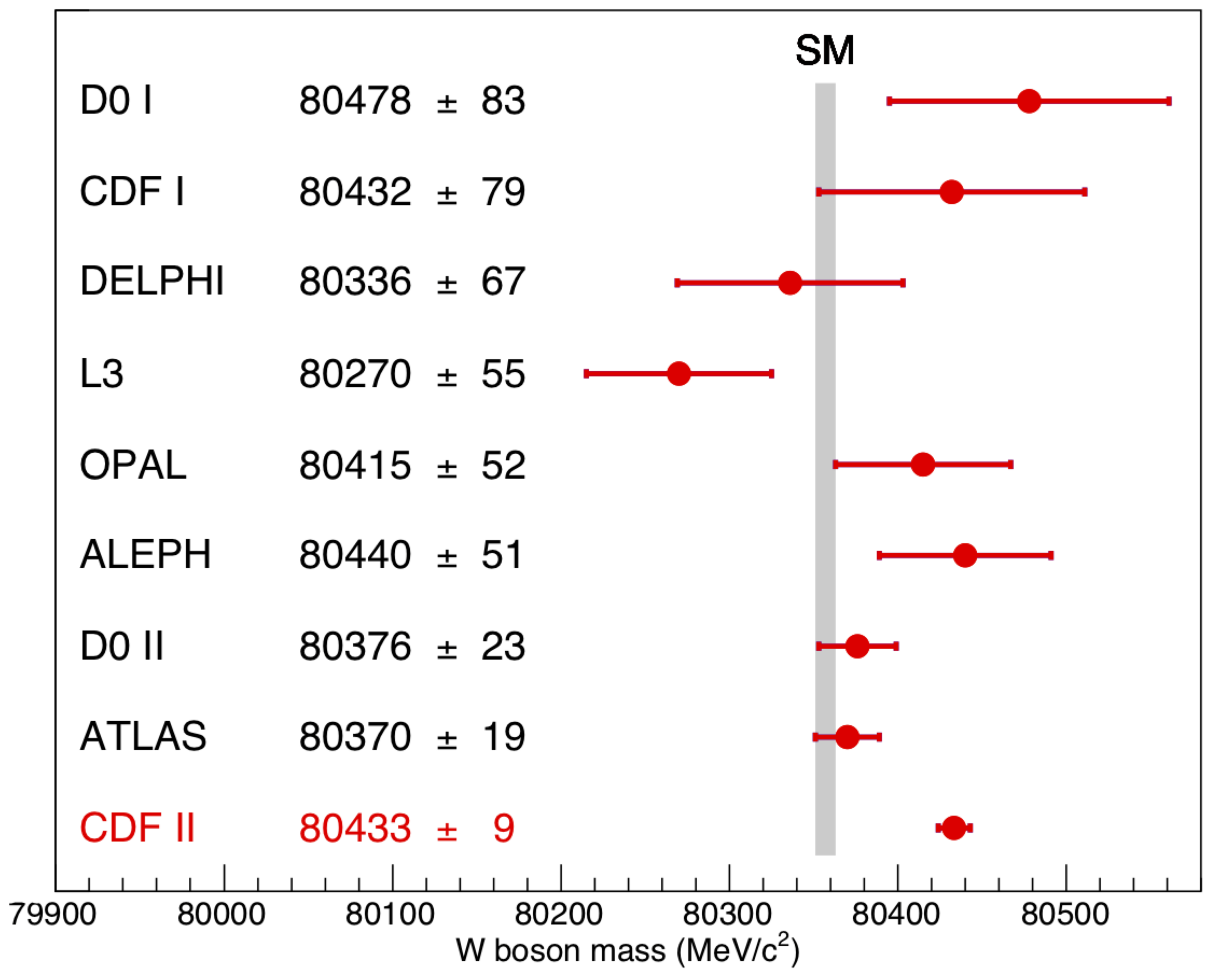
Individual pulls

(Remove observable from fit → Predict)



Introduction

Most Recent updates



W mass by Tevatron CDF experiment

Consistent with previous CDF measurement

Significant tension, not only with SM, but also with available LHC measurements

$$t\bar{t} \to \ell + \text{jets}$$

$$m_t = 171.77 \pm 0.38\ \text{GeV}$$

CMS-PAS-TOP-20-008

Top mass by CMS

Most precise measurement to date

Introduction

Relevance of W-boson mass in EWPO

- One of the most precise observables in the EW sector ~O(0.01%)
- And one for which the SM prediction is known to higher precision

$$M_{\rm W} = M_{\rm W}^0 - c_1\,{\rm dH} - c_2\,{\rm dH}^2 + c_3\,{\rm dH}^4 + c_4({\rm dh}-1) - c_5\,{\rm d}\alpha + c_6\,{\rm dt} - c_7\,{\rm dt}^2 - c_8\,{\rm dH}\,{\rm dt} + c_9\,{\rm dh}\,{\rm dt} - c_{10}\,{\rm d}\alpha_{\rm s} + c_{11}\,{\rm dZ},$$

$${\rm dH} = \ln\left(\frac{M_{\rm H}}{100\ {\rm GeV}}\right), \quad {\rm dh} = \left(\frac{M_{\rm H}}{100\ {\rm GeV}}\right)^2, \quad {\rm dt} = \left(\frac{m_{\rm t}}{174.3\ {\rm GeV}}\right)^2 - 1,$$

$${\rm dZ} = \frac{M_{\rm Z}}{91.1875\ {\rm GeV}} - 1, \quad {\rm d}\alpha = \frac{\Delta\alpha}{0.05907} - 1, \quad {\rm d}\alpha_{\rm s} = \frac{\alpha_{\rm s}(M_{\rm Z})}{0.119} - 1,$$

$$M_{\rm W}^0 = 80.3779\ {\rm GeV}, \quad c_1 = 0.05427\ {\rm GeV}, \quad c_2 = 0.008931\ {\rm GeV},$$
$$c_3 = 0.0000882\ {\rm GeV}, \quad c_4 = 0.000161\ {\rm GeV}, \quad c_5 = 1.070\ {\rm GeV},$$
$$c_6 = 0.5237\ {\rm GeV}, \quad c_7 = 0.0679\ {\rm GeV}, \quad c_8 = 0.00179\ {\rm GeV},$$
$$c_9 = 0.0000664\ {\rm GeV}, \quad c_{10} = 0.0795\ {\rm GeV}, \quad c_{11} = 114.9\ {\rm GeV}.$$

M. Awramik, M. Czakon, A. Freitas, G. Weiglein, Phys. Rev D69 (2004) 053006

Full EW 2-loop
+ leading 3-loop
& some 4-loop

- Probe of important SM relations, e.g. custodial symmetry:

$$\rho = \frac{M_W^2}{M_Z^2\cos^2\theta_W} \approx 1$$

Introduction

Relevance of Top-Quark mass in EWPO

- The top quark mass is one of the inputs of the SM ⇒ its value of particular relevance, among others for the prediction of the W mass

$$
\begin{aligned}
M_{\mathrm{W}} = {} & M_{\mathrm{W}}^0 - c_1\,\mathrm{dH} - c_2\,\mathrm{dH}^2 + c_3\,\mathrm{dH}^4 + c_4(\mathrm{dh}-1) - c_5\,\mathrm{d}\alpha + c_6\,\mathrm{dt} - c_7\,\mathrm{dt}^2 \\
& - c_8\,\mathrm{dH}\,\mathrm{dt} + c_9\,\mathrm{dh}\,\mathrm{dt} - c_{10}\,\mathrm{d}\alpha_{\mathrm{s}} + c_{11}\,\mathrm{dZ},
\end{aligned}
$$

$$
\mathrm{dH} = \ln\left(\frac{M_{\mathrm{H}}}{100\ \mathrm{GeV}}\right), \quad \mathrm{dh} = \left(\frac{M_{\mathrm{H}}}{100\ \mathrm{GeV}}\right)^2, \quad \mathrm{dt} = \left(\frac{m_{\mathrm{t}}}{174.3\ \mathrm{GeV}}\right)^2 - 1,
$$

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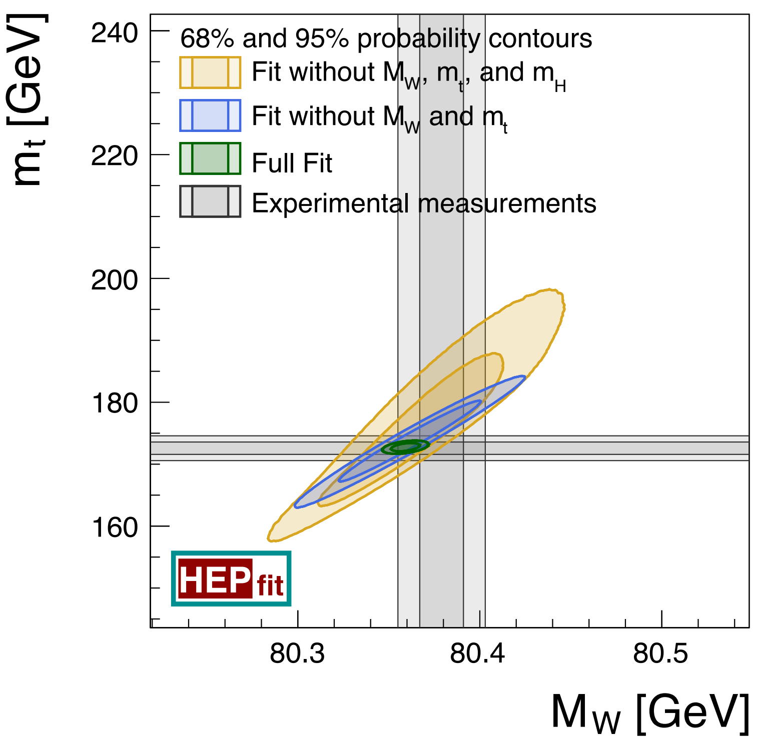

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J.B. et al., arXiv: 2112.07274 [hep-ph] (Accepted for pub. In PRD)

SM parametric uncertainties

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

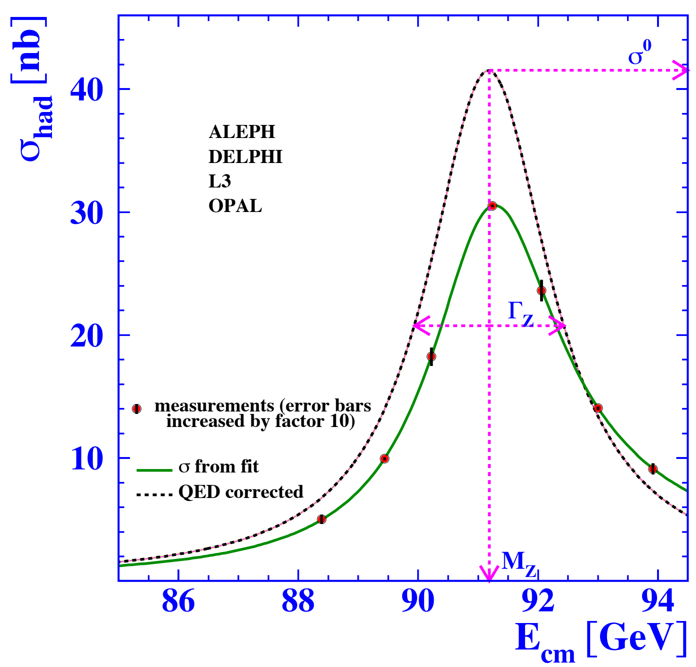
$m_t^{(2021)}$=172.58±0.45 GeV

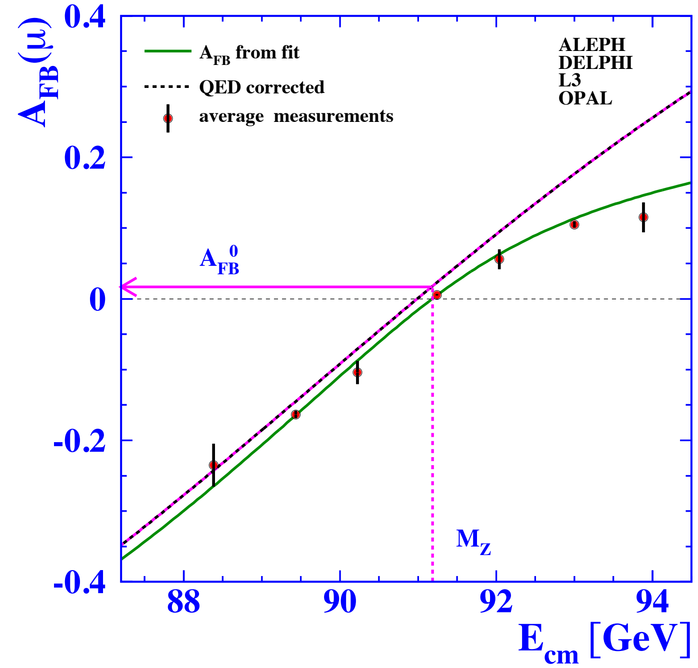
Status of EWPO

Updates on the M_W and m_t combinations

Z pole measurements

- Z lines shape measurements date back to the LEP/SLD era: **LEP and SLD Collaborations, arXiv: 0509008 [hep-ex]**





Results depend on measuring precisely the integrated luminosity
Obtained via low-angle Bhabha scattering (known to 0.061% during LEP era)

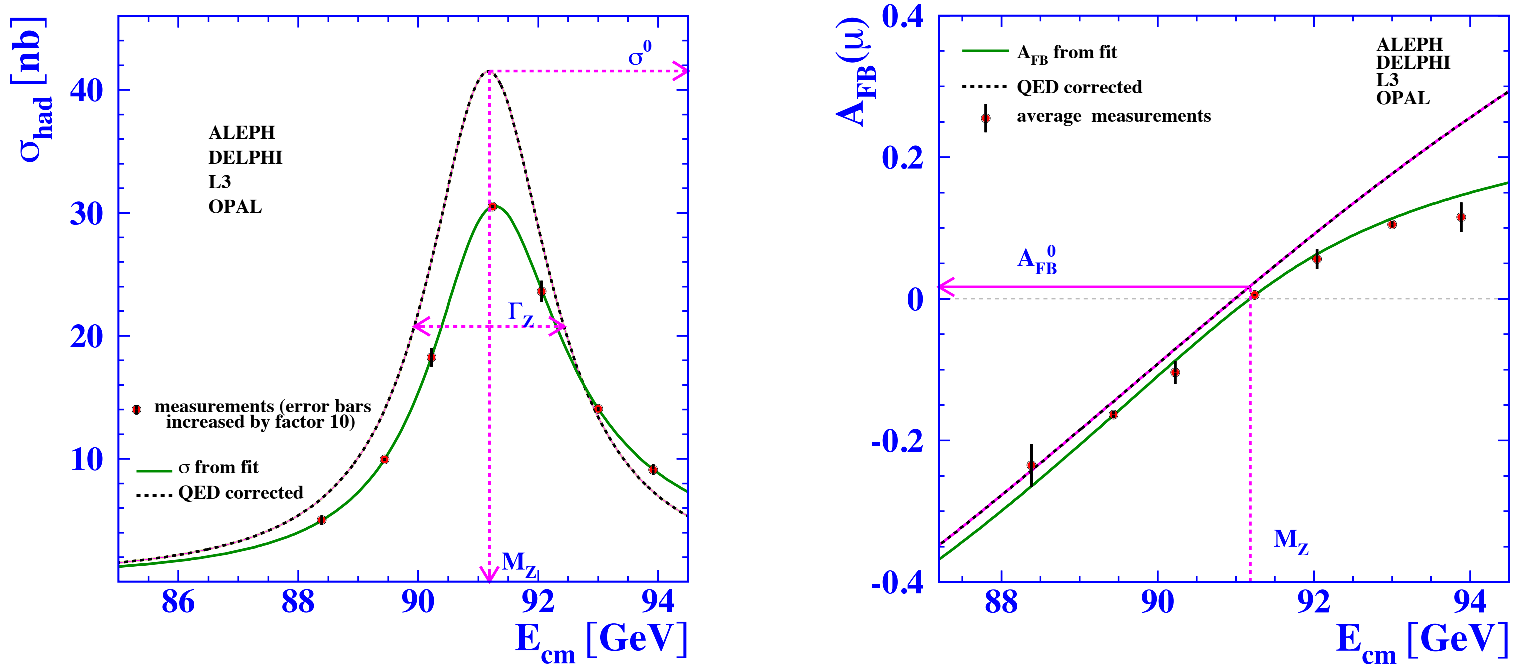
- Recently revisited using updated (more accurate) prediction of Bhabha process:
  - ✓ New corrections decrease the Bhabha cross section by 0.048% (uncertainty 0.037%) **P. Janot, S. Jadach, Phys.Lett.B 803 (2020) 135319**
    - ➡ Increase the measured luminosity ➡ Decrease measured value for the on-peak hadronic cross section (Z width also slightly modified)

$$\sigma^0_{\rm had} = 41.4802 \pm 0.0325\,{\rm nb},$$
$$\Gamma_Z = 2.4955 \pm 0.0023\,{\rm GeV}$$

Z pole measurements

- Z lines shape measurements date back to the LEP/SLD era:

LEP and SLD Collaborations, arXiv: 0509008 [hep-ex]



Results depend on measuring precisely the integrated luminosity
Obtained via low-angle Bhabha scattering (known to 0.061% during LEP era)

- Recently revisited using updated (more accurate) prediction of Bhabha process:

The updated results remove past tension with SM in the value of the effective # of ν : N_ν

$$R^0_{\rm inv} = N_\nu \left(\frac{\Gamma_{\nu\bar\nu}}{\Gamma_{\ell\ell}}\right)_{\rm SM} \quad \text{with} \quad R^0_{\rm inv} = \left(\frac{12\pi R^0_\ell}{\sigma^0_{\rm had} m_Z^2}\right)^{\frac{1}{2}} - R^0_\ell - (3+\delta_\tau)$$

$$N_\nu = 2.9840 \pm 0.0082 \quad \longrightarrow \quad N_\nu = 2.9963 \pm 0.0074$$

~2 σ → **0.5 σ**

Z pole measurements

- Z-pole forward backward asymmetry of the b-quark:

✓ Longstanding anomaly in the EW fit:

$A_{\rm FB}^{0,b} = 0.0992 \pm 0.0016$ **2.6 σ** $A_{\rm FB,SM}^{0,b} = 0.1035 \pm 0.0005$

EXP **2016 SM EW fit**

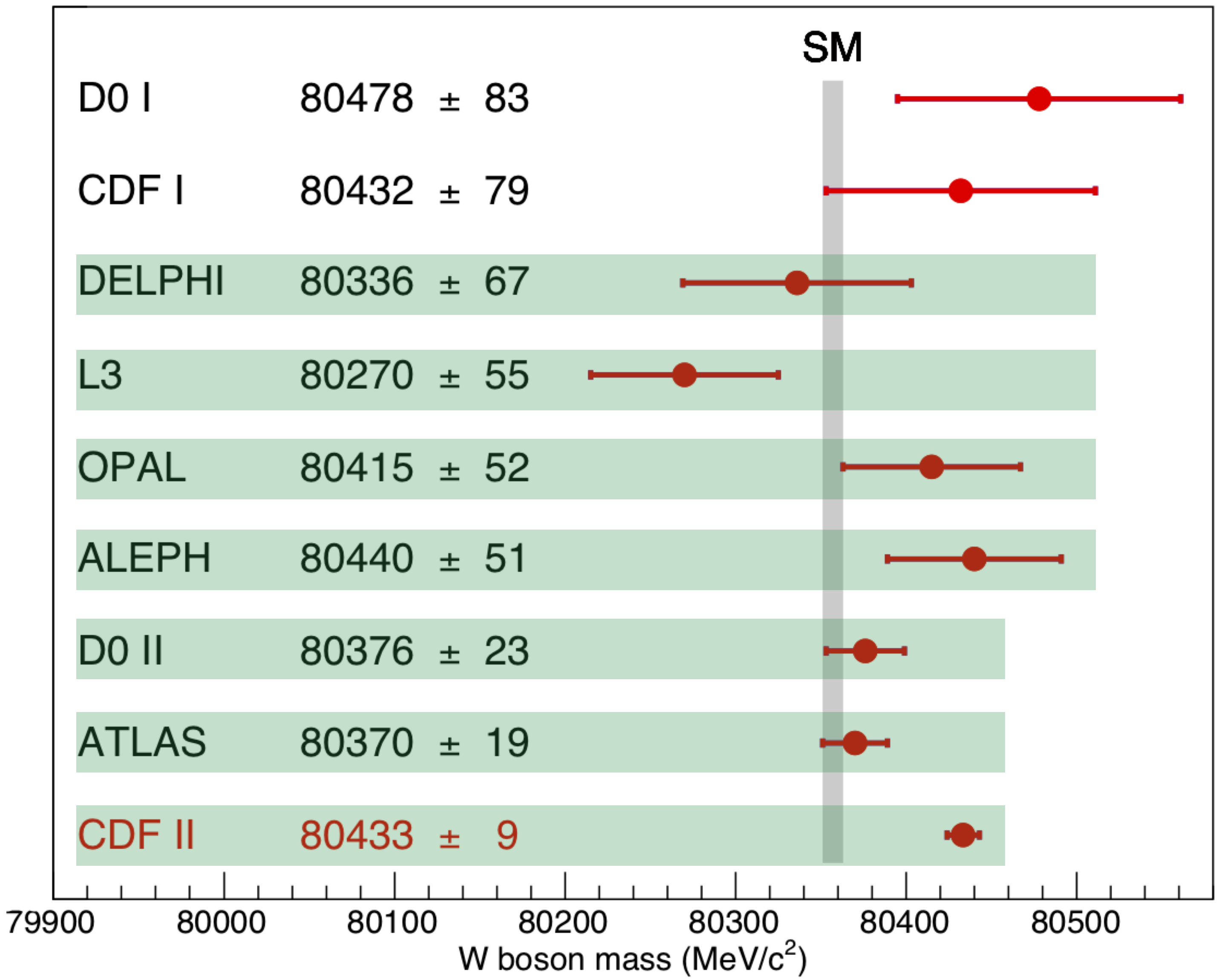
- Also revisited recently, including:
  - ✓ Reassessment of QCD uncertainties using modern Parton shower simulations (Pythia 8)
  - ✓ NNLO (2-loop) massive b-quark corrections

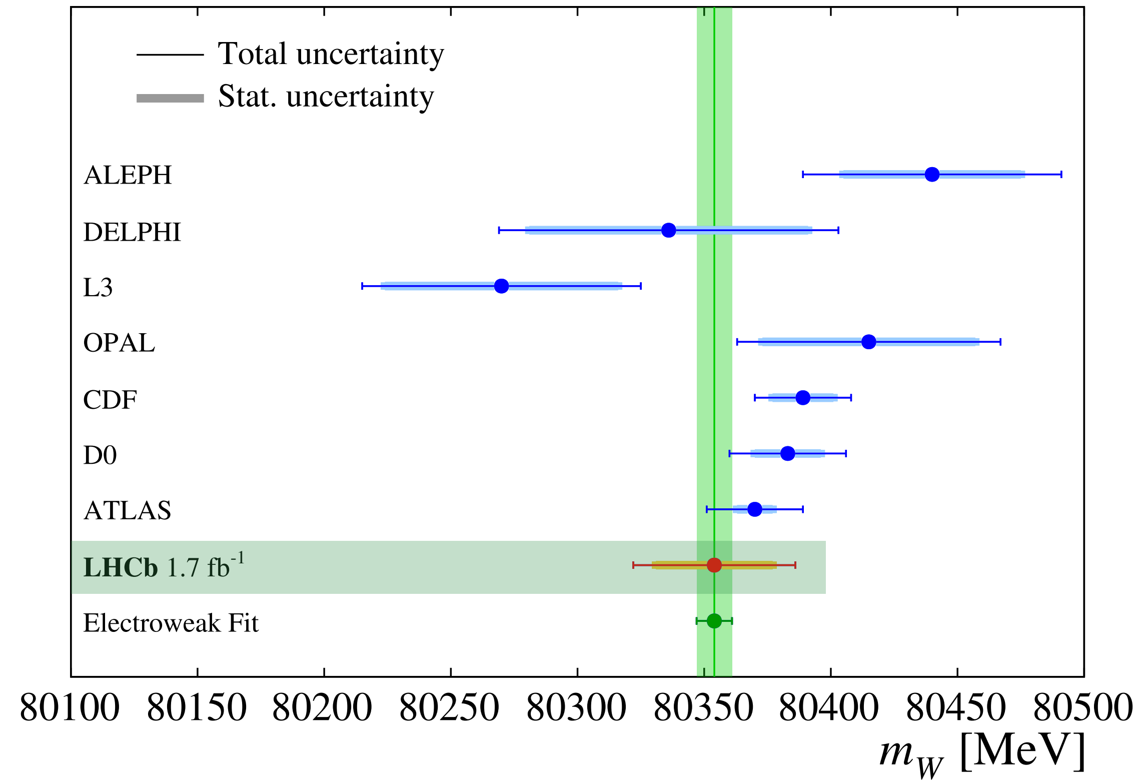
$$A_{\rm FB}^{0,b} = 0.0992 \pm 0.0016 \to 0.0996 \pm 0.0016$$ **(Stat dominated)**

  - ✓ New corrections tend to reduce the discrepancy with the SM (more later)

Naive W mass combination

- Theorist combination of W mass measurements:





Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

- Combine hadron collider measurements assuming common uncertainty of 4.7 MeV
- Combine in an uncorrelated manner with LEP2 result

Naive W mass combination

- Theorist combination of W mass measurements:

$$M_W = 80.4133 \pm 0.0080 \text{ GeV}$$

Standard average scenario

- But this comes from a combination of measurements in significant tension…

CDF vs. **ATLAS: 3.0 σ** **LHCb: 2.4 σ** **LEP2: 1.7 σ**

$$\frac{\chi^2}{n_{\mathrm{d.o.f.}}} = 3.59 \longrightarrow \frac{\chi^2}{n_{\mathrm{d.o.f.}}} = 1.00$$

PDG: scale uncertainty

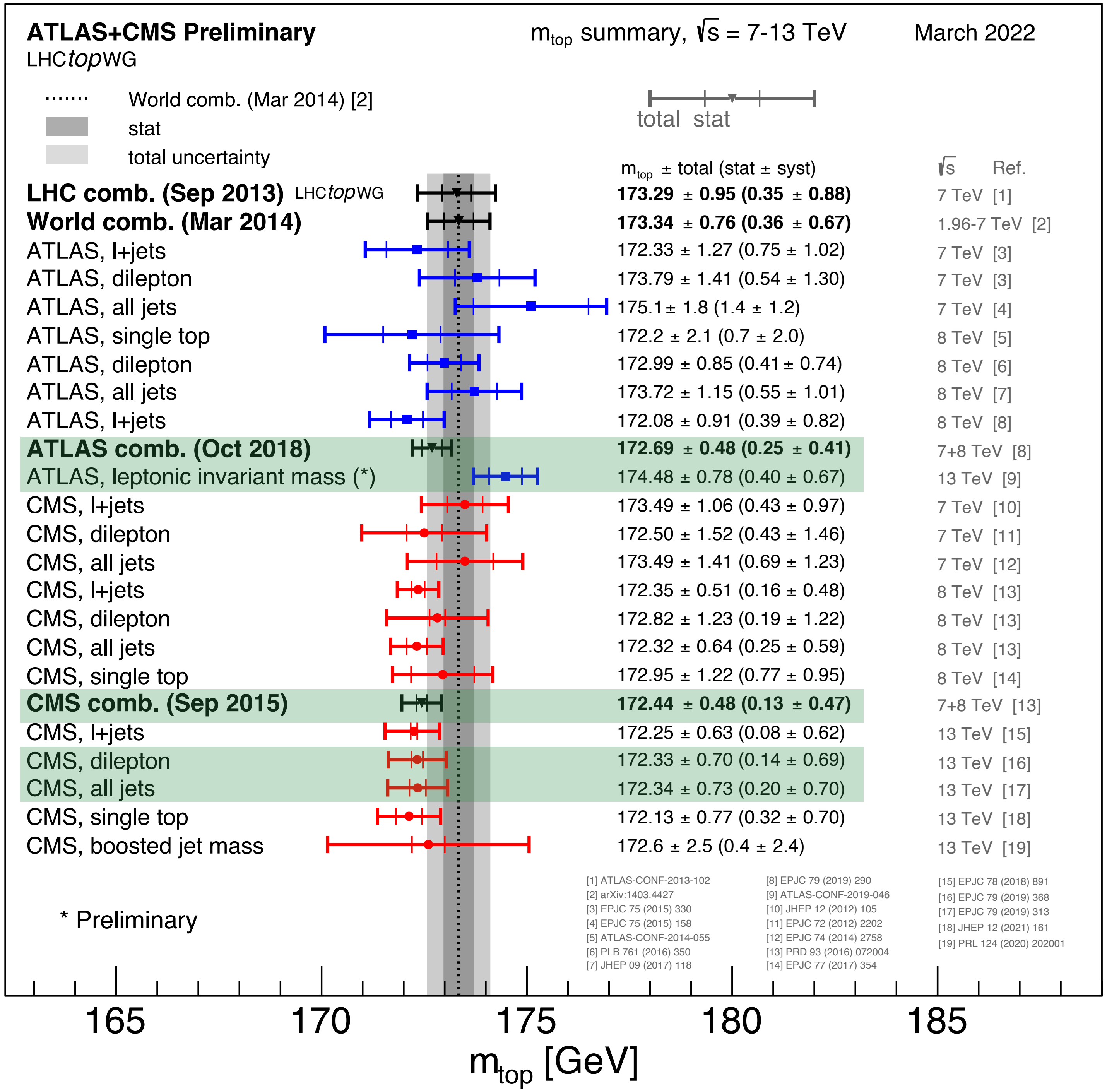
- Following the PDG procedure we assume the discrepancy is due to unknown/underestimated systematics and inflate error accordingly:

$$M_W = 80.4133 \pm 0.015 \text{ GeV}$$

Conservative average scenario

Naive Top mass combination

- Theorist combination of Top quark measurements:



$$t\bar{t} \to \ell + \text{jets}$$

$$m_t = 171.77 \pm 0.38 \text{ GeV}$$

CMS-PAS-TOP-20-008

We also include Tevatron combination:

$$\mathbf{m_t = 174.3 \pm 0.35 \pm 0.54 \text{ GeV}}$$

aXiv: 1608.01881 [hep-ex]

We combine these measurements assuming systematics correlated by

$$\rho_{ij}^{sys} = \frac{\min(\sigma_i^{sys}, \sigma_j^{sys})}{\max(\sigma_i^{sys}, \sigma_j^{sys})}$$

$$m_t = 171.79 \pm 0.38 \text{ GeV}$$

Standard average scenario

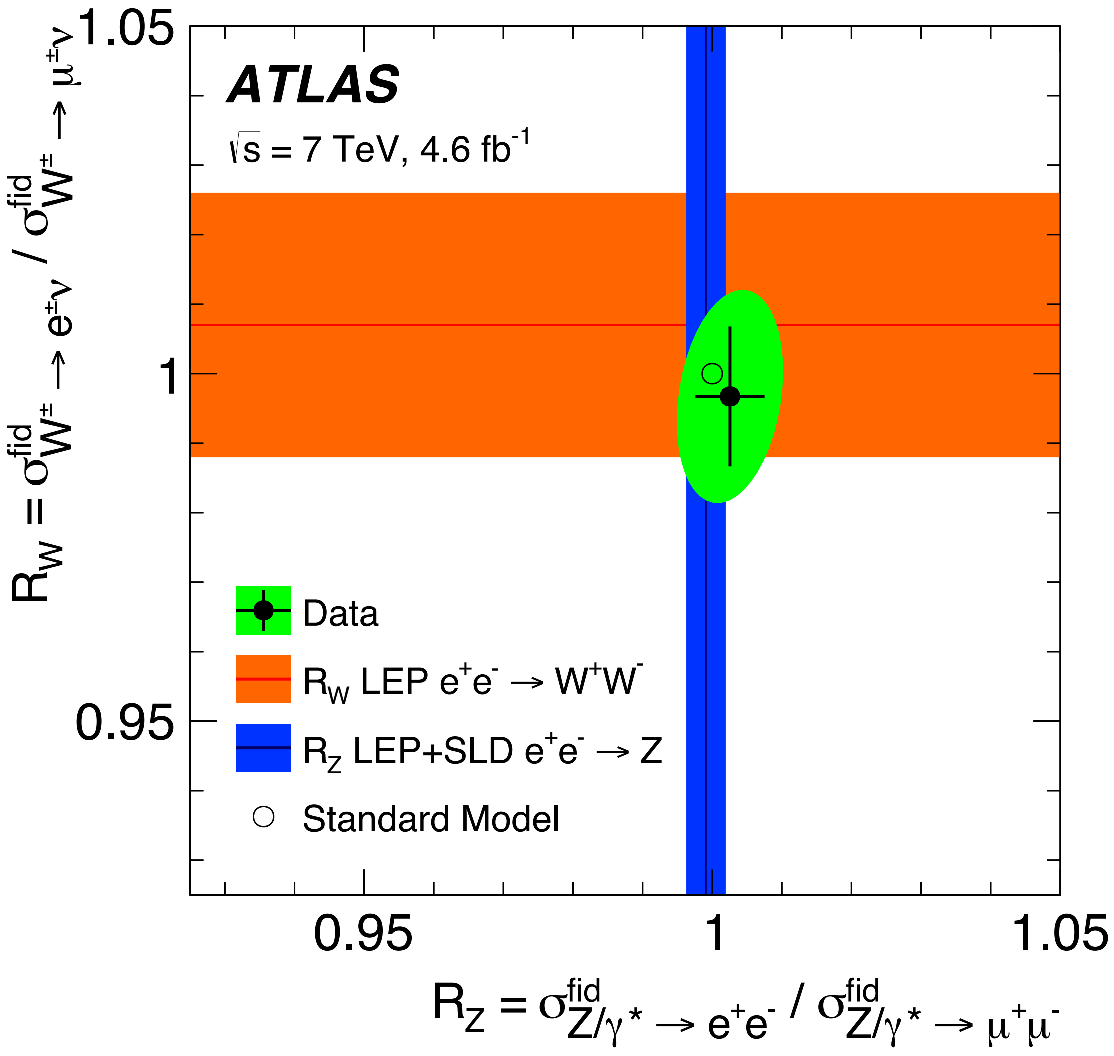
$$m_t = 171.79 \pm 1.0 \text{ GeV}$$

Conservative average scenario

LHC relevant observables for the EW fit

- Apart from the Higgs, Top and W mass, the LHC contributes to the EW fit with several observables that become relevant, in particular, to test fermion universality of EW interactions

- Ratios of W and Z decays (tests of lepton universality), e.g. ATLAS:



ATLAS, Eur. Phys. J. C 77 (2017) 367

$$\left.\frac{\mathrm{BR}_{W\to e\nu}}{\mathrm{BR}_{W\to \mu\nu}}\right|_{\mathrm{ATLAS}} = 0.997 \pm 0.010$$

$$\left.\frac{\mathrm{BR}_{Z\to ee}}{\mathrm{BR}_{Z\to \mu\mu}}\right|_{\mathrm{ATLAS}} = 1.0026 \pm 0.005$$

Even for NC, precision similar to LEP/SLD

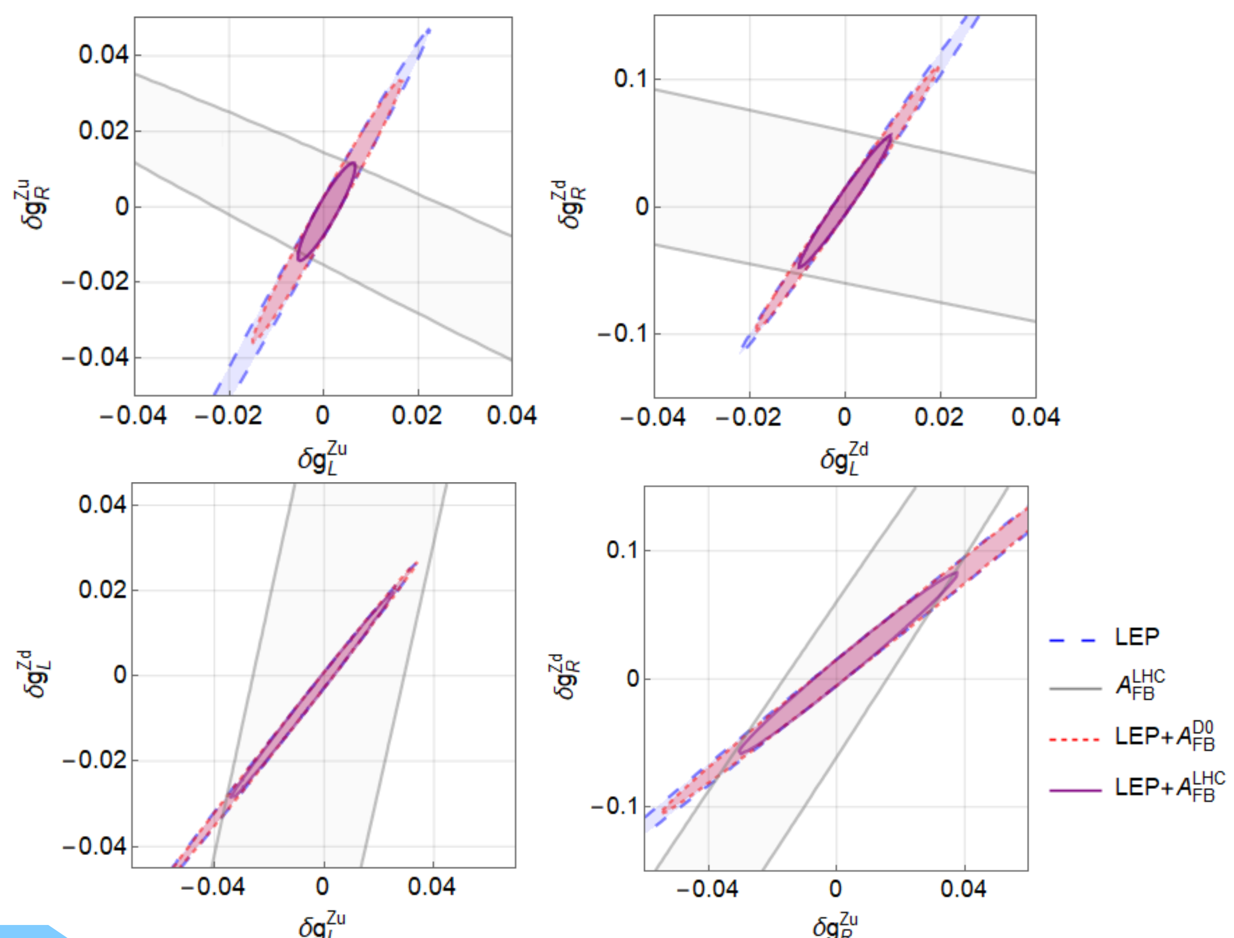
$$\left.\frac{\mathrm{BR}_{Z\to ee}}{\mathrm{BR}_{Z\to \mu\mu}}\right|_{\mathrm{LEP/SLD}} = 0.9991 \pm 0.0028$$

LHC relevant observables for the EW fit

- Apart from the Higgs, Top and W mass, the LHC contributes to the EW fit with several observables that become relevant, in particular, to test fermion universality of EW interactions
- LHC forward-backward asymmetry in Drell-Yan (for quark non-universal fit)

LEP/SLD Z-pole observables blind to a particular direction of light-quark couplings

$$\delta g_L^{Zu} + \delta g_L^{Zd} + \frac{3g_L^2 - g_Y^2}{4g_Y^2}\delta g_R^{Zu} + \frac{3g_L^2 + g_Y^2}{2g_Y^2}\delta g_R^{Zd}$$



Can be resolved including the LHC Drell-Yan FB asymmetry as a function of the dilepton rapidity Y

$$A_{FB}(Y,\hat{s}) = \frac{\sigma_F(Y,\hat{s}) - \sigma_B(Y,\hat{s})}{\sigma_F(Y,\hat{s}) + \sigma_B(Y,\hat{s})},$$

V. Breso-Pla, A. Falkowski, M. Gonzalez-Alonso, JHEP 08 (2021) 021

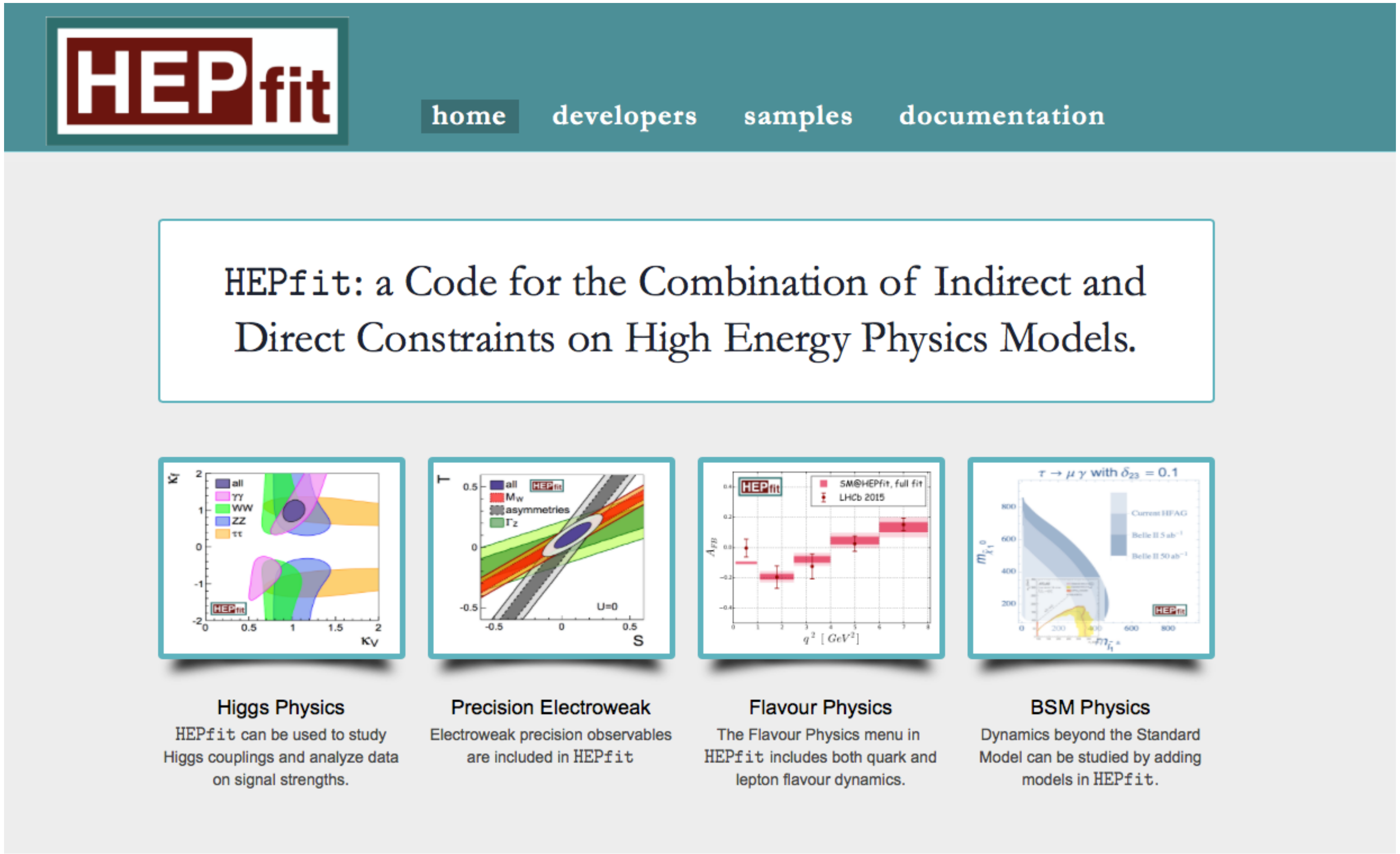
The Standard Model
Electroweak Precision Data Fit

The HEPfit code

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on GitHub)

  https://github.com/silvest/HEPfit

- Webpage: http://hepfit.roma1.infn.it



The HEPfit code: Models and Observables

Some models/observables already available in the code

Models

Standard Model

Oblique pars: S,T,U
ε_i parameters
Modified *Zbb* couplings
κ-framework
SMEFT: dim 6
HEFT

General 2HDM
Georgi-Machacek

SUSY-MSSM (WIP)
LR models

Observables*

EWPO
LEP 2 obs: $e^+e^-\to ff$, W^+W^-
LHC Higgs observables
LHC diboson
LHC Top
Flavor: ΔF=2, UT, B decays
LFV

Theory constr.: Unitarity, Perturbativity, ...

*Not all observables available for all models

The HEPfit code: Models and Observables

Some models/observables already available in the code

Models

In this talk

- Standard Model
- Oblique pars: S,T,U
- ε_i parameters
- Modified *Zbb* couplings
- κ-framework
- SMEFT: dim 6
- HEFT
- General 2HDM
- Georgi-Machacek
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- EWPO
- LEP 2 obs: $e^+e^- \to ff$, W^+W^-
- LHC Higgs observables
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- Flavor: ΔF=2, UT, B decays
- LFV
- Theory constr.: Unitarity, Perturbativity, ...

*Not all observables available for all models

The HEPfit code: EWPO

- EWPO implemented using the state-of-the-art of theory calculations:
  - ✓ Γ_W : Only EW one loop
    D.Y. Bardin, P.K. Khristova, O. Fedorenko, Nucl. Phys B197 (1982) 1-44
    D.Y. Bardin, S. Riemann, T. Riemann, Z. Phys C32 (1986) 121-125
  - ✓ M_W : Full EW 2-loop + leading 3-loop & some 4-loop
    M. Awramik, M. Czakon, A. Freitas, G. Weiglein, Phys. Rev D69 (2004) 053006
  - ✓ $\sin^2\theta^f_{\rm Eff}$ (light ferm): Full EW 2-loop + leading higher order
    M. Awramik, M. Czakon, A. Freitas, JHEP 0611 (2006) 048
    M. Awramik, M. Czakon, A. Freitas, B.A. Kniehl, Nucl. Phys. B813 (2009) 174-187
  - ✓ Γ_Z^f : Full fermionic EW 2-loop
    A. Freitas, JHEP 1404 (2014) 070
  - ✓ $\sin^2\theta^b_{\rm Eff}$: Full 2-loop bosonic corrections
    I. Dubovyk, A. Freitas, J. Gluza, T. Riemann, J. Usovitsch, Phys. Lett. B 762 (2016) 184-189
  - ✓ Leading 3-loop fermionic corrections
    L. Cheng, A. Freitas, JHEP 07 (2020) 210

- Experimental vs. Theoretical uncertainties:

	$M_{\rm W}$	$\Gamma_{\rm Z}$	$\sigma^0_{\rm had}$	$R_{\rm b}$	$\sin^2\theta^\ell_{\rm eff}$
Exp. error	15 MeV	2.3 MeV	37 pb	6.6×10^{-4}	1.6×10^{-4}
Theory error	4 MeV	0.5 MeV	6 pb	1.5×10^{-4}	0.5×10^{-4}

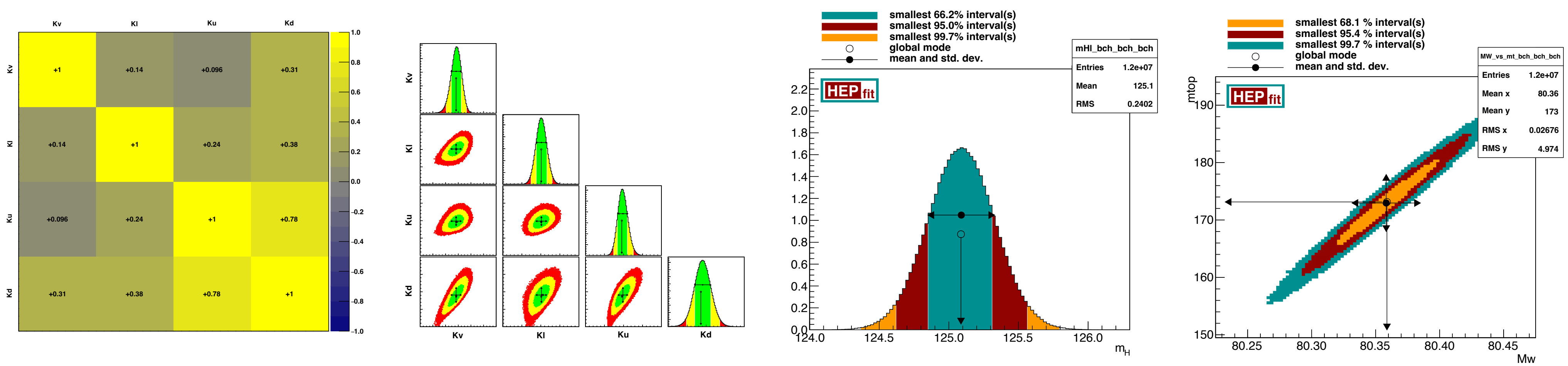
A. Freitas, PoS(LL2014)050 [arXiv: 1406.6980]

The HEPfit code: EWPO

- Fit methodology:
  - ✓ Bayesian Statistical approach using the built-in HEPfit interface with the Bayesian Analysis Toolkit BAT
  - ✓ SM theoretical uncertainties are included in the fits. Treated as nuisance parameters and marginalized over:

	M_W	Γ_Z	σ^0_{had}	R_b	$\sin^2\theta^\ell_{eff}$
Exp. error	15 MeV	2.3 MeV	37 pb	6.6×10^{-4}	1.6×10^{-4}
Theory error	4 MeV	0.5 MeV	6 pb	1.5×10^{-4}	0.5×10^{-4}

  - ✓ Results expressed in terms of the mean and variance of the posterior predictive from the fit



The SM EW fit

- SM EW fit results: Different fits to study the consistency between SM/EWPD

	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11762 ± 0.00095 $[0.11576, 0.11946]$	0.11685 ± 0.00278 $[0.11145, 0.12233]$	0.3	0.12181 ± 0.00470 $[0.1126, 0.1310]$	-0.8	0.1177 ± 0.0010 $[0.1157, 0.1197]$	–
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	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 $[171.64, 173.09]$	181.45 ± 1.49 $[178.53, 184.42]$	-6.3	187.58 ± 9.52 $[169.1, 206.1]$	-1.7	171.80 ± 0.38 $[171.05, 172.54]$	–
m_H [GeV]	125.21 ± 0.12	125.20 ± 0.12 $[124.97, 125.44]$	93.36 ± 4.99 $[82.92, 102.89]$	4.3	247.98 ± 125.35 $[100.8, 640.4]$	-0.9	125.21 ± 0.12 $[124.97, 125.45]$	–
M_W [GeV]	80.4133 ± 0.0080	80.3706 ± 0.0045 $[80.3617, 80.3794]$	80.3499 ± 0.0056 $[80.3391, 80.3610]$	6.5	80.4129 ± 0.0080 $[80.3973, 80.4284]$	0.1	80.3496 ± 0.0057 $[80.3386, 80.3608]$	6.5
Γ_W [GeV]	2.085 ± 0.042	2.08903 ± 0.00053 $[2.08800, 2.09006]$	2.08902 ± 0.00052 $[2.08799, 2.09005]$	-0.1	2.09430 ± 0.00224 $[2.0900, 2.0988]$	-0.2	2.08744 ± 0.00059 $[2.08627, 2.08859]$	0.0
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.231471 ± 0.000055 $[0.231362, 0.231580]$	0.231469 ± 0.000056 $[0.231361, 0.231578]$	0.8	0.231460 ± 0.000138 $[0.23119, 0.23173]$	0.8	0.231558 ± 0.000062 $[0.231436, 0.231679]$	0.7
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14742 ± 0.00044 $[0.14656, 0.14827]$	0.14744 ± 0.00044 $[0.14657, 0.14830]$	-0.3	0.14750 ± 0.00108 $[0.1454, 0.1496]$	-0.3	0.14675 ± 0.00049 $[0.14580, 0.14770]$	-0.1
Γ_Z [GeV]	2.4955 ± 0.0023	2.49455 ± 0.00065 $[2.49329, 2.49581]$	2.49437 ± 0.00068 $[2.49301, 2.49569]$	0.5	2.49530 ± 0.00204 $[2.4912, 2.4993]$	0.0	2.49397 ± 0.00068 $[2.49262, 2.49531]$	0.6
σ_h^0 [nb]	41.480 ± 0.033	41.4892 ± 0.0077 $[41.4741, 41.5041]$	41.4914 ± 0.0080 $[41.4757, 41.5070]$	-0.3	41.4613 ± 0.0303 $[41.402, 41.521]$	0.4	41.4923 ± 0.0080 $[41.4766, 41.5081]$	-0.4
R_ℓ^0	20.767 ± 0.025	20.7487 ± 0.0080 $[20.7329, 20.7645]$	20.7451 ± 0.0087 $[20.7281, 20.7621]$	0.8	20.7587 ± 0.0217 $[20.716, 20.801]$	0.2	20.7468 ± 0.0087 $[20.7298, 20.7637]$	0.7
$A_{\rm FB}^{0,\ell}$	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_b^0	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_c^0	0.1721 ± 0.0030	0.172198 ± 0.000054 $[0.172093, 0.172302]$	0.172197 ± 0.000054 $[0.172094, 0.172303]$	-0.1	0.172404 ± 0.000183 $[0.17206, 0.17278]$	-0.1	0.172189 ± 0.000054 $[0.172084, 0.172295]$	-0.1
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016	0.10335 ± 0.00030 $[0.10276, 0.10396]$	0.10337 ± 0.00032 $[0.10275, 0.10400]$	-2.3	0.10338 ± 0.00077 $[0.10189, 0.10490]$	-2.1	0.10288 ± 0.00034 $[0.10220, 0.10354]$	-2.0
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07385 ± 0.00023 $[0.07341, 0.07430]$	0.07387 ± 0.00023 $[0.07341, 0.07434]$	-0.9	0.07392 ± 0.00059 $[0.07275, 0.07507]$	-0.9	0.07348 ± 0.00025 $[0.07298, 0.07398]$	-0.8
$\mathcal{A}_b$	0.923 ± 0.020	0.934770 ± 0.000039 $[0.934693, 0.934847]$	0.934772 ± 0.000040 $[0.934693, 0.934849]$	-0.6	0.934593 ± 0.000166 $[0.93426, 0.93491]$	-0.6	0.934721 ± 0.000041 $[0.934642, 0.934801]$	-0.6
$\mathcal{A}_c$	0.670 ± 0.027	0.66796 ± 0.00021 $[0.66754, 0.66838]$	0.66797 ± 0.00021 $[0.66755, 0.66839]$	0.1	0.66817 ± 0.00054 $[0.66712, 0.66922]$	0.1	0.66766 ± 0.00022 $[0.66722, 0.66810]$	0.1
$\mathcal{A}_s$	0.895 ± 0.091	0.935678 ± 0.000039 $[0.935600, 0.935755]$	0.935677 ± 0.000040 $[0.935599, 0.935754]$	-0.4	0.935716 ± 0.000098 $[0.935523, 0.935909]$	-0.5	0.935621 ± 0.000041 $[0.935541, 0.935702]$	-0.5
${\rm BR}_{W\to\ell\bar{\nu}_\ell}$	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
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025	0.231471 ± 0.000055 $[0.231362, 0.231580]$	0.231474 ± 0.000056 $[0.231363, 0.231584]$	-0.2	0.231460 ± 0.000138 $[0.23119, 0.23173]$	-0.1	0.231558 ± 0.000062 $[0.231436, 0.231679]$	-0.5
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000031 $[0.172159, 0.172282]$	0.172220 ± 0.000032 $[0.172159, 0.172282]$	-0.7	0.172424 ± 0.000180 $[0.17209, 0.17279]$	-0.7	0.172212 ± 0.000032 $[0.172149, 0.172275]$	-0.7

"Posterior": The full fit results

"Indirect/Prediction":
Drop each observable at a time → fit → predict the removed observable

"Full Indirect":
Drop exp. data for SM inputs → Obtain indirect determination from EWPO fit

"Full Prediction":
Drop exp. data for EWPO → Obtain prediction from exp. values of SM inputs

The SM EW fit

- SM EW fit results: Different fits to study the consistency between SM/EWPD

	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	–
		$[0.11576, 0.11946]$	$[0.11145, 0.12233]$		$[0.1126, 0.1310]$		$[0.1157, 0.1197]$	
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	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
		$[2.08800, 2.09006]$	$[2.08799, 2.09005]$		$[2.0900, 2.0988]$		$[2.08627, 2.08859]$	
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	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
		$[0.231362, 0.231580]$	$[0.231361, 0.231578]$		$[0.23119, 0.23173]$		$[0.231436, 0.231679]$	
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	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_h^0 [nb]								
R^0_ℓ								
$A^{0,\ell}_{\rm FB}$								
$\mathcal{A}_\ell$ (SLD								
R^0_b								
R^0_c								
$A^{0,b}_{\rm FB}$								
$A^{0,c}_{\rm FB}$								
$\mathcal{A}_b$								
$\mathcal{A}_c$								
		$[0.66754, 0.66838]$	$[0.66755, 0.66839]$		$[0.66712, 0.66922]$		$[0.66722, 0.66810]$	
$\mathcal{A}_s$	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
		$[0.935600, 0.935755]$	$[0.935599, 0.935754]$		$[0.935523, 0.935909]$		$[0.935541, 0.935702]$	
${\rm BR}_{W\to\ell\bar\nu_\ell}$	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
		$[0.108345, 0.108431]$	$[0.108345, 0.108431]$		$[0.10808, 0.10851]$		$[0.108340, 0.108432]$	
$\sin^2\theta_{\rm eff}^{\rm lept}$ (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
		$[0.172159, 0.172282]$	$[0.172159, 0.172282]$		$[0.17209, 0.17279]$		$[0.172149, 0.172275]$	

Tension between Forward Backward b asymmetry and SM prediction

Model	Pred. $A_{\rm FB}^{b,0}$ *standard average*	Pull	Pred. $A_{\rm FB}^{b,0}$ *conservative average*	Pull
SM	0.10337 ± 0.00032	$-2.3\,\sigma$	0.10325 ± 0.00034	$-2.2\,\sigma$

"Posterior": The full fit results

"Indirect/Prediction":
Drop each observable at a time → fit → predict the removed observable

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Drop exp. data for EWPO → Obtain prediction from exp. values of SM inputs

The SM EW fit

- SM EW fit results: Different fits to study the consistency between SM/EWPD

	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11762 ± 0.00095 [0.11576, 0.11946]	0.11685 ± 0.00278 [0.11145, 0.12233]	0.3	0.12181 ± 0.00470 [0.1126, 0.1310]	−0.8	0.1177 ± 0.0010 [0.1157, 0.1197]	–
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.02766 ± 0.0001	0.027535 ± 0.000096 [0.027349, 0.027726]	.026174 ± 0.000334 [0.025522, 0.026826]	4.3	.028005 ± 0.000675 [0.02667, 0.02932]	−0.5	0.02766 ± 0.00010 [0.02746, 0.02786]	–
M_Z [GeV]	91.1875 ± 0.0021	91.1911 ± 0.0020 [91.1872, 91.1950]	91.2314 ± 0.0069 [91.2178, 91.2447]	−6.1	91.2108 ± 0.0390 [91.136, 91.288]	−0.6	91.1875 ± 0.0021 [91.1834, 91.1916]	–
m_t [GeV]	171.79 ± 0.38	172.36 ± 0.37 [171.64, 173.09]	181.45 ± 1.49 [178.53, 184.42]	−6.3	187.58 ± 9.52 [169.1, 206.1]	−1.7	171.80 ± 0.38 [171.05, 172.54]	–
m_H [GeV]	125.21 ± 0.12	125.20 ± 0.12 [124.97, 125.44]	93.36 ± 4.99 [82.92, 102.89]	4.3	247.98 ± 125.35 [100.8, 640.4]	−0.9	125.21 ± 0.12 [124.97, 125.45]	–
M_W [GeV]	80.4133 ± 0.0080	80.3706 ± 0.0045 [80.3617, 80.3794]	80.3499 ± 0.0056 [80.3391, 80.3610]	6.5	80.4129 ± 0.0080 [80.3973, 80.4284]	0.1	80.3496 ± 0.0057 [80.3386, 80.3608]	6.5
Γ_W [GeV]	2.085 ± 0.042	2.08903 ± 0.00053 [2.08800, 2.09006]	2.08902 ± 0.00052 [2.08799, 2.09005]	−0.1	2.09430 ± 0.00224 [2.0900, 2.0988]	−0.2	2.08744 ± 0.00059 [2.08627, 2.08859]	0.0
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.231471 ± 0.000055 [0.231362, 0.231580]	.231469 ± 0.000056 [0.231361, 0.231578]	0.8	.231460 ± 0.000138 [0.23119, 0.23173]	0.8	.231558 ± 0.000062 [0.231436, 0.231679]	0.7
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14742 ± 0.00044 [0.14656, 0.14827]	0.14744 ± 0.00044 [0.14657, 0.14830]	−0.3	0.14750 ± 0.00108 [0.1454, 0.1496]	−0.3	0.14675 ± 0.00049 [0.14580, 0.14770]	−0.1
Γ_Z [GeV]	2.4955 ± 0.0023	2.49455 ± 0.00065 [2.49329, 2.49581]	2.49437 ± 0.00068 [2.49301, 2.49569]	0.5	2.49530 ± 0.00204 [2.4912, 2.4993]	0.0	2.49397 ± 0.00068 [2.49262, 2.49531]	0.6
σ_h^0 [nb]								
R_ℓ^0								
$A_{\rm FB}^{0,\ell}$								
$\mathcal{A}_\ell$ (SLD								
R_b^0								
R_c^0								
$A_{\rm FB}^{0,b}$								
$A_{\rm FB}^{0,c}$								
$\mathcal{A}_b$								
$\mathcal{A}_c$								
$\mathcal{A}_s$								
${\rm BR}_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.0009	0.108388 ± 0.000022 [0.108345, 0.108431]	.108388 ± 0.000022 [0.108345, 0.108431]	0.2	.108291 ± 0.000109 [0.10808, 0.10851]	0.3	.108386 ± 0.000023 [0.108340, 0.108432]	0.2
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.0002	0.231471 ± 0.000055 [0.231362, 0.231580]	.231474 ± 0.000056 [0.231363, 0.231584]	−0.2	.231460 ± 0.000138 [0.23119, 0.23173]	−0.1	.231558 ± 0.000062 [0.231436, 0.231679]	−0.5
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000031 [0.172159, 0.172282]	.172220 ± 0.000032 [0.172159, 0.172282]	−0.7	.172424 ± 0.000180 [0.17209, 0.17279]	−0.7	.172212 ± 0.000032 [0.172149, 0.172275]	−0.7

"Posterior": The full fit results

"Indirect/Prediction":
Drop each observable at a time → fit
→ predict the removed observable

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exp. values of SM inputs

Tension between W mass average and SM prediction

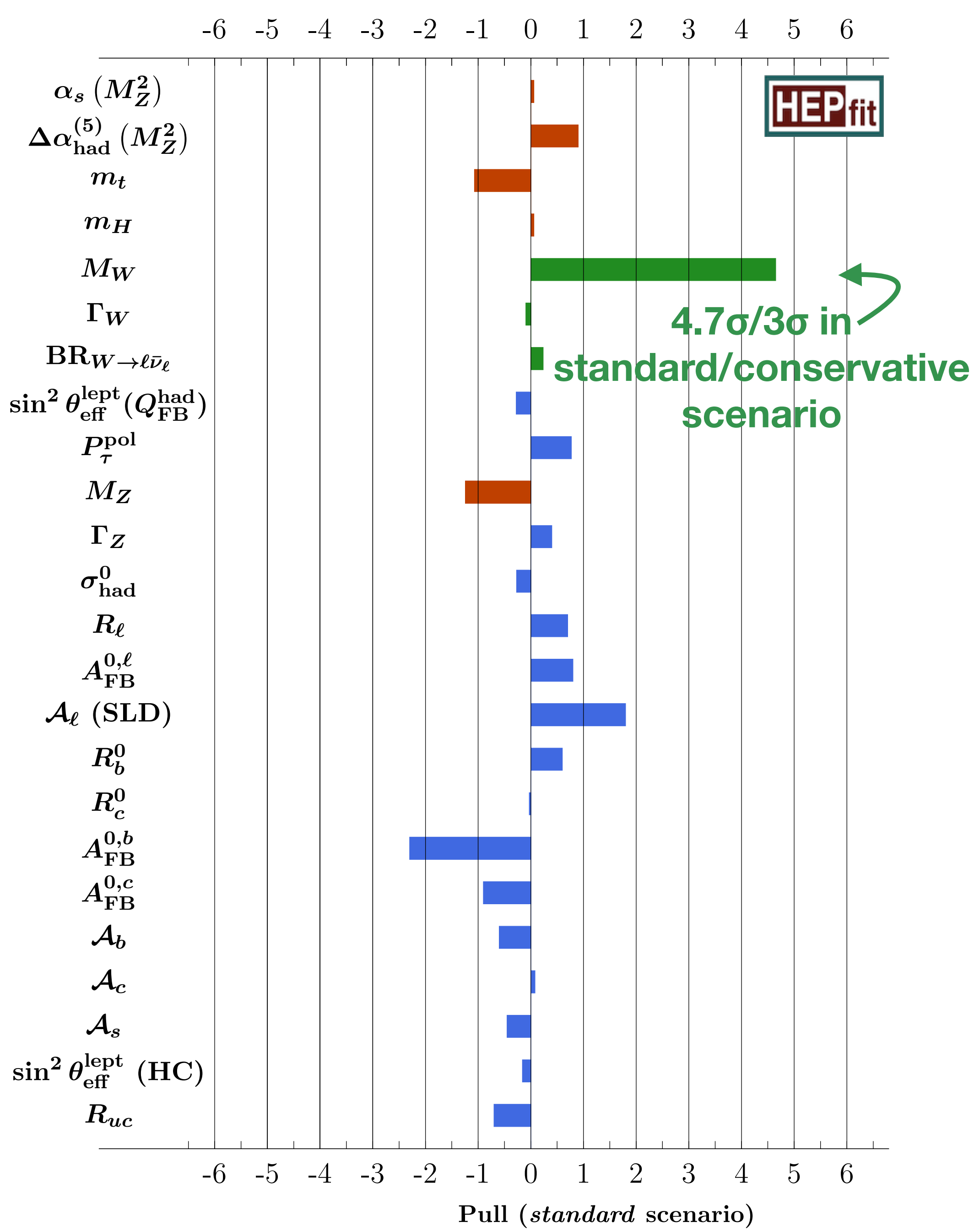
Model	Pred. M_W [GeV] *standard average*	Pull	Pred. M_W [GeV] *conservative average*	Pull
SM	80.3499 ± 0.0056	$6.5\,\sigma$	80.3505 ± 0.0077	$3.7\,\sigma$

Compared to the less than 2σ tension w/o the CDF measurement

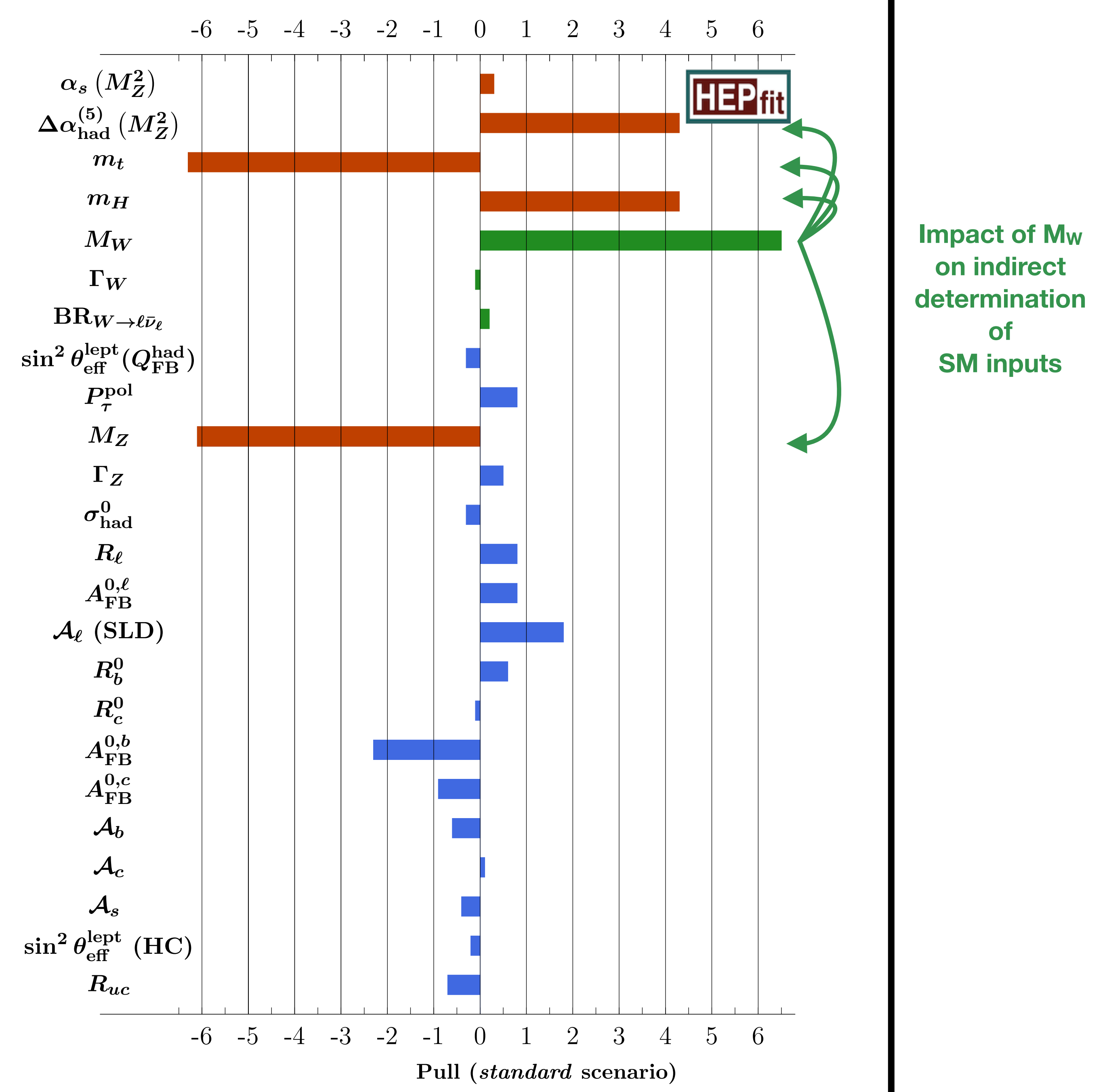
The SM EW fit

- SM EW fit results: Different fits to study the consistency between SM/EWPD

“Posterior”



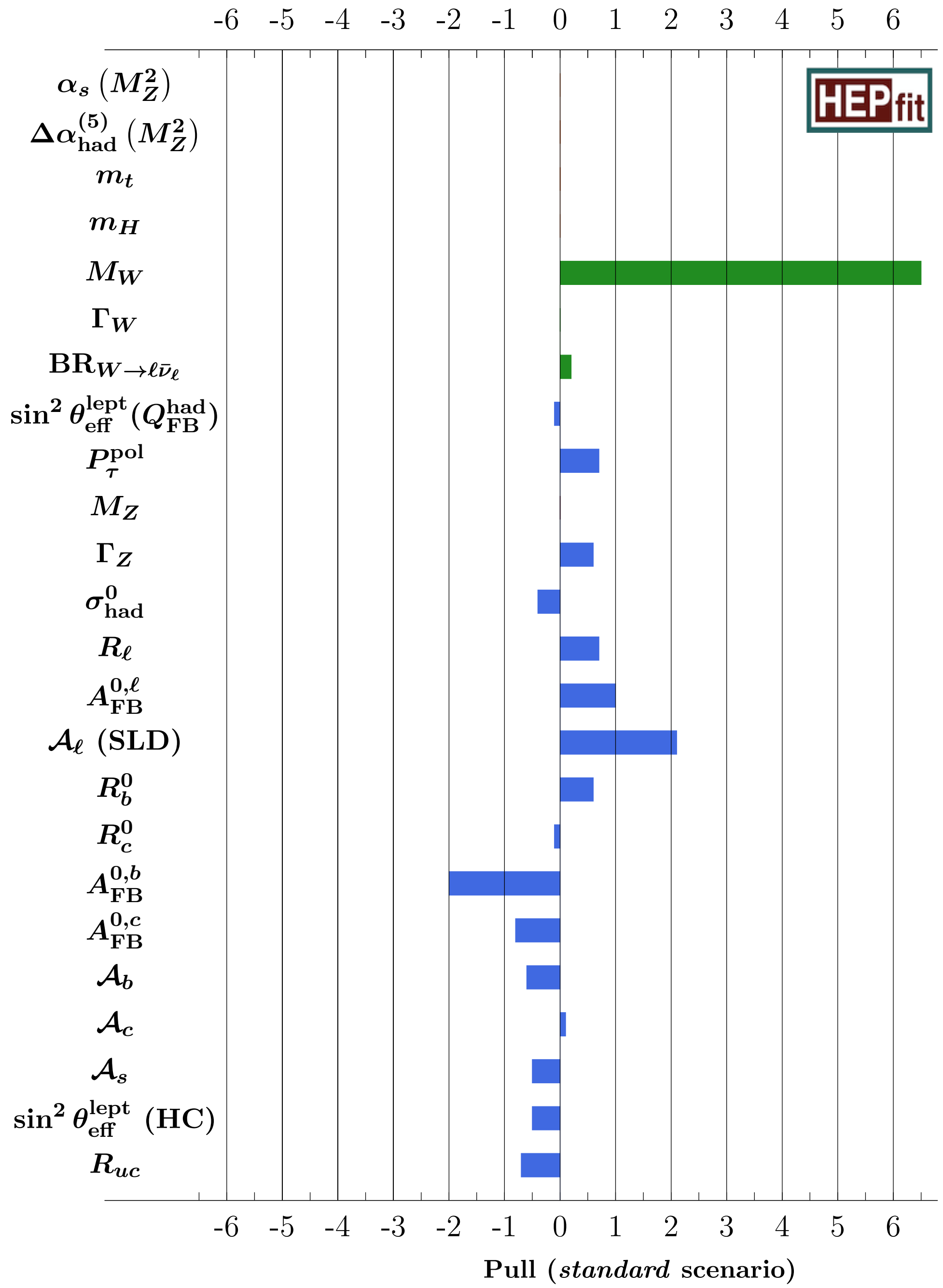
“Indirect/Prediction”



The SM EW fit

- SM EW fit results: Different fits to study the consistency between SM/EWPD

"Full Prediction"



Overall consistency of the SM fit

1) Run toy experiments centered around the Full prediction results

2) Compute the fraction of toys in which the largest pull is larger than the one observed in real data

→ p value

Standard average scenario

p-value: 2.5×10^{-5} (4.2 σ)

Conservative average

p-value: 0.1 (1.6 σ)

The SM EW fit

- Could this discrepancy be due to theory? SM theory prediction:

$$
\begin{aligned}
M_\mathrm{W} \; = \; & M_\mathrm{W}^0 - c_1\,\mathrm{dH} - c_2\,\mathrm{dH}^2 + c_3\,\mathrm{dH}^4 + c_4(\mathrm{dh}-1) - c_5\,\mathrm{d}\alpha + c_6\,\mathrm{dt} - c_7\,\mathrm{dt}^2 \\
& - c_8\,\mathrm{dH}\,\mathrm{dt} + c_9\,\mathrm{dh}\,\mathrm{dt} - c_{10}\,\mathrm{d}\alpha_\mathrm{s} + c_{11}\,\mathrm{dZ},
\end{aligned}
$$

$$
\mathrm{dH} = \ln\left(\frac{M_\mathrm{H}}{100\ \mathrm{GeV}}\right), \quad \mathrm{dh} = \left(\frac{M_\mathrm{H}}{100\ \mathrm{GeV}}\right)^2, \quad \mathrm{dt} = \left(\frac{m_\mathrm{t}}{174.3\ \mathrm{GeV}}\right)^2 - 1,
$$

$$
\mathrm{dZ} = \frac{M_\mathrm{Z}}{91.1875\ \mathrm{GeV}} - 1, \quad \mathrm{d}\alpha = \frac{\Delta\alpha}{0.05907} - 1, \quad \mathrm{d}\alpha_\mathrm{s} = \frac{\alpha_\mathrm{s}(M_\mathrm{Z})}{0.119} - 1,
$$

$$
\begin{aligned}
M_\mathrm{W}^0 &= 80.3779\ \mathrm{GeV}, & c_1 &= 0.05427\ \mathrm{GeV}, & c_2 &= 0.008931\ \mathrm{GeV}, \\
c_3 &= 0.0000882\ \mathrm{GeV}, & c_4 &= 0.000161\ \mathrm{GeV}, & c_5 &= 1.070\ \mathrm{GeV}, \\
c_6 &= 0.5237\ \mathrm{GeV}, & c_7 &= 0.0679\ \mathrm{GeV}, & c_8 &= 0.00179\ \mathrm{GeV}, \\
c_9 &= 0.0000664\ \mathrm{GeV}, & c_{10} &= 0.0795\ \mathrm{GeV}, & c_{11} &= 114.9\ \mathrm{GeV}.
\end{aligned}
$$

Accurate to better than 0.5 MeV for values of the SM inputs within 2σ from their central values

- Uncertainty in the calculation

	M_W
Exp. error	15 MeV
Theory error	4 MeV

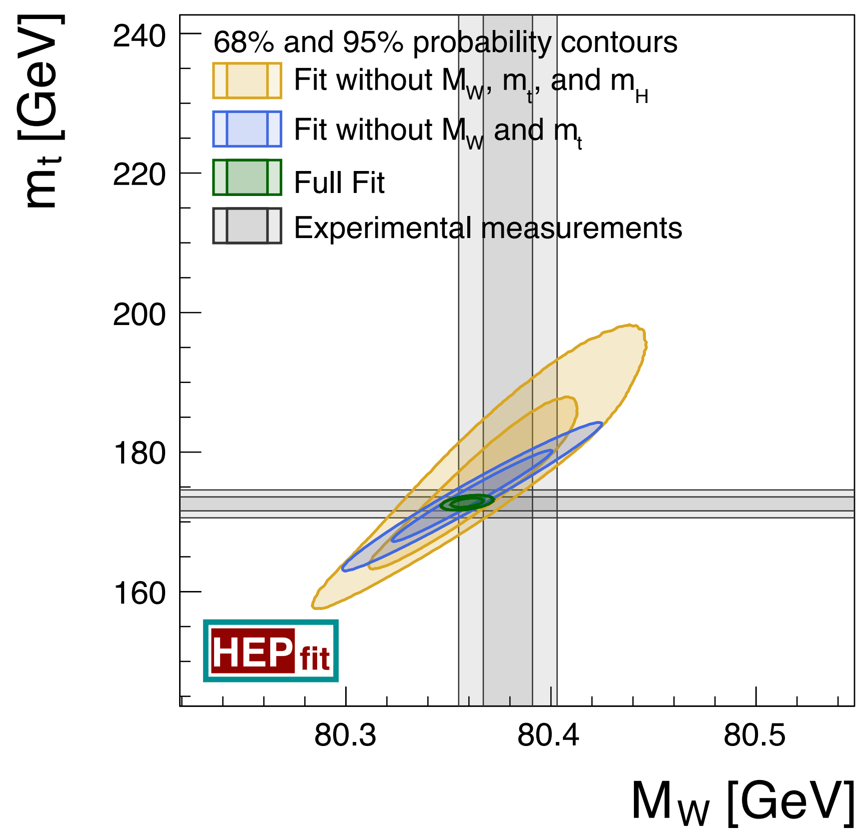
⊕ 4/7 MeV (parametric uncertainty)
→ ~ 6-8 MeV vs. ~60 MeV discrepancy

The SM EW fit

- SM EW fit results: Different fits to study the consistency between SM/EWPD

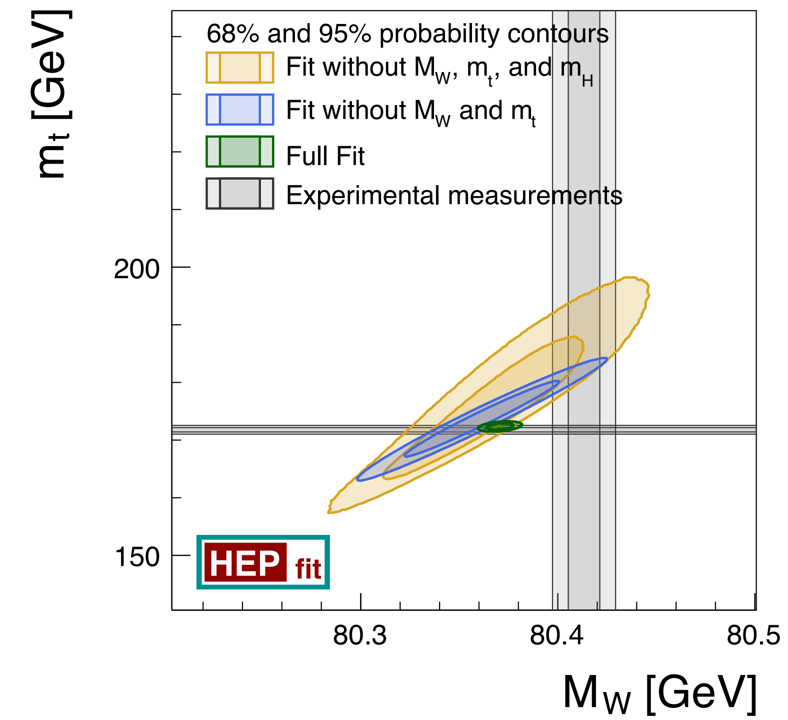
68% and 95% probability contours in the M_W-m_t place

(Before April 2022)

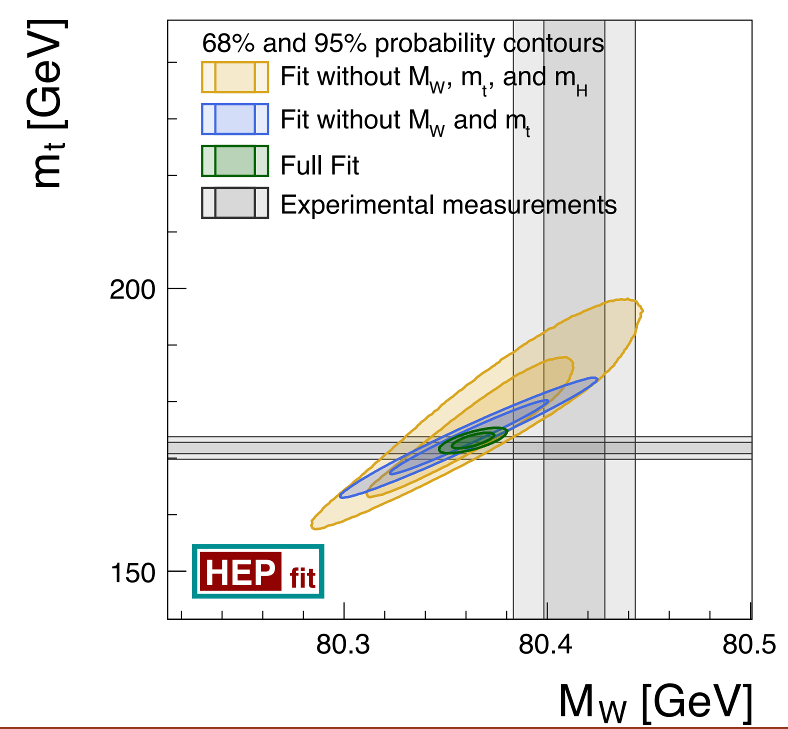


⟹

Standard average scenario



Conservative average scenario



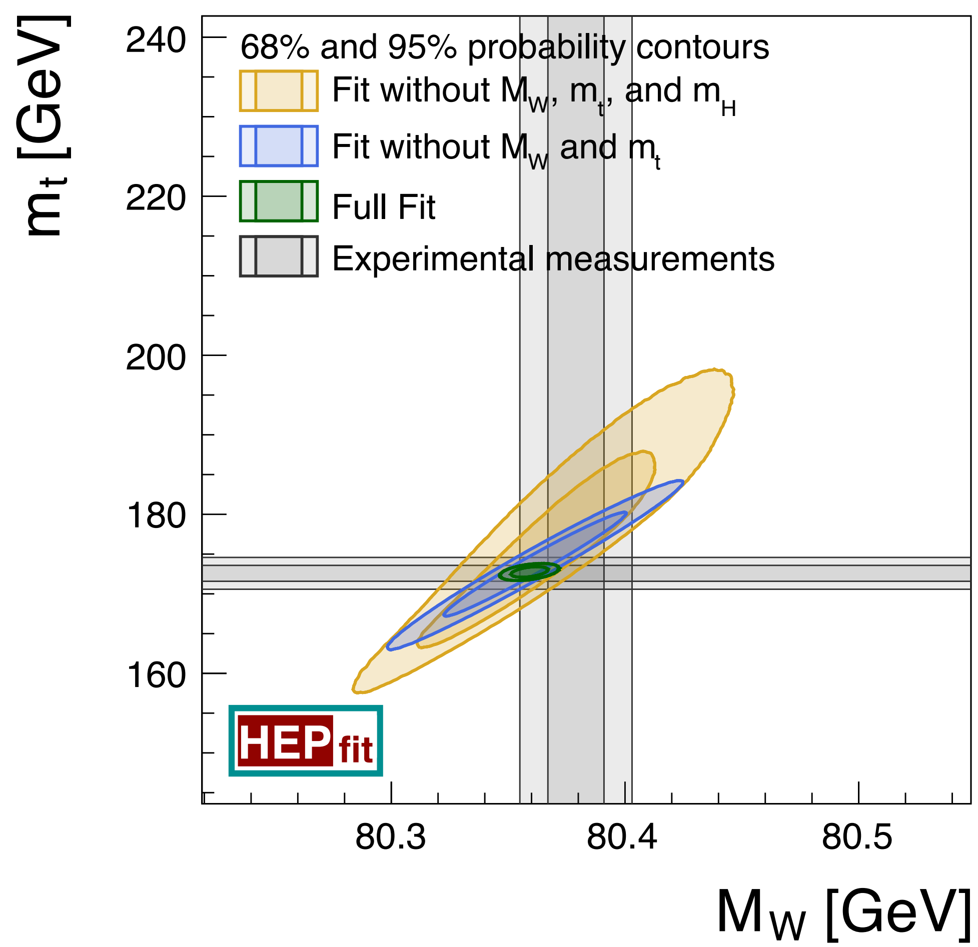
Not only the new W mass, but also the new Top mass value push the SM away from the data

The SM EW fit: Summary

Consistency of the SM with Electroweak Precision Tests

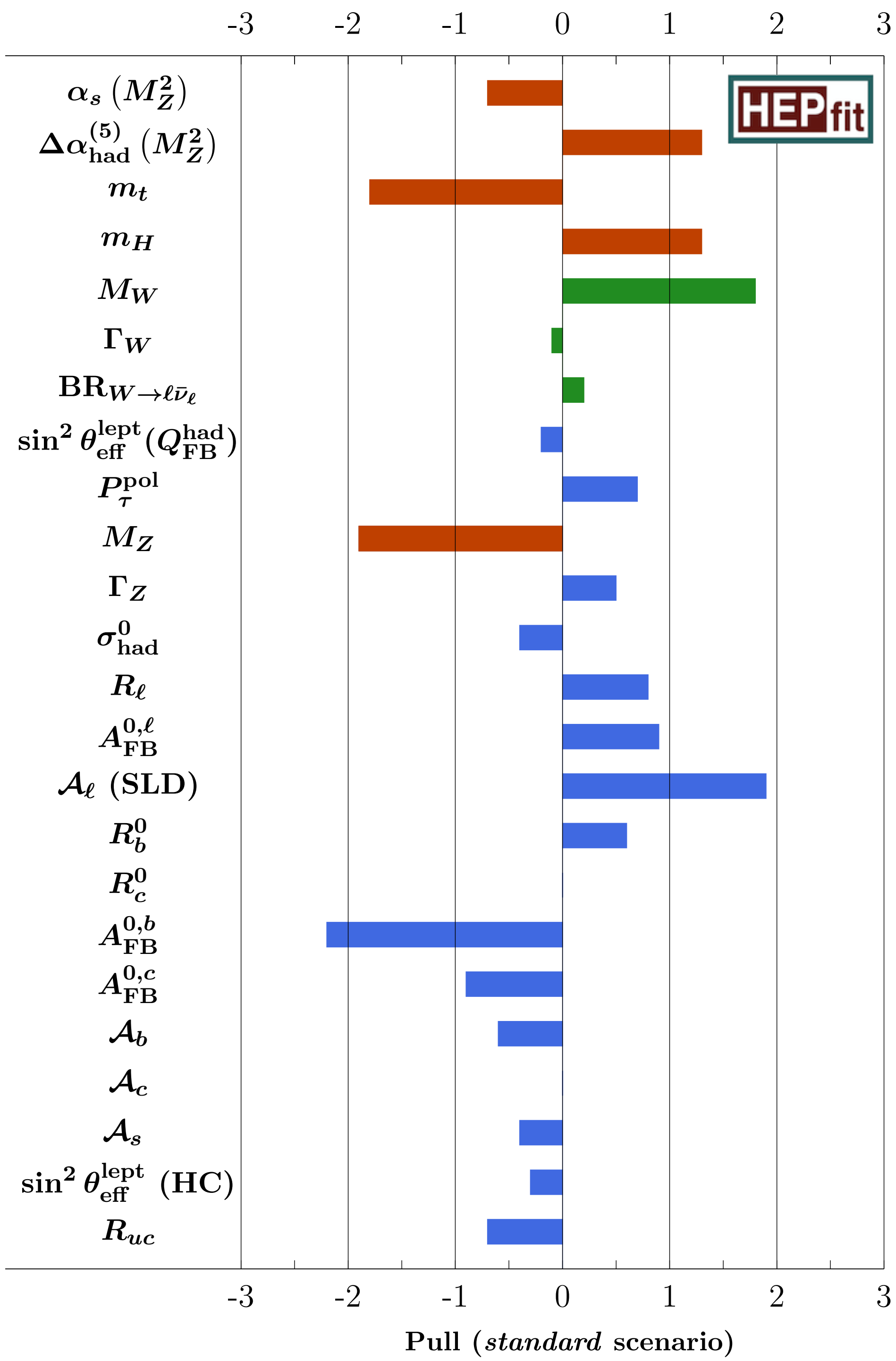
(Before April 2022)

J.B. et al., arXiv: 2112.07274 [hep-ph] (Accepted for pub. In PRD)



Individual pulls

(Remove observable from fit → Predict)



Overall consistency of the SM fit at 1σ

p-value: 0.45

The SM EW fit: Summary

Consistency with Electroweak Precision Tests?

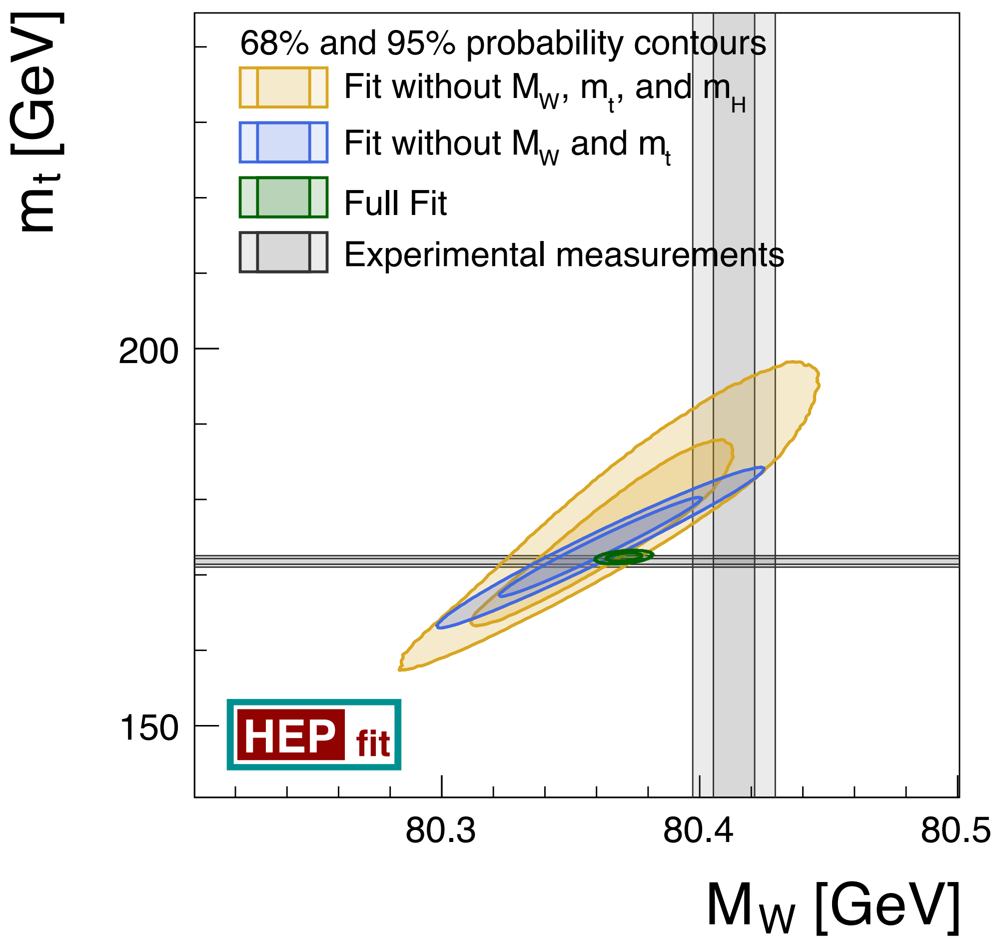
(June 2022)

April 8, 2022

CDF M_W measurement (8.8 fb^{-1})

M_W = 80.434±0.009 GeV

$M_{W,\,SM}$ = 80.350±0.006 GeV

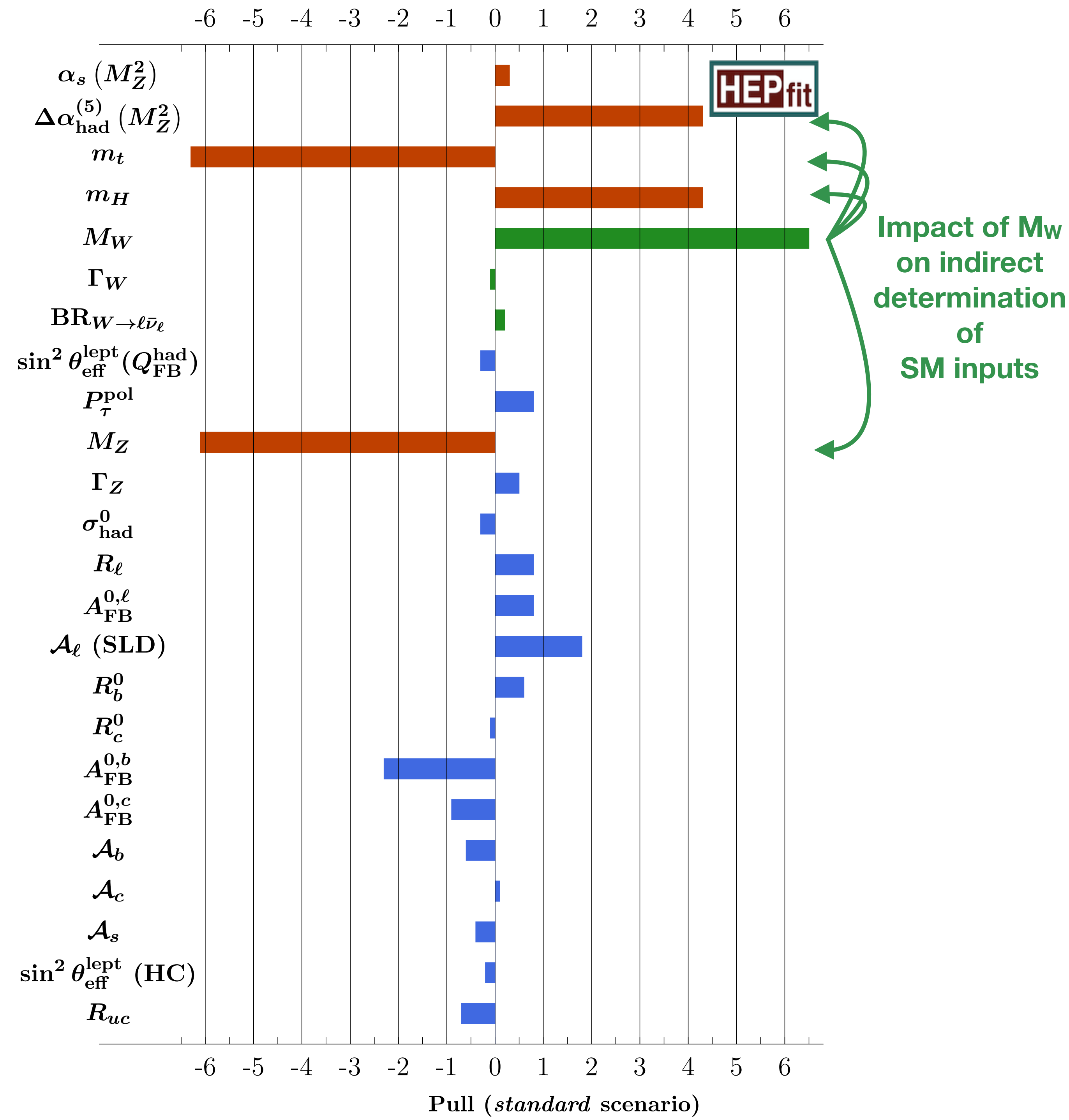


Overall tension in the SM fit: 4.2 σ

p-value: 2.5×10^{-5}

Individual pulls

(Remove observable from fit → Predict)



J.B., M. Pierini, L. Reina, L. Silvestrini, arXiv: 2204.04204 [hep-ph]

The SM EW fit: New Physics?

Consistency with Electroweak Precision Tests?

April 8, 2022
CDF M_W measurement (8.8 fb^{-1})
M_W = 80.434±0.009 GeV
$M_{W,SM}$ = 80.350±0.006 GeV

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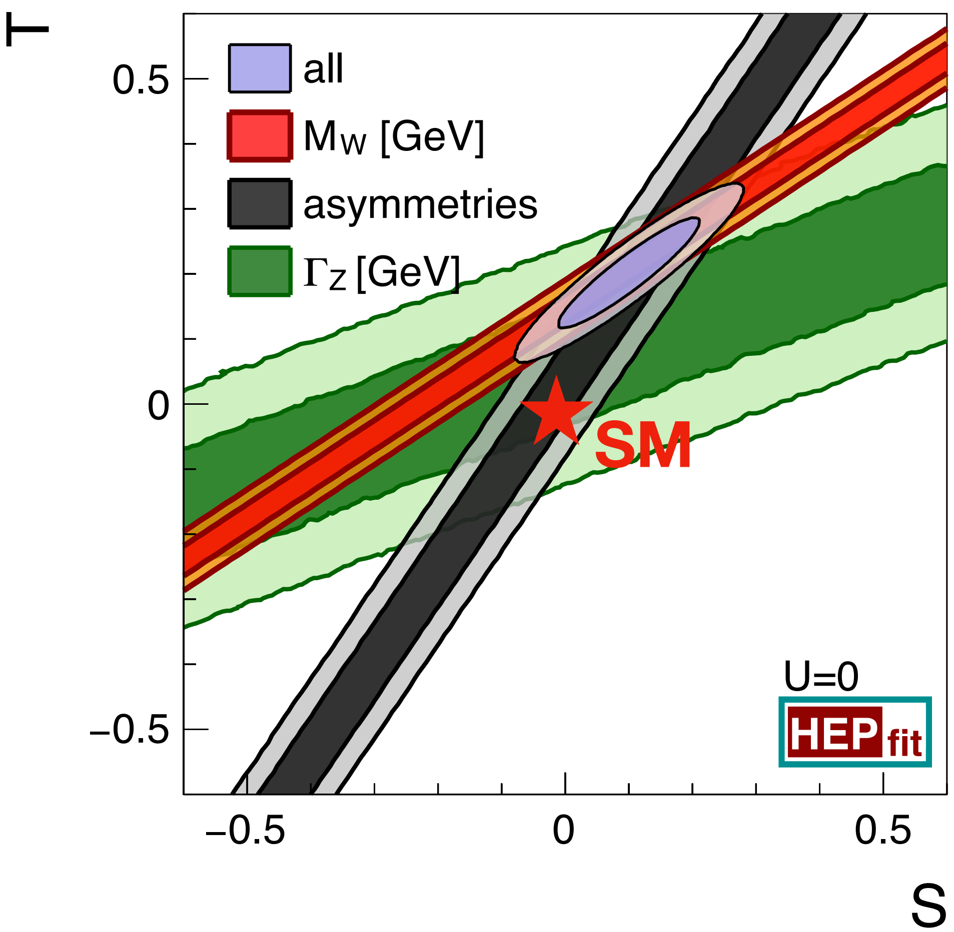

Overall tension in the SM fit: 4.2 σ
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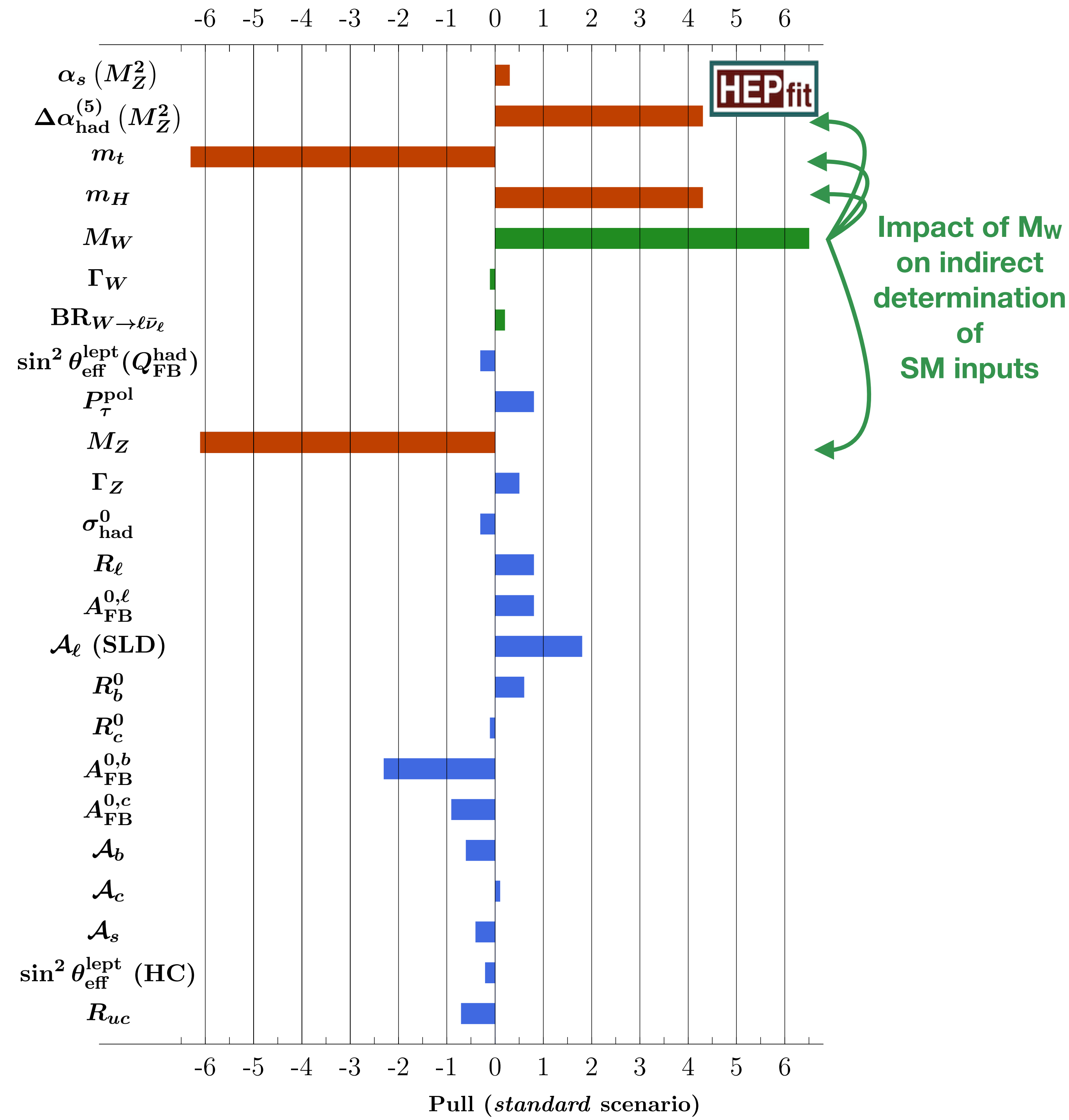
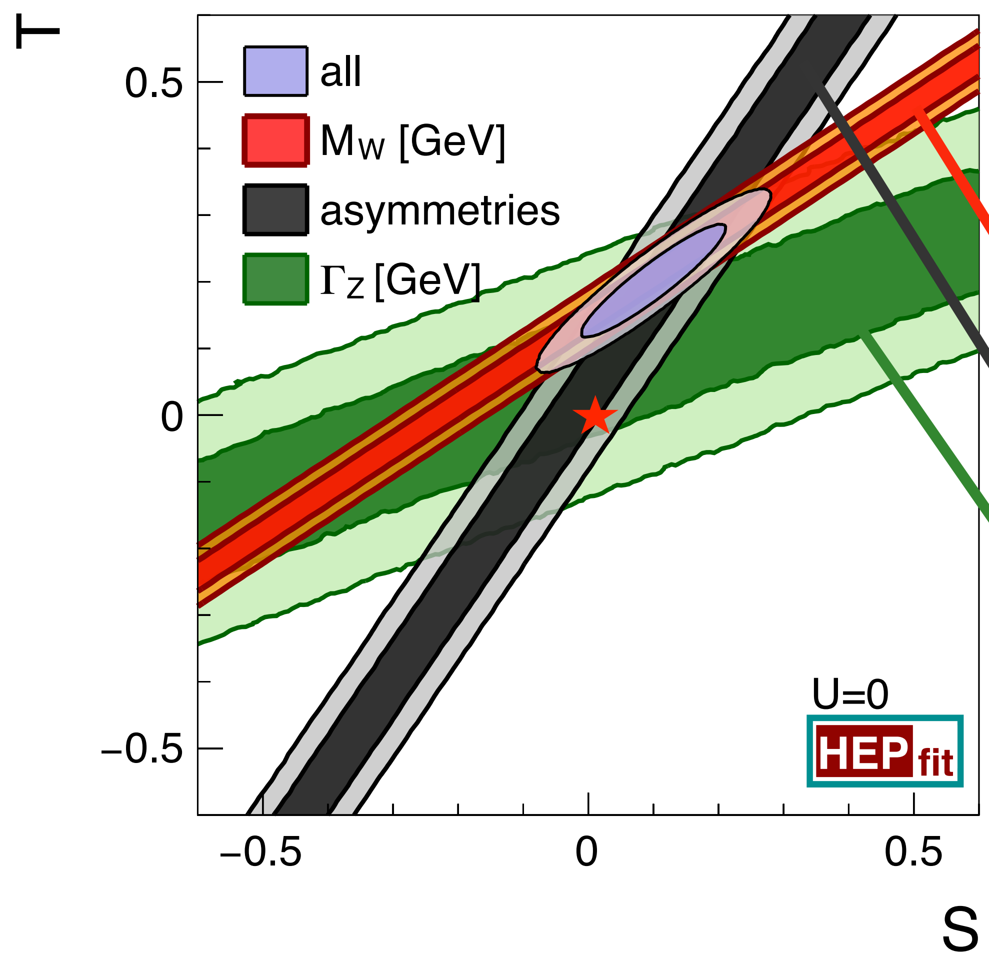
Individual pulls
(Remove observable from fit → Predict)



New Physics
Interpretations

Is this new physics? Oblique parameters

- The obvious place to look at… new physics contributing to the gauge boson self-energies → Oblique Parameters (S, T, W, Y, U,…)
  - ✓ EWPO depend on 3 combinations, traditionally chosen as S, T, U…
  - ✓ …though U is expected to be dim. 8 while S,T arise to dim 6



$$\alpha S = 4e^2\left[\Pi_{33}^{\mathrm{NP}\,\prime}(0) - \Pi_{3Q}^{\mathrm{NP}\,\prime}(0)\right]$$

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

$$\alpha U = 4e^2\left[\Pi_{11}^{\mathrm{NP}\,\prime}(0) - \Pi_{33}^{\mathrm{NP}\,\prime}(0)\right]$$

$$A = S - 2c_W^2\, T - \frac{(c_W^2 - s_W^2)}{2s_W^2} U$$

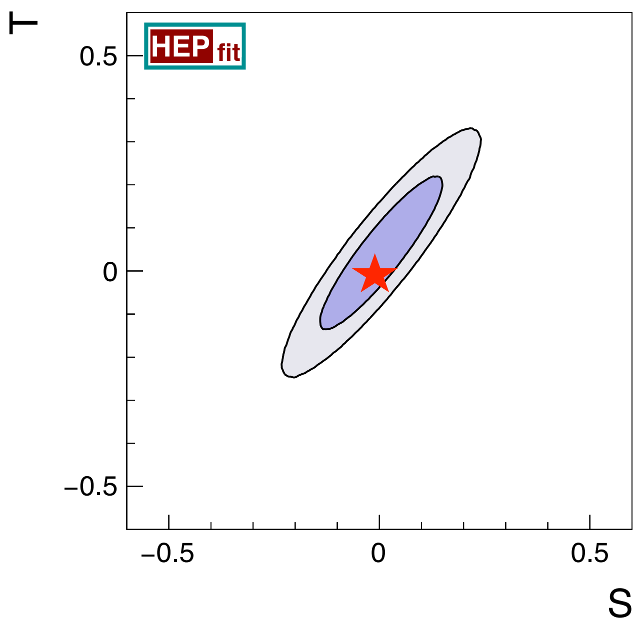
$$B = S - 4c_W^2 s_W^2\, T$$

$$C = -10(3 - 8s_W^2)\, S + (63 - 126 s_W^2 - 40 s_W^4)\, T$$

EW symmetry linearly realized
$\Rightarrow$ U (dim 8) $\ll$ S, T (dim 6)

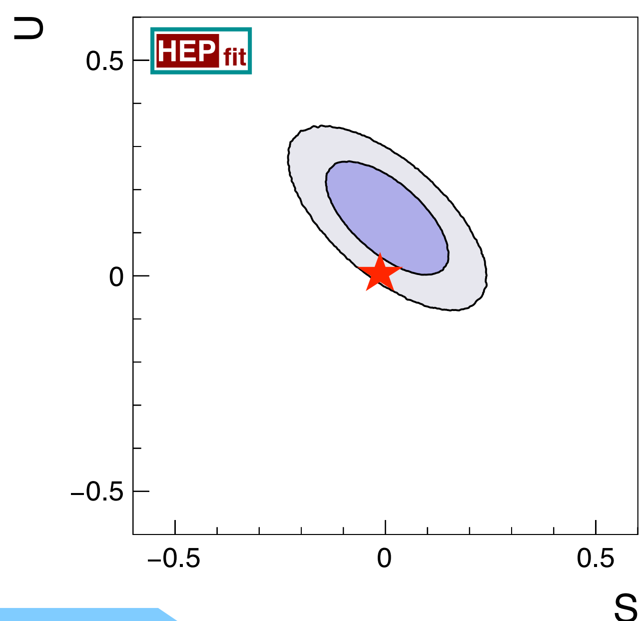
Is this new physics? Oblique parameters

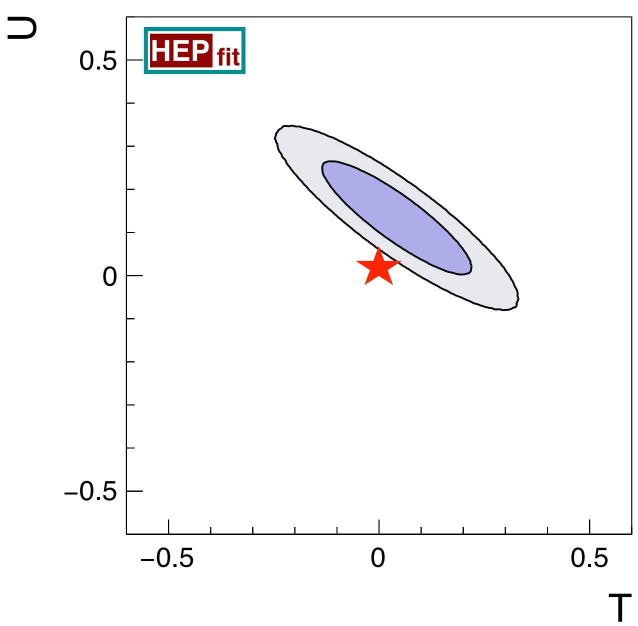
- The obvious place to look at… new physics contributing to the gauge boson self-energies → Oblique Parameters (S, T, W, Y, U,…)
  - ✓ EWPO depend on 3 combinations, traditionally chosen as S, T, U…
  - ✓ …though U is expected to be dim. 8 while S, T arise to dim 6



	Result	Correlation		Result	Correlation		
	$(\mathrm{IC}_{\mathrm{ST}}/\mathrm{IC}_{\mathrm{SM}} = 25.0/80.2)$			$(\mathrm{IC}_{\mathrm{STU}}/\mathrm{IC}_{\mathrm{SM}} = 25.3/80.2)$			
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

$$\left(\mathrm{IC} \equiv -2\overline{\log \mathcal{L}} + 4\sigma^2_{\log \mathcal{L}}\right)$$



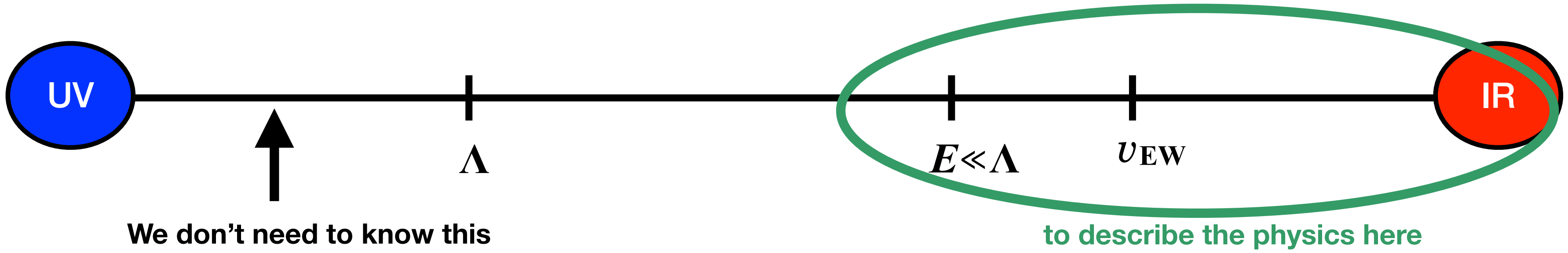


W mass prediction

Model	Pred. M_W [GeV] *standard average*	Pull
ST	80.366 ± 0.029	$1.6\,\sigma$
STU	80.32 ± 0.54	$0.2\,\sigma$

Is this new physics? Dimension-6 SMEFT

- Effective Field Theories:



- The **SMEFT:** SM particles and symmetries at low energies, with <u>*the Higgs scalar in an $SU(2)_L$ doublet*</u> + mass gap with new physics (entering at scale Λ)

$$\mathcal{L}_{\rm UV}(?) \underset{E \ll \Lambda}{\longrightarrow} \qquad \mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

- Leading Order (LO) Beyond the SM effects (assuming B & L)

  ⇒ Dim-6 SMEFT: 2499 operators

- In this talk, we will follow the conventions of the *Warsaw basis:*

  ⇒ Only 8 combinations of 10 operators enter at tree-level in the EW fit (under the assumption of flavour universal new physics)

Is this new physics? Dimension-6 SMEFT

- SMEFT operators and the EW fit (in the $\{\alpha, G_F, M_Z\}$ EW input scheme):
  - ✓ Bosonic operators: contribute to oblique corrections

$$\mathcal{O}_{\phi D} = \left|\phi^\dagger i D_\mu \phi\right|^2 \qquad \mathcal{O}_{\phi WB} = (\phi^\dagger \sigma_a \phi) W^a_{\mu\nu} B^{\mu\nu}$$

$$\Delta T = -\frac{1}{2\alpha} C_{\phi D} \frac{v^2}{\Lambda^2} \qquad \Delta S = \frac{4 s_w c_w}{\alpha} C_{\phi WB} \frac{v^2}{\Lambda^2}$$

  - ✓ Non-oblique corrections to EW Vff couplings (7 operators)

$$\mathcal{O}^{(1)}_{\phi f} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\overline{f} \gamma^\mu f) \qquad \mathcal{O}^{(3)}_{\phi f} = (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\overline{f} \gamma^\mu \sigma_a f)$$

$$\delta g_L^{u(\nu),d(e)} = -\frac{1}{2}\left(C^{(1)}_{\phi q(l)} \mp C^{(3)}_{\phi q(l)}\right) \frac{v^2}{\Lambda^2} \qquad \delta g_R^{u,d,e} = -\frac{1}{2} C^{(1)}_{\phi u,d,e} \frac{v^2}{\Lambda^2}$$

$$\delta V_L^{q,l} = C^{(3)}_{\phi q,l} \frac{v^2}{\Lambda^2}$$

  - ✓ Also sensitive to. $\mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$ through indirect effects: the extraction of G_F from μ decay is corrected by:

$$\delta_{G_F} = \left((C^{(3)}_{\phi \ell})_{11} + (C^{(3)}_{\phi \ell})_{22} - \frac{1}{2}((C_{\ell\ell})_{1221} + (C_{\ell\ell})_{2112})\right) \frac{v^2}{\Lambda^2}$$

Is this new physics? Dimension-6 SMEFT

- SMEFT operators and the EW fit (in the $\{\alpha, G_F, M_Z\}$ EW input scheme):
  - ✓ Fit combinations:

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

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

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

  - ✓ Z-pole/EW couplings (7) depend on:

$$\hat{C}_{\varphi f}^{(3)} - \frac{c_w^2}{2 s_w^2} \hat{C}_{ll} \qquad \qquad \hat{C}_{\varphi f}^{(1)} + Y_f \hat{C}_{ll}$$

  - ✓ W mass/width depend on:

$$\hat{C}_{\varphi l}^{(3)} - \hat{C}_{ll}/2$$

and breaks the degeneracy (the other 2 degeneracies in this basis can be solved with Higgs or diBoson data)

Is this new physics? Dimension-6 SMEFT

- SMEFT operators and the EW fit (in the $\{\alpha, G_F, M_Z\}$ EW input scheme):

✓ Fit results under U(3)^5 flavor assumptions (units of TeV^{-2}):

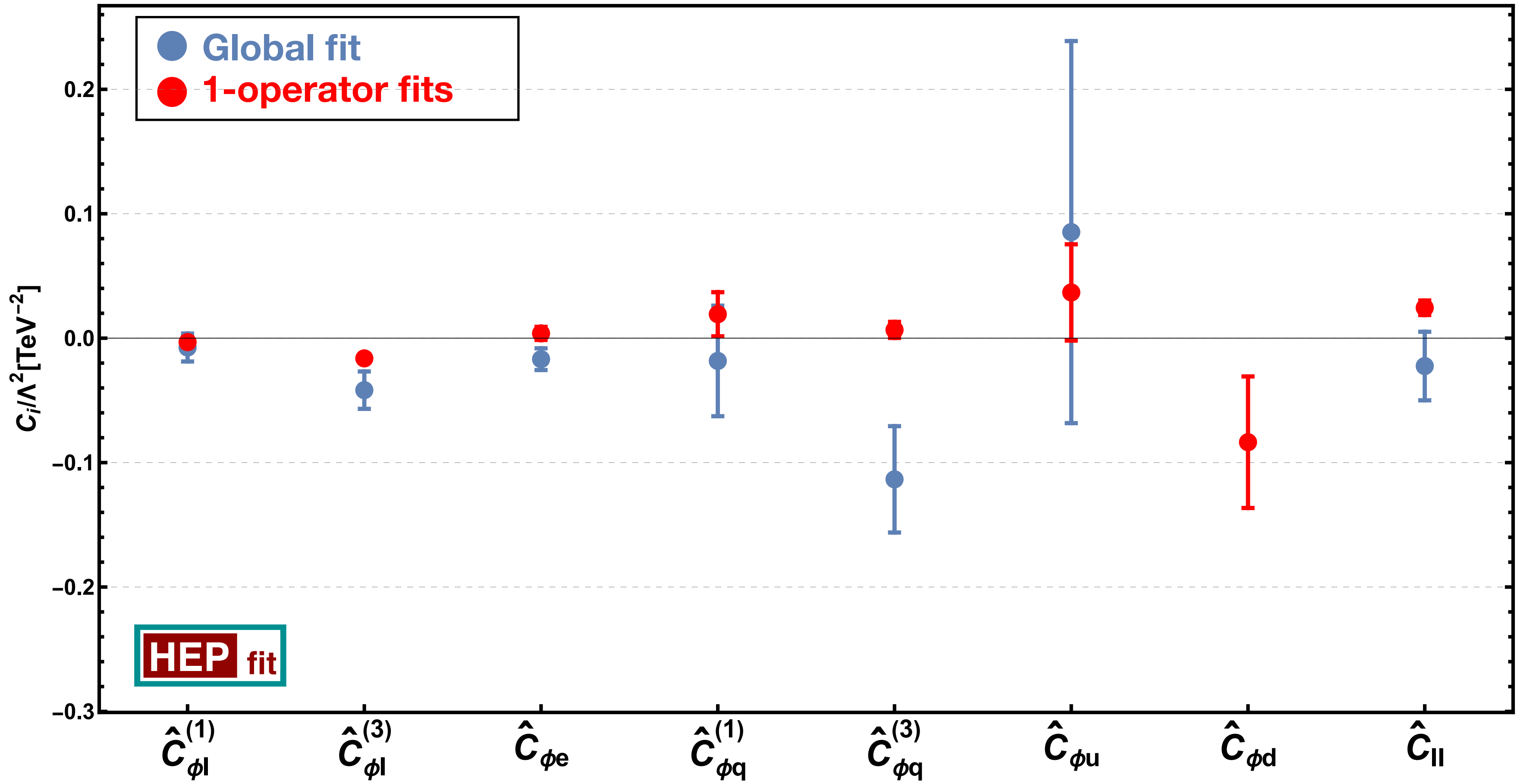
	Result	Correlation Matrix							
		$(\mathrm{IC}_{\mathrm{SMEFT}}/\mathrm{IC}_{\mathrm{SM}} = 31.8/79.7)$			$\left(\mathrm{IC} \equiv -2\overline{\log \mathcal{L}} + 4\sigma^2_{\log \mathcal{L}}\right)$				
$\hat{C}^{(1)}_{\varphi l}$	-0.007 ± 0.011	1.00							
$\hat{C}^{(3)}_{\varphi l}$	-0.042 ± 0.015	-0.68	1.00						
$\hat{C}_{\varphi e}$	-0.017 ± 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				
$\hat{C}^{(3)}_{\varphi q}$	-0.113 ± 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

✓ SM tension with the W mass more apparent when looking at individual fits to the operators modifying that observable

$$\frac{\Delta M_W}{M_W} = -\frac{2s^2}{c^2-s^2}\left(C^{(3)}_{\phi l} + \frac{c^2}{4s^2}C_{\phi D} + \frac{c}{s}C_{\phi WB} - \frac{1}{2}C_{ll}\right)\frac{v^2}{\Lambda^2}$$

Is this new physics? Dimension-6 SMEFT

- SMEFT operators and the EW fit (in the $\{\alpha, G_F, M_Z\}$ EW input scheme):
  - ✓ SM tension with the W mass more apparent when looking at individual fits to the operators modifying that observable



Individual operator fits

Operator	$\mathcal{O}_{\phi l}^{(1)}$	$\mathcal{O}_{\phi l}^{(3)}$	$\mathcal{O}_{\phi e}$	$\mathcal{O}_{\phi q}^{(1)}$	$\mathcal{O}_{\phi q}^{(3)}$
$\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	-0.003 ± 0.004	-0.016 ± 0.003 (-5.0σ)	0.004 ± 0.005	0.019 ± 0.018	0.007 ± 0.006

Operator	$\mathcal{O}_{\phi u}$	$\mathcal{O}_{\phi d}$	$\mathcal{O}_{\phi WB}$	$\mathcal{O}_{\phi D}$	$\mathcal{O}_{ll}$
$\frac{C_i}{\Lambda^2}$ [TeV^{-2}]	0.037 ± 0.039	-0.084 ± 0.053	-0.012 ± 0.002 (-5.6σ)	-0.034 ± 0.005 (-6.3σ)	0.024 ± 0.0058 (-4.2σ)

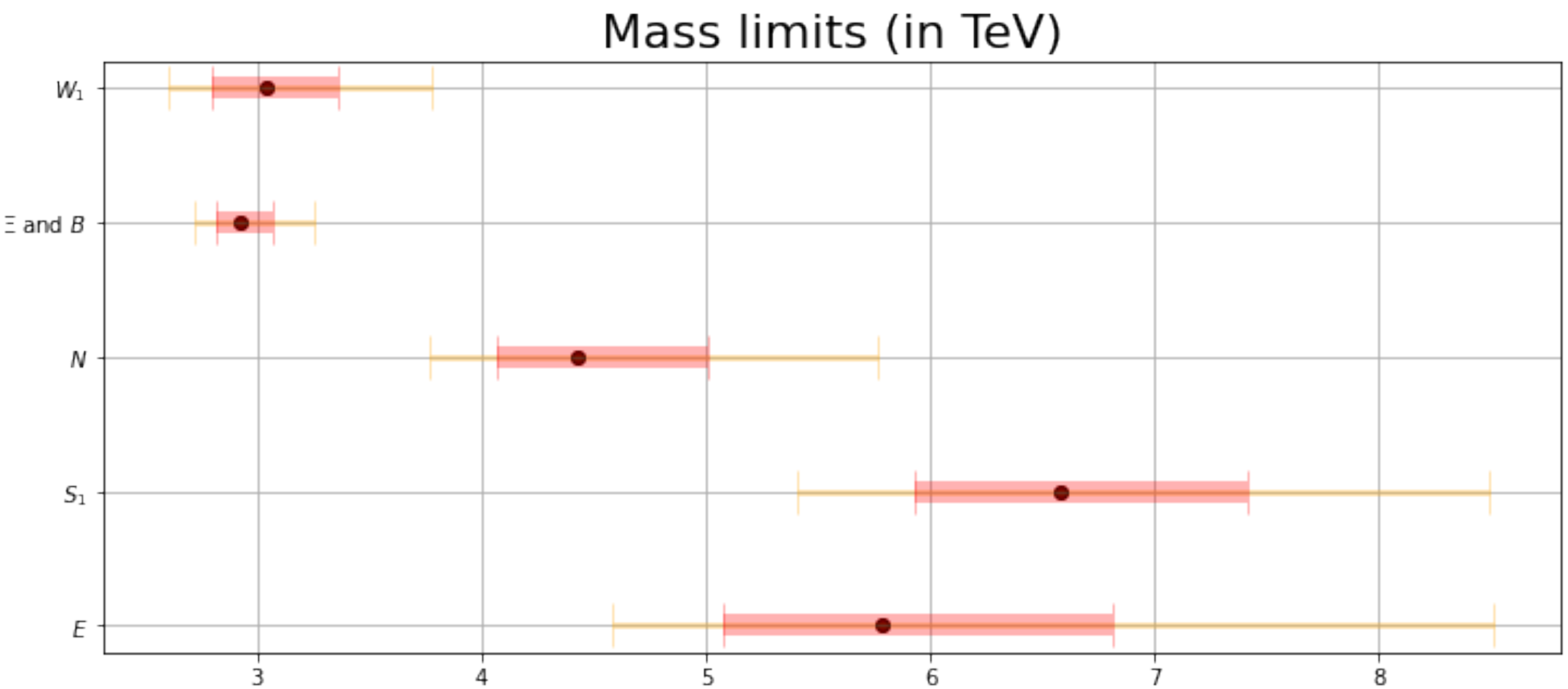
Is this new physics? Dimension-6 SMEFT

- Possible new physics explanations explained in several papers, via matching of the SMEFT results to UV completions

J. B., J.C. Criado, M. Pérez- Victoria, J. Santiago, JHEP 1803 (2018) 109

E. Bagnaschi, J. Ellis, M. Madigan, K. Mimasu. V. Sanz, T. You, arXiv: 2204.05260 [hep-ph]

Selected scenarios explaining W mass anomaly at tree level



Model	Pull	Best-fit mass (TeV)	1-σ mass range (TeV)	2-σ mass range (TeV)	1-σ coupling^2 range
W_1	6.4	3.0	[2.8, 3.6]	[2.6, 3.8]	[0.09, 0.13]
B	6.4	2.9	[2.8, 3.1]	[2.7, 3.2]	[0.011, 0.017]
Ξ	6.4	2.9	[2.8, 3.1]	[2.7, 3.2]	[0.011, 0.017]
N	5.1	4.4	[4.1, 5.0]	[3.8, 5.8]	[0.040, 0.060]
S_1	4.8	6.6	[5.9, 7.4]	[5.4, 8.5]	[0.018, 0.028]
E	3.5	5.8	[5.1, 6.8]	[4.6, 8.5]	[0.022, 0.039]

Is this new physics? Dimension-6 SMEFT

- SMEFT operators and the EW fit (in the $\{\alpha, G_F, M_Z\}$ EW input scheme):
  - ✓ SM tension with the W mass more apparent when looking at individual fits to the operators modifying that observable

Interplay with other measurements

- The required NP SMEFT contributions is not very large (from the point of view of the NP interaction scale) but still could spoil the agreement with the SM of other precision measurements outside the EW fit, e.g. CKM unitarity (O(0.07%) precision)

V. Cirigliano et al., Phys.Rev.D 106 (2022) 7, 075001

$$\Delta_{\rm CKM} = \frac{v^2}{\Lambda^2}\left(2\left(\hat{C}^{(3)}_{\varphi q} - \hat{C}^{(3)}_{\varphi l} + \hat{C}_{ll}\right) - 2C^{(3)}_{lq}\right)$$

$$\Delta^{\rm EWfit}_{\rm CKM}\Big|_{C^{(3)}_{lq}=0} = -0.012 \pm 0.005 \text{ vs. } -0.0015 \pm 0.0007 \text{ (exp)}$$

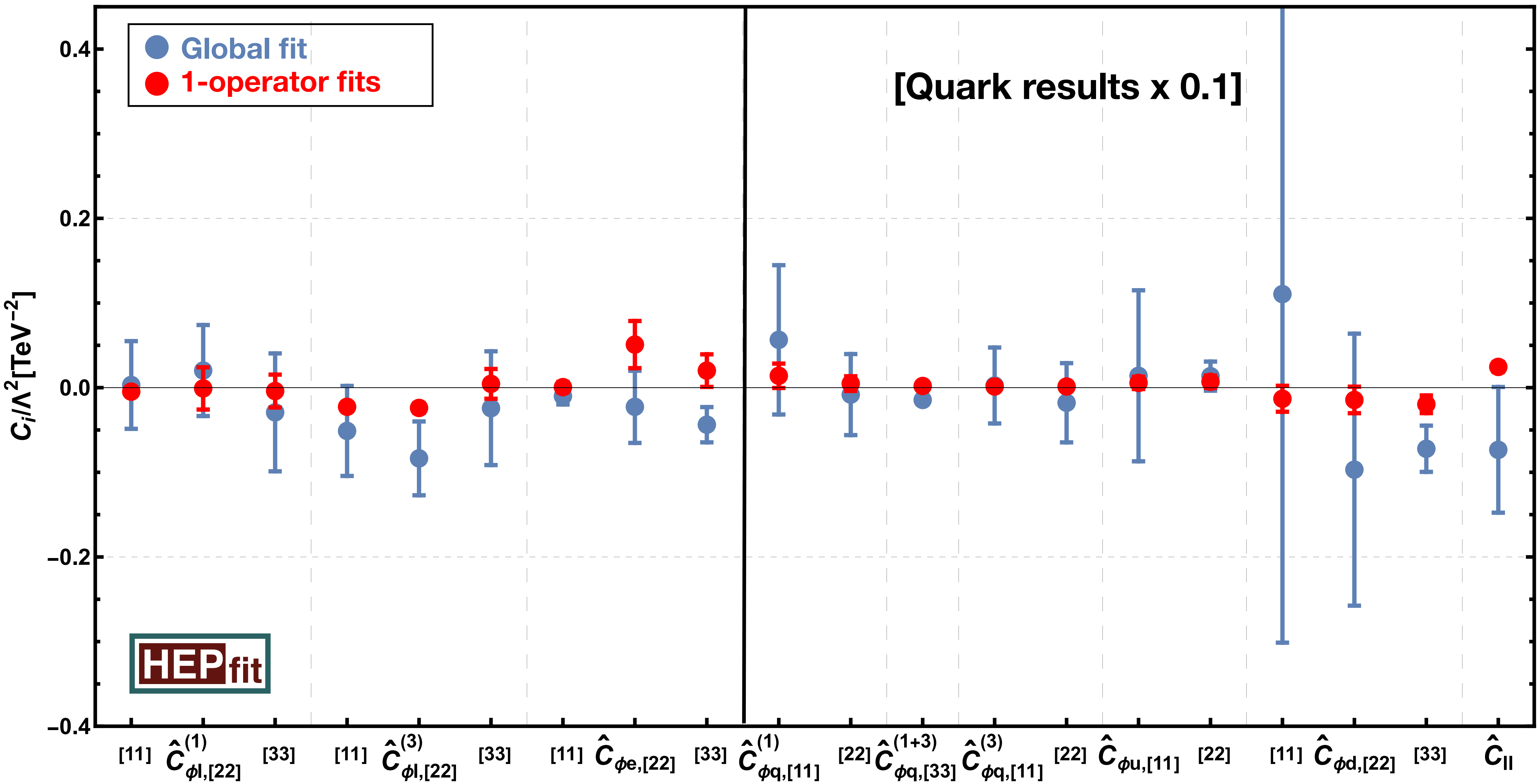
	Result	Result with CKM
$\hat{C}^{(1)}_{\varphi l}$	-0.007 ± 0.011	-0.013 ± 0.009
$\hat{C}^{(3)}_{\varphi l}$	-0.042 ± 0.015	-0.034 ± 0.014
$\hat{C}_{\varphi e}$	-0.017 ± 0.009	-0.021 ± 0.009
$\hat{C}^{(1)}_{\varphi q}$	-0.0181 ± 0.044	-0.048 ± 0.04
$\hat{C}^{(3)}_{\varphi q}$	-0.114 ± 0.043	-0.041 ± 0.015
$\hat{C}_{\varphi u}$	0.086 ± 0.154	-0.12 ± 0.11
$\hat{C}_{\varphi d}$	-0.626 ± 0.248	-0.38 ± 0.22
C_{Δ}	-0.19 ± 0.09	-0.027 ± 0.011

Both sets of constraints can however be decoupled by removing the $U(3)^5$ assumption

-5.6σ -6.3σ -4.2σ

Is this new physics? Dimension-6 SMEFT

- SMEFT operators and the EW fit (in the $\{\alpha, G_F, M_Z\}$ EW input scheme):
  - ✓ Fit results under general flavor assumptions (units of TeV^{-2}):

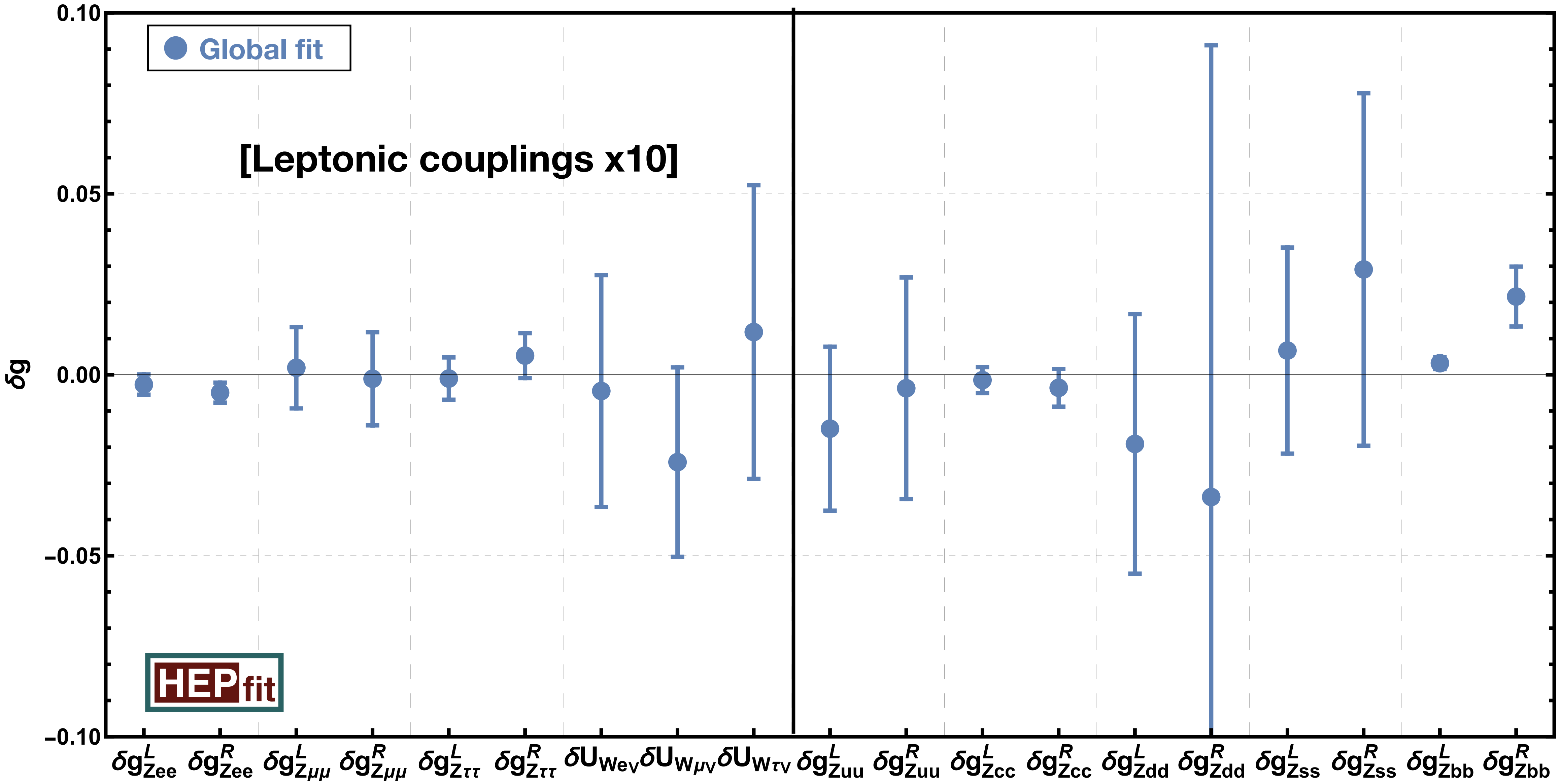


  - ✓ All Wilson coefficients can still be constrained with available EW data
  - ✓ Δ_{CKM} corrected by other weakly constrained operators, e.g. $O_{\varphi ud}$ (RH CC)

Still, the message is the importance of being global in SMEFT analyses, and include all observables of comparable precision to keep track of correlated modifications

Is this new physics? Dimension-6 SMEFT

- SMEFT operators and the EW fit (in the $\{\alpha, G_F, M_Z\}$ EW input scheme):
  - ✓ Fit results under general flavor assumptions. Allowed coupling deviations:



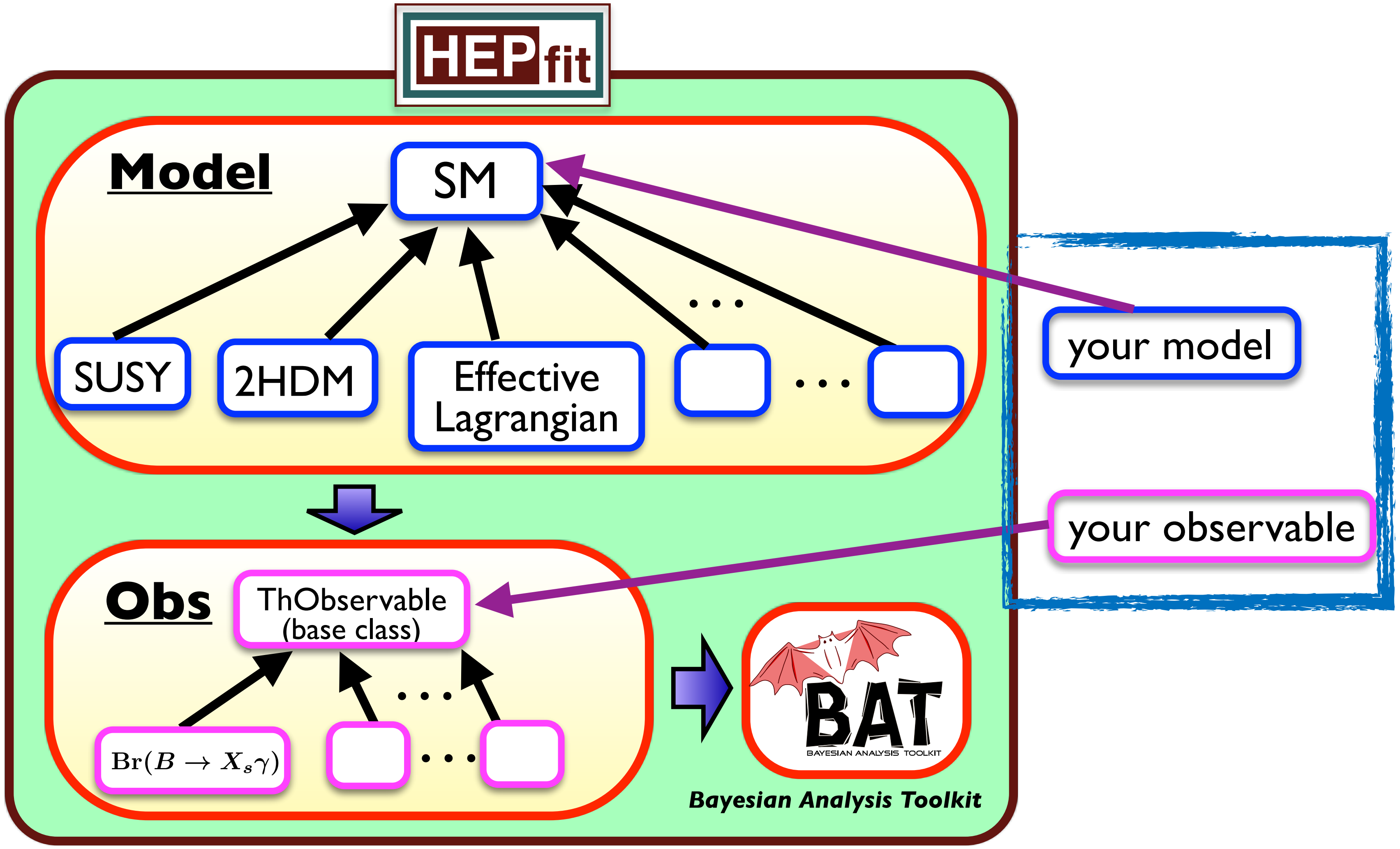
  - ✓ All couplings can still be constrained with available EW data

LH leptons: 0.1-0.3%	**LH light quarks: 1-8%**	**LH HF quarks: 0.4-1%**
RH leptons: 0.1-0.6%	**RH light quarks: O(1)**	**RH HF quarks: 4-12%**

The HEPfit code

If you are interested in the EW fit for other models
Or to combine with different observables

- HEPfit functionality is not restricted to the model/observables already implemented in the code



- Users can **add new models and/or observables as external modules**
- You just need to know a little C++. See backup slides for details

Summary and Conclusions

Summary and Conclusions

- The EW precision data fit has been traditionally a powerful tool to test the consistency of the SM and constrain new physics
- While M_W has been in some tension for a while, the new CDF measurement, with the same central value but a much smaller error increases this tension to
  - ✓ $6.5\sigma/3.7\sigma$ if taking all uncertainties at face value/accounting for the possibility of underestimated systematics → largest tension in the EW fit
- The new CMS m_t measurement also pushes the m_t average towards smaller values, slightly increasing the tension in the EW fit
  - ✓ Impossible to reconcile the SM with M_W within reasonable values of m_t
- Is this new physics?
  - ✓ Easily explained in terms of new physics contributing to the T parameter or other SMEFT operators. Easy to explain within simple specific models.
  - ✓ Careful: In presence of a (isolated) tension, global SMEFT analyses combining EW, Higgs, Top, Flavor are even more relevant from model-building point of view
    - E.g. Some directions of SMEFT EW fit not consistent with CKM unitarity

Backup slides
Adding your own models/observables

Adding your model and Observables to HEPfit

- Check template in examples/myModel
- In myModel.h:

```
#include <HEPfit.h>

/**
 * @class myModel
 * @brief My own Model.
 */
class myModel: public StandardModel {
public:

    static const int NmyModelvars = 4; /* Define number of mandatory parameters in the model. */
    static const std::string myModelvars[NmyModelvars]; /* Vector of model variable names. */
```

Extend the SM (typically) or, if more convenient, the NPBase model, or the NPd6SMEFT model, …

```
double c1, c2, c3, c4; /* Model Parameters */

double getc1() const { return c1; }
double getc2() const { return c2; }
double getc3() const { return c3; }
double getc4() const { return c4; }
```

Define number and variables for model parameters and get methods

Adding your model and Observables to HEPfit

- In myModel.cpp:

```
#include "myModel.h"

/* Define mandatory model parameters here. */
const std::string myModel::myModelvars[NmyModelvars] = {"c1", "c2", "c3", "c4"};

myModel::myModel()
:   StandardModel()
{
    /* Define all the parameters here and port them as observables too */
    ModelParamMap.insert(std::make_pair("c1", std::cref(c1)));
    ModelParamMap.insert(std::make_pair("c2", std::cref(c2)));
    ModelParamMap.insert(std::make_pair("c3", std::cref(c3)));
    ModelParamMap.insert(std::make_pair("c4", std::cref(c4)));
}
```

Assign names to parameters and link to variables

```
/* Model parameters and their derived quantities can be set here. */
void myModel::setParameter(const std::string name, const double& value)
{
    if(name.compare("c1") == 0)
        c1 = value;
    else if(name.compare("c2") == 0)
        c2 = value;
    else if(name.compare("c3") == 0)
        c3 = value;
    else if(name.compare("c4") == 0)
        c4 = value;
    else
        StandardModel::setParameter(name,value);
}
```

Link to parameter names to variables and values in the setParameter method

Adding your model and Observables to HEPfit

- Finally register the model in the "Model Factory" in myModel_MCMC.cpp:

```
/* register user-defined model named ModelName defined in class ModelClass using the following syntax: */
ModelF.addModelToFactory("myModel", boost::factory<myModel*>() );
```

- **Custom Observables** do not depend on having a custom model or not. Defined as functions of parameters already defined in a HEPfit model, in a custom model or a combination of both
- Need to be added to the ThObsFactory, e.g. in myModel_MCMC.cpp

```
/* register user-defined ThObservable named ThObsName defined in class ThObsClass using the following syntax: */
ThObsF.addObsToFactory("BIN1", boost::bind(boost::factory<yield*>(), _1, 1) );
ThObsF.addObsToFactory("BIN2", boost::bind(boost::factory<yield*>(), _1, 2) );
ThObsF.addObsToFactory("BIN3", boost::bind(boost::factory<yield*>(), _1, 3) );
ThObsF.addObsToFactory("BIN4", boost::bind(boost::factory<yield*>(), _1, 4) );
ThObsF.addObsToFactory("BIN5", boost::bind(boost::factory<yield*>(), _1, 5) );
ThObsF.addObsToFactory("BIN6", boost::bind(boost::factory<yield*>(), _1, 6) );
ThObsF.addObsToFactory("C_3", boost::factory<C_3*>() );
ThObsF.addObsToFactory("C_4", boost::factory<C_4*>() );
```

Require argument

Do not require extra arguments