SMEFT Analysis of m_W

2204.05260: Emanuele Bagnaschi, John Ellis, MM, Ken Mimasu, Veronica Sanz, Tevong You

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The W boson mass at CDF II

CDF Collaboration, *Science 376 (2022) no. 6589* → $m_W = 80433.5 \pm 9.4 \text{ MeV}$

SM electroweak fit *1803.01853 J. Haller et. al* → $m_W = 80354 \pm 7 \text{ MeV}$

→ m_W *as predicted from a SM fit to electroweak precision data, not including measurements of* m_W

A discrepancy of ~ 7σ

The W boson mass

CDF Collaboration, *Science 376 (2022) no. 6589*

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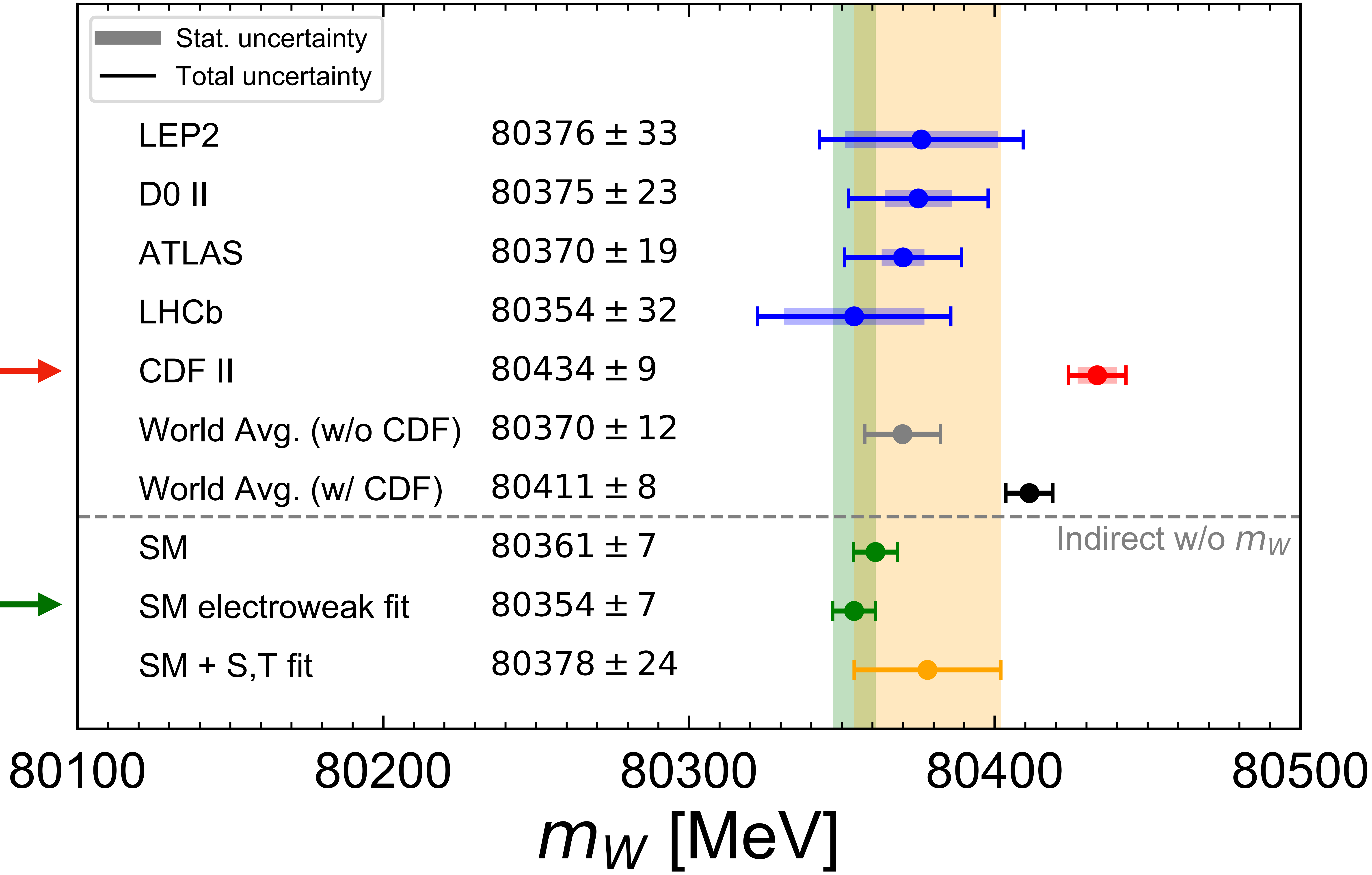

The W boson mass

Further incompatibility with direct measurements of m_W at ATLAS, LHCb, LEP and D0

CDF Collaboration, *Science 376 (2022) no. 6589*

SM electroweak fit
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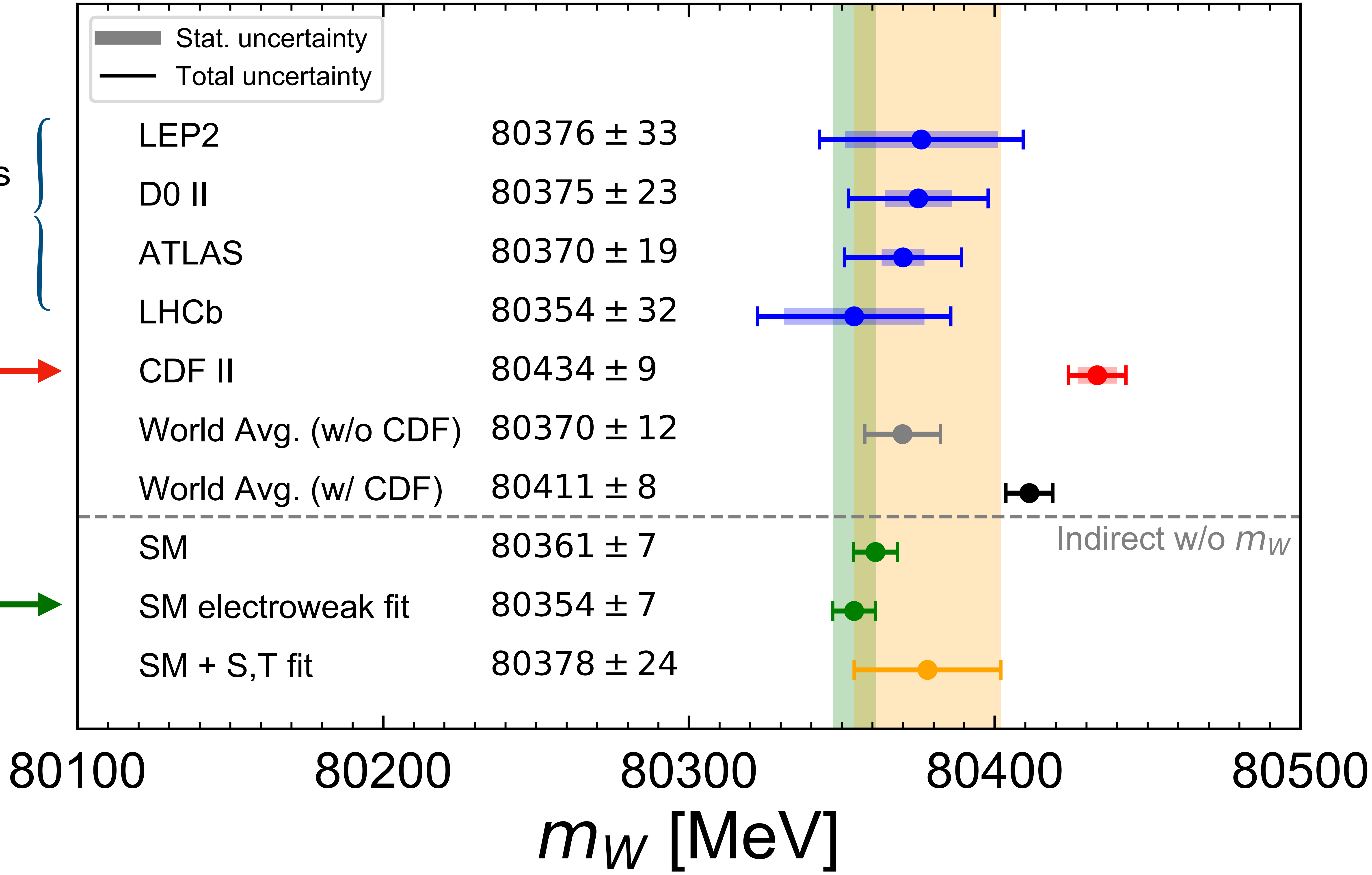
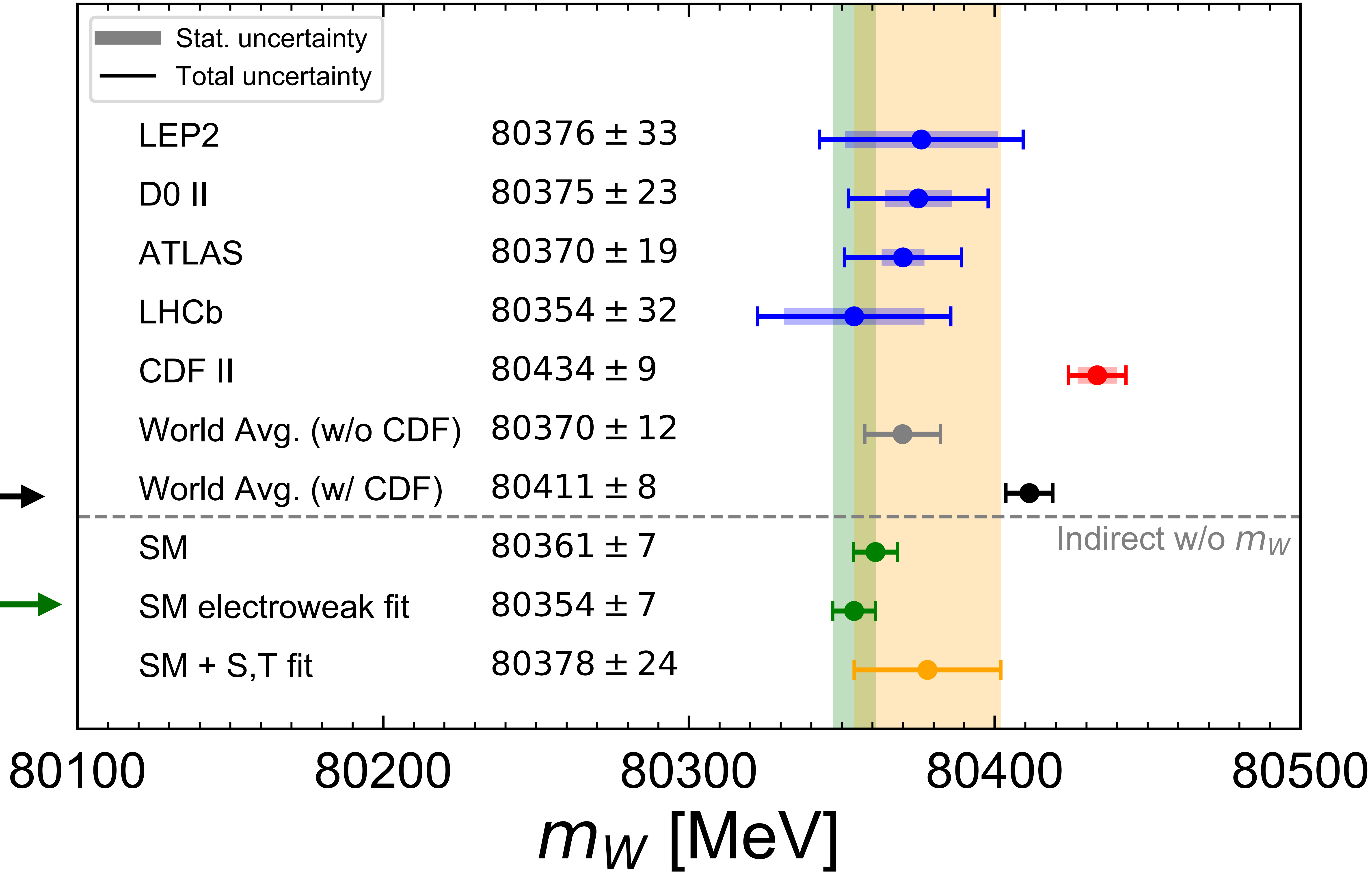


The W boson mass

World average of direct m_W measurements including CDF

SM electroweak fit
1803.01853 J. Haller et. al



The SMEFT

Can new physics beyond the SM mitigate the m_W tension?

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Using the **SMEFT**, we can address this question in a **model-independent** manner, assuming heavy new physics:

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{C^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots \qquad E \ll \Lambda$$

this work

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Is this new physics consistent with other data?

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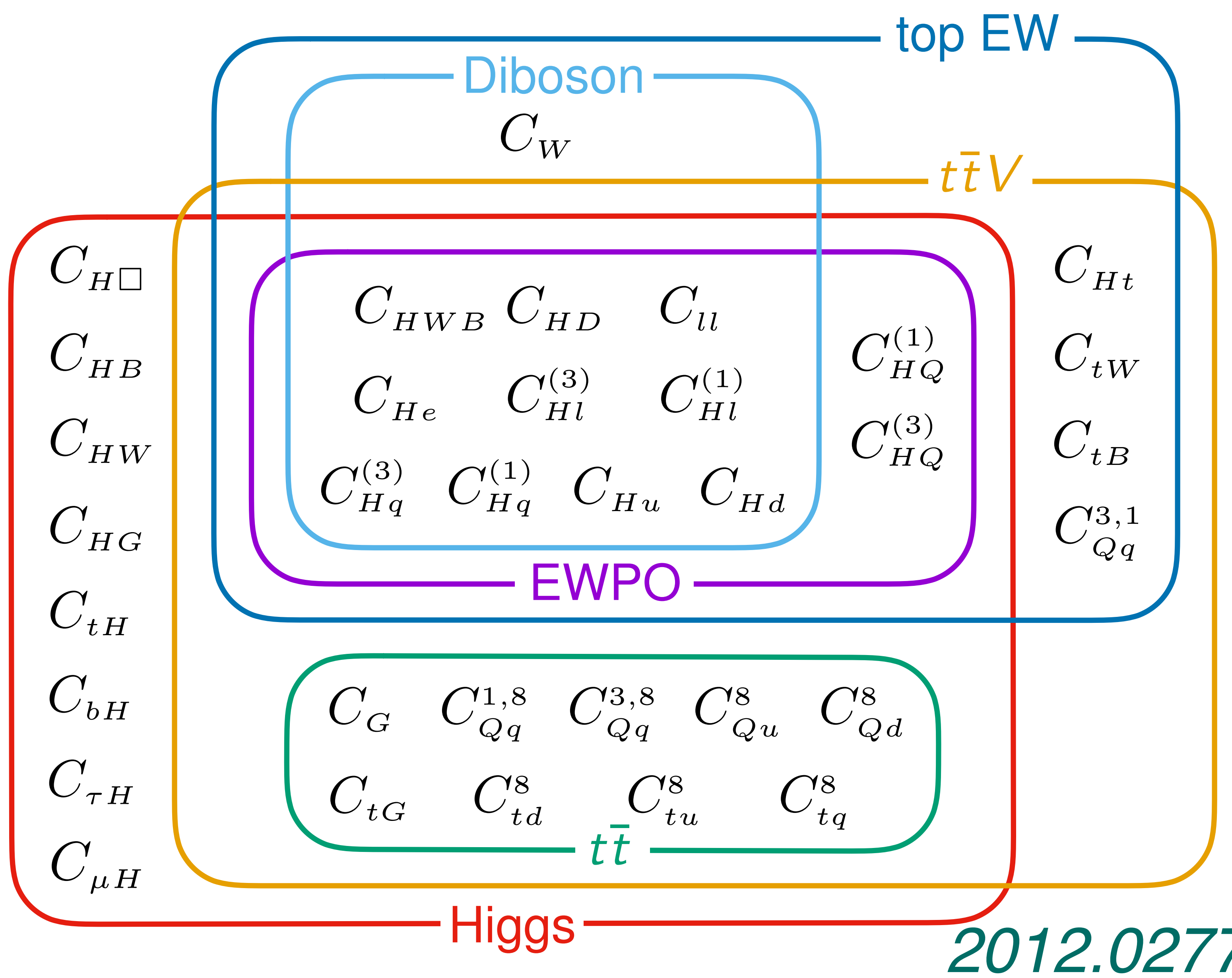
Is this new physics consistent with other data?

We will incorporate the m_W data into a **global fit,** analysing the consistency of new physics with existing Higgs, diboson and electroweak precision data.



2012.02779 Ellis et. al

Our analysis

`Fitmaker` *https://gitlab.com/kenmimasu/fitrepo*

- An update of our previous SMEFT analysis of Higgs, diboson and electroweak precision data using **`Fitmaker`** *2012.02779 Ellis et. al*

  → now including CDF II and LHCb measurements of m_W

- Dimension-6 operators in the Warsaw basis, at linear order only

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{\Lambda^2}\sigma_i + \mathcal{O}(\Lambda^{-4})$$

- Flavour universal $SU(3)^5$ → 20 operators

Data

Electroweak precision observables include:

Combination of W boson mass at CDF, D0 & LEP

$$m_W = 80424.2 \pm 8.7 \text{ MeV}$$

CDF Collaboration, Science 376 (2022) no. 6589

Precision measurements at the Z resonance

$$\{\Gamma_Z, \sigma^0_{\text{had.}}, R^0_l, A^l_{FB}, A_l, R^0_b, R^0_c, A^b_{FB}, A^c_{FB}, A_b, A_c\} \, .$$

Phys. Rept. 427 (2006) 257–454, hep-ex/0509008

W boson mass at the LHC

ATLAS *Eur. Phys. J. C 78 (2018), arXiv:1701.07240*

LHCb *JHEP 01 (2022) 036, [arXiv:2109.01113].*

See 2204.05260 for details of the diboson and Higgs datasets

m_W in the SMEFT

$$\hat{\alpha}_{EW}^{-1} = 127.95$$
$$\hat{G}_F = 1.16638 \times 10^{-5}\ \text{GeV}^{-2}$$
$$\hat{m}_Z = 91.1876\ \text{GeV}$$

Electroweak input parameters: $\{\hat{\alpha}_{EW}, \hat{M}_Z, \hat{G}_F\}$

$$\frac{\delta m_W^2}{\hat{m}_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w}\frac{v^2}{4\Lambda^2}\left(\frac{\cos\theta_w}{\sin\theta_w}C_{HD} + \frac{\sin\theta_w}{\cos\theta_w}\left(4C_{Hl}^{(3)} - 2C_{ll}\right) + 4C_{HWB}\right)$$

where $m_W^2 = \hat{m}_W^2 + \delta m_W^2$, $\hat{m}_W$ derived from input parameters in the SM.

m_W

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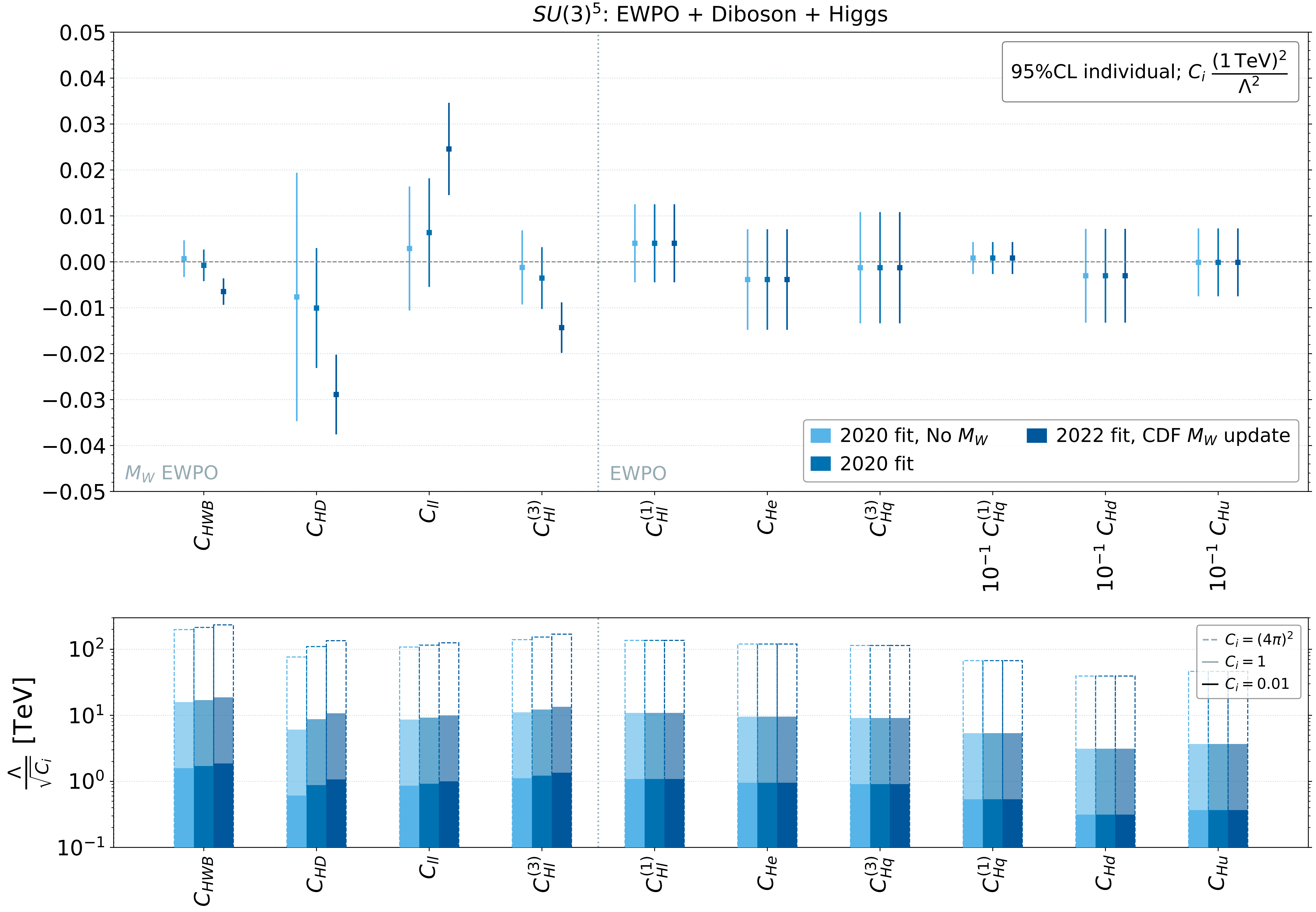
4 operators can induce a shift in m_W at linear order:

$$\mathcal{O}_{HWB} \equiv H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}, \qquad \mathcal{O}_{HD} \equiv \left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right),$$
$$\mathcal{O}_{\ell\ell} \equiv \left(\bar{\ell}\gamma_\mu \ell\right)\left(\bar{\ell}\gamma^\mu \ell\right), \qquad \mathcal{O}_{H\ell}^{(3)} \equiv \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{\ell}\tau^I\gamma^\mu \ell\right)$$

We neglect possible measurement bias in extracting m_W in the SMEFT *Bjørn, Trott, 1606.06502*

Individual SMEFT constraints

$$\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w}\frac{v^2}{4\Lambda^2}\left(\frac{\cos\theta_w}{\sin\theta_w}C_{HD} + \frac{\sin\theta_w}{\cos\theta_w}\left(4C_{Hl}^{(3)} - 2C_{ll}\right) + 4C_{HWB}\right)$$



*Only the most relevant operators are shown here

Marginalised SMEFT constraints

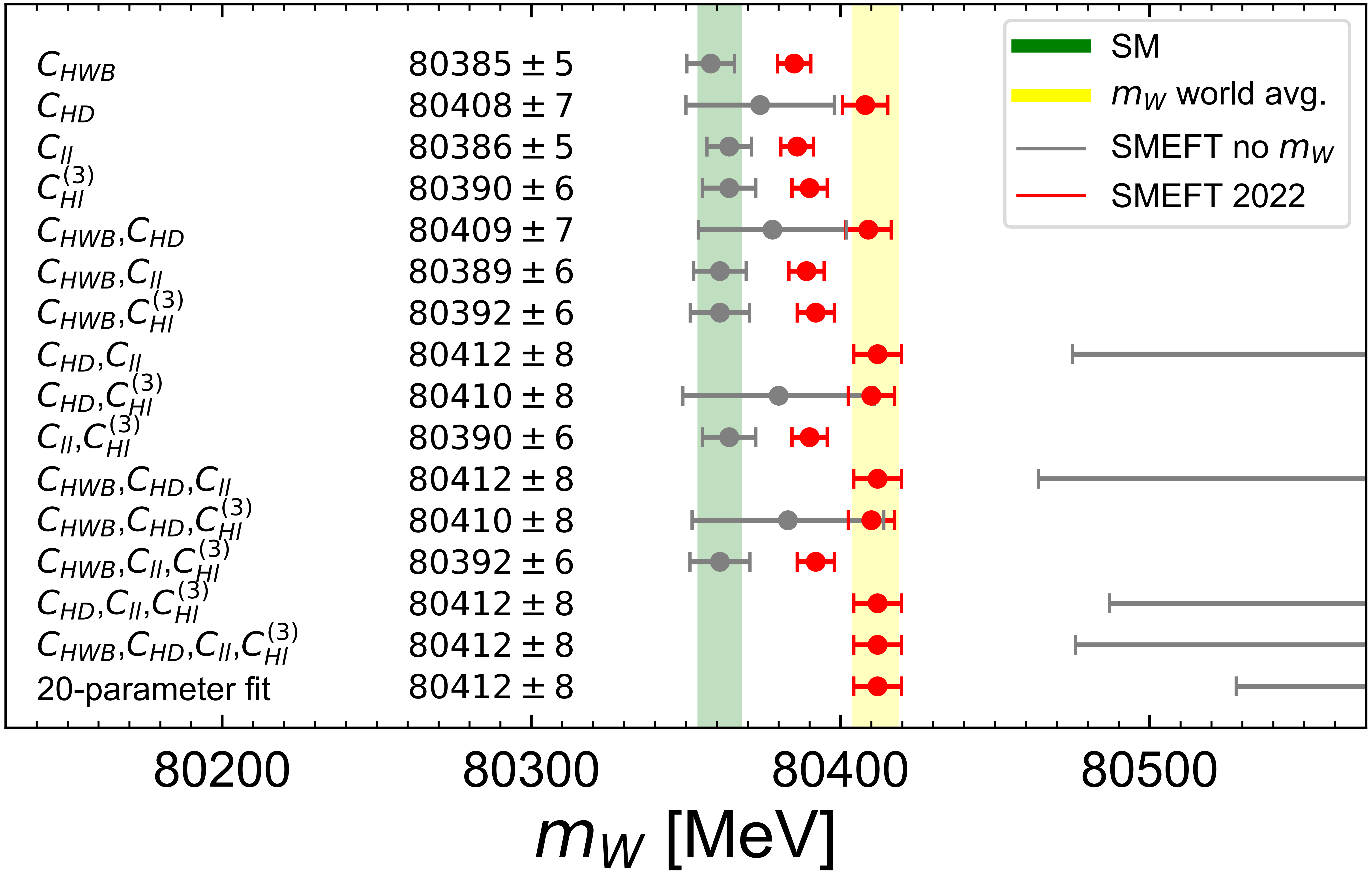
*Only the most relevant operators are shown here.

All others are included in the marginalisation.

m_W in the SMEFT

Grey: SMEFT fit, excluding direct measurements of m_W

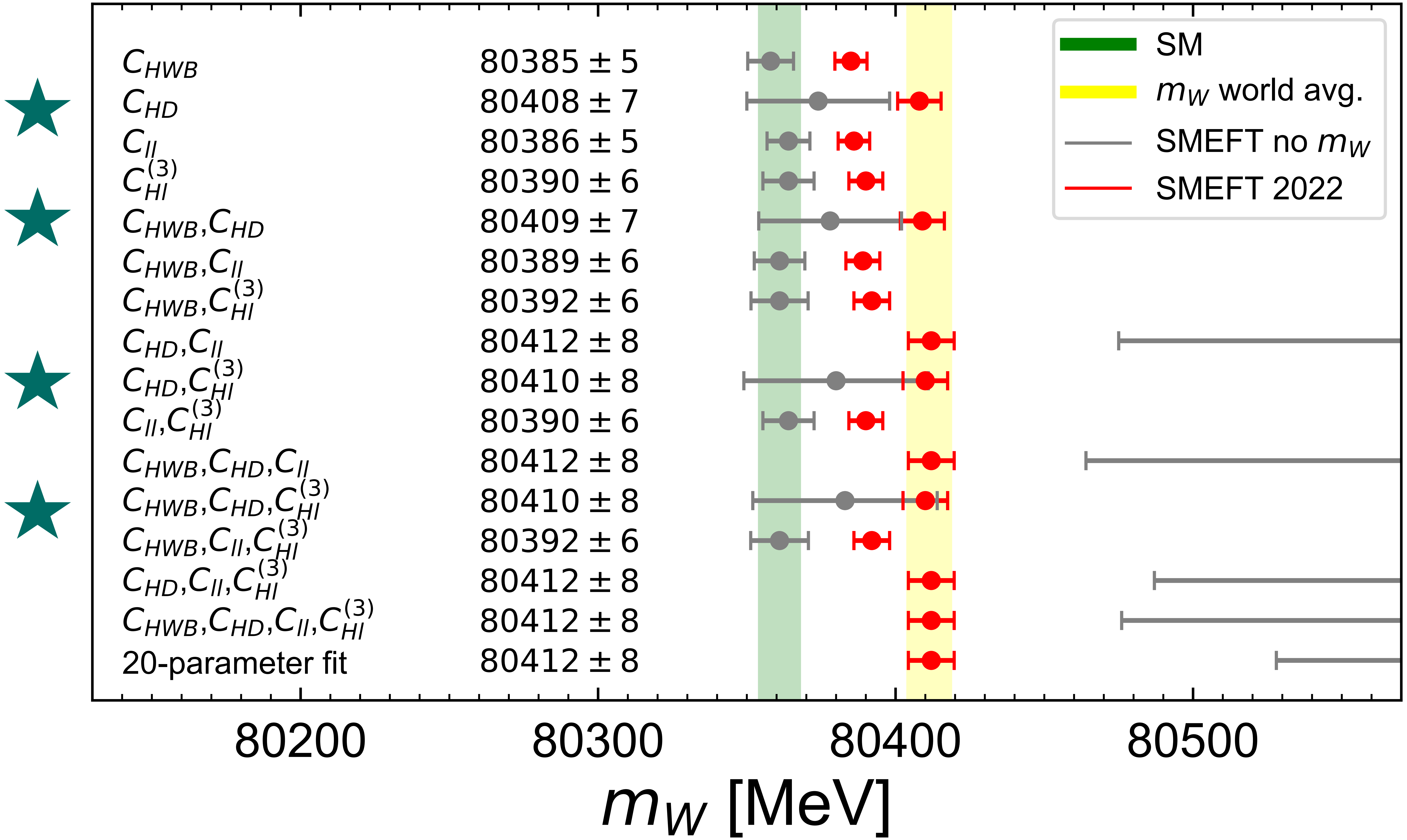
Red: SMEFT fit, including direct measurements of m_W



m_W in the SMEFT

C_{HD} is the least constrained of the one-param fits

Fits including C_{HD} show compatibility with the CDF m_W measurement



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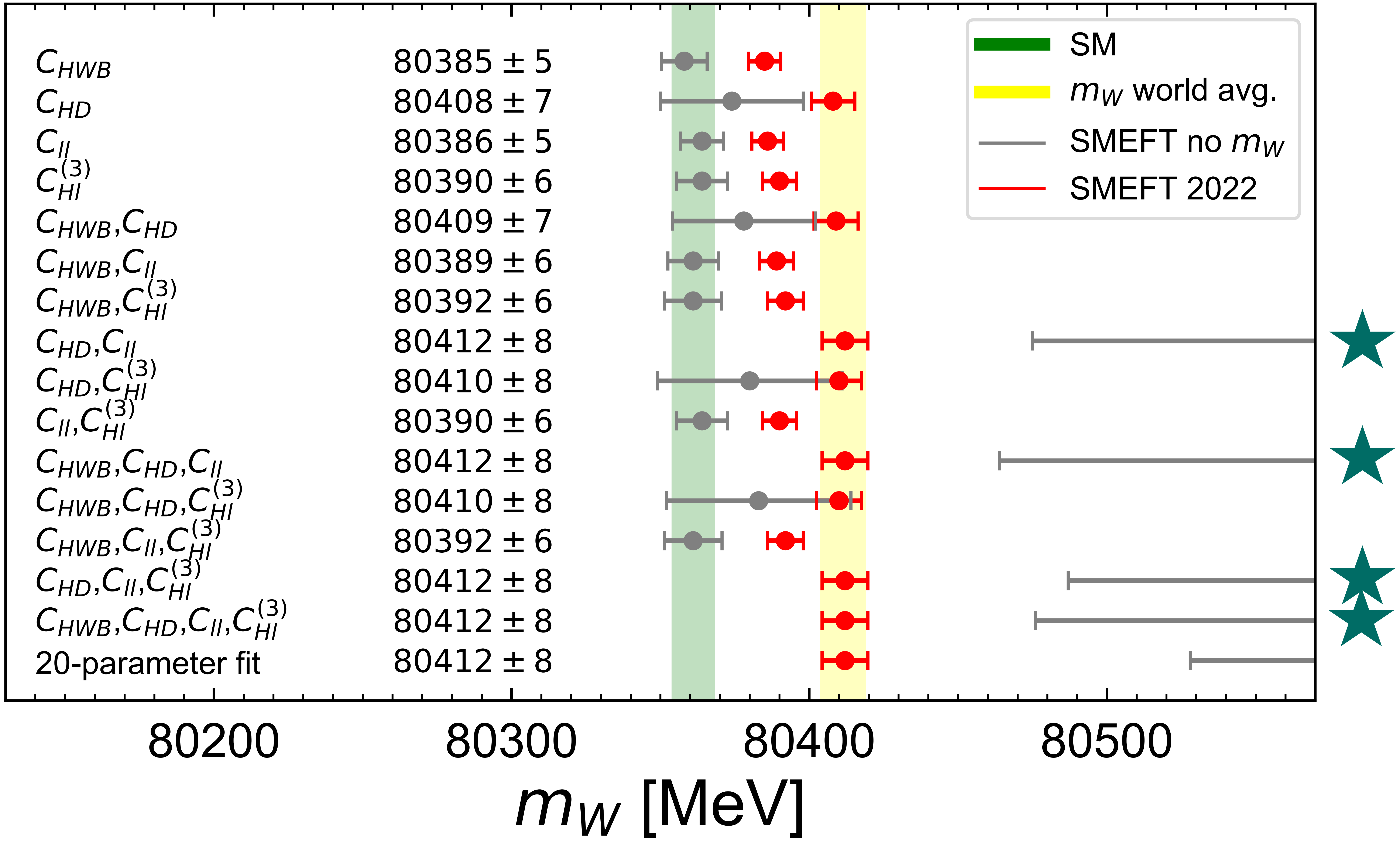
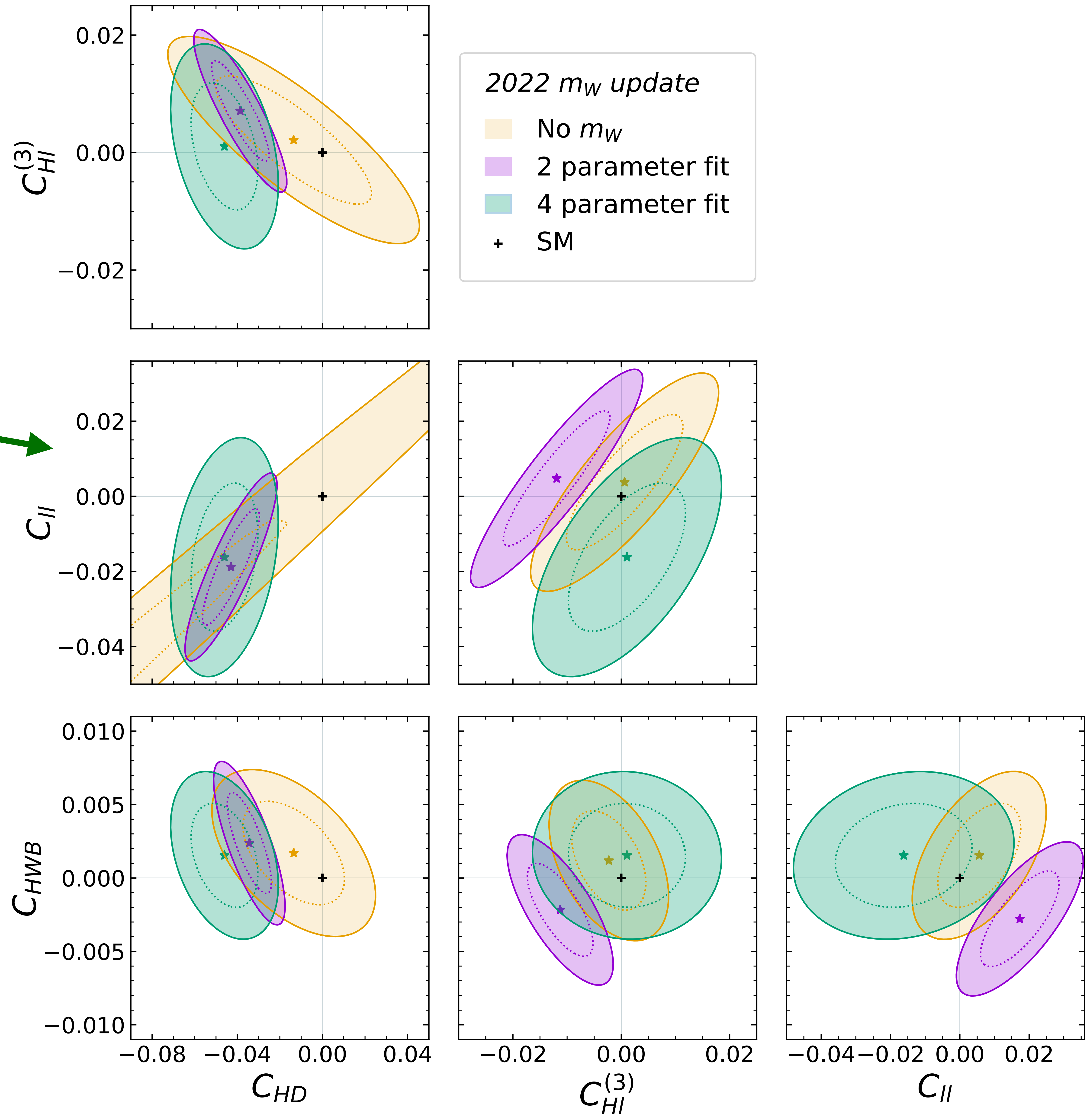
Fits including C_{HD}, C_{ll} indicate a flat direction



SMEFT constraints

A flat direction between C_{HD}, C_{ll} is lifted by m_W



Both the 2 and 4-parameter fits show C_{HD} always bounded away from zero

We see good compatibility between the fits with/without m_W

Constraints from CKM unitarity

The SMEFT is constrained by the consistency of β - decay data with CKM unitarity:

2204.04559 M. Blennow et. al
2204.08440 V. Cirigliano et. al

$$\Delta_{CKM} = 2\frac{v^2}{\Lambda^2}\left[C_{Hq}^{(3)} - C_{H\ell}^{(3)} + C_{\ell\ell} - C_{\ell q}^{(3)}\right]$$

where $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 - 1$

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Recall $C_{Hl}^{(3)}, C_{ll}, C_{HD}, C_{HWB}$ contribute to m_W

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Measurements of $0^+ \to 0^+$ nucleon transitions and kaon decays:

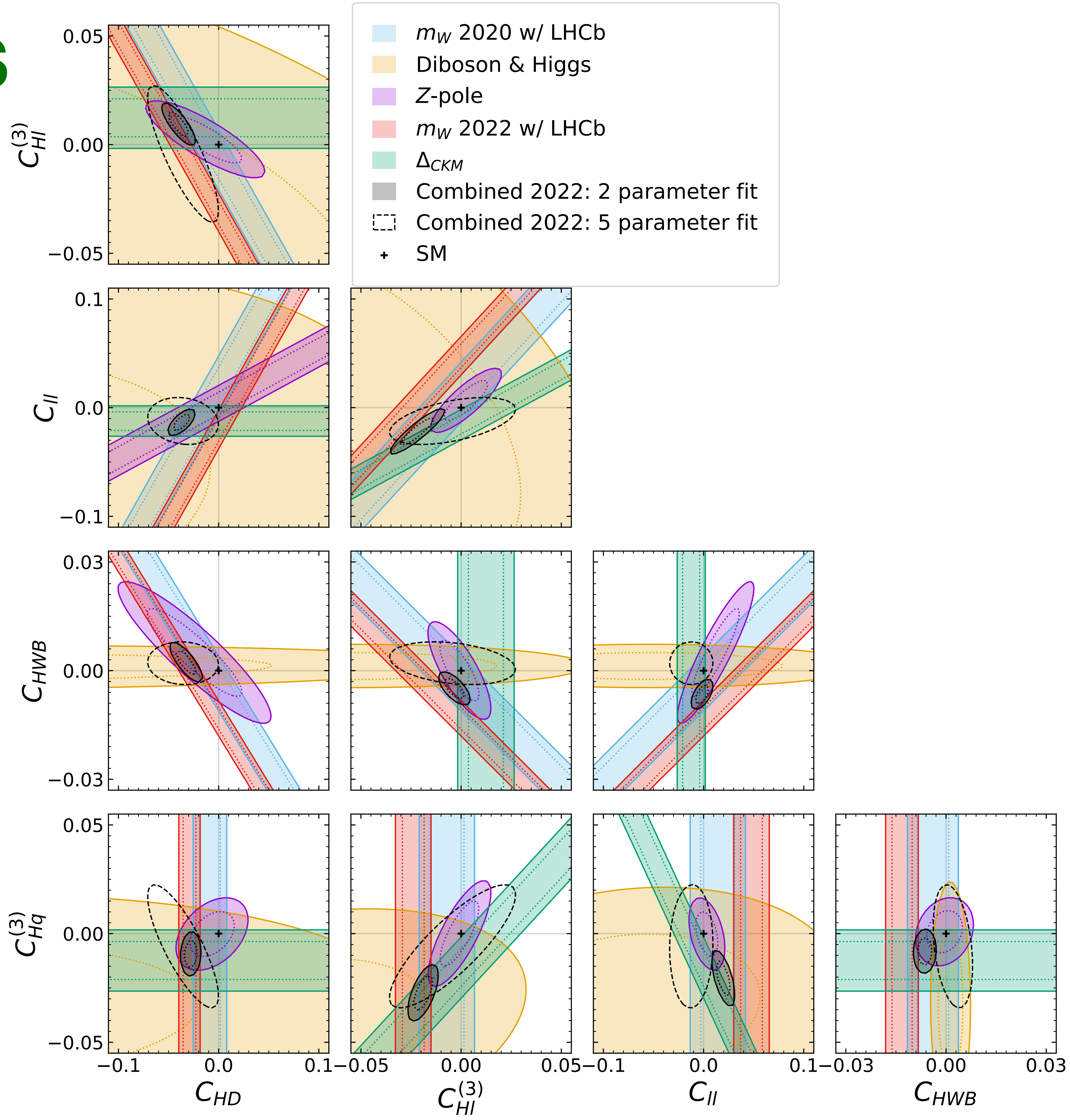
$$\Delta_{CKM} = -0.0015 \pm 0.0007$$

Breakdown of constraints

Measurements of Δ_{CKM} or m_W can be used to break the flat direction in C_{HD}, C_{ll} parameter-space

Diboson and Higgs data are crucial for constraining C_{HWB}

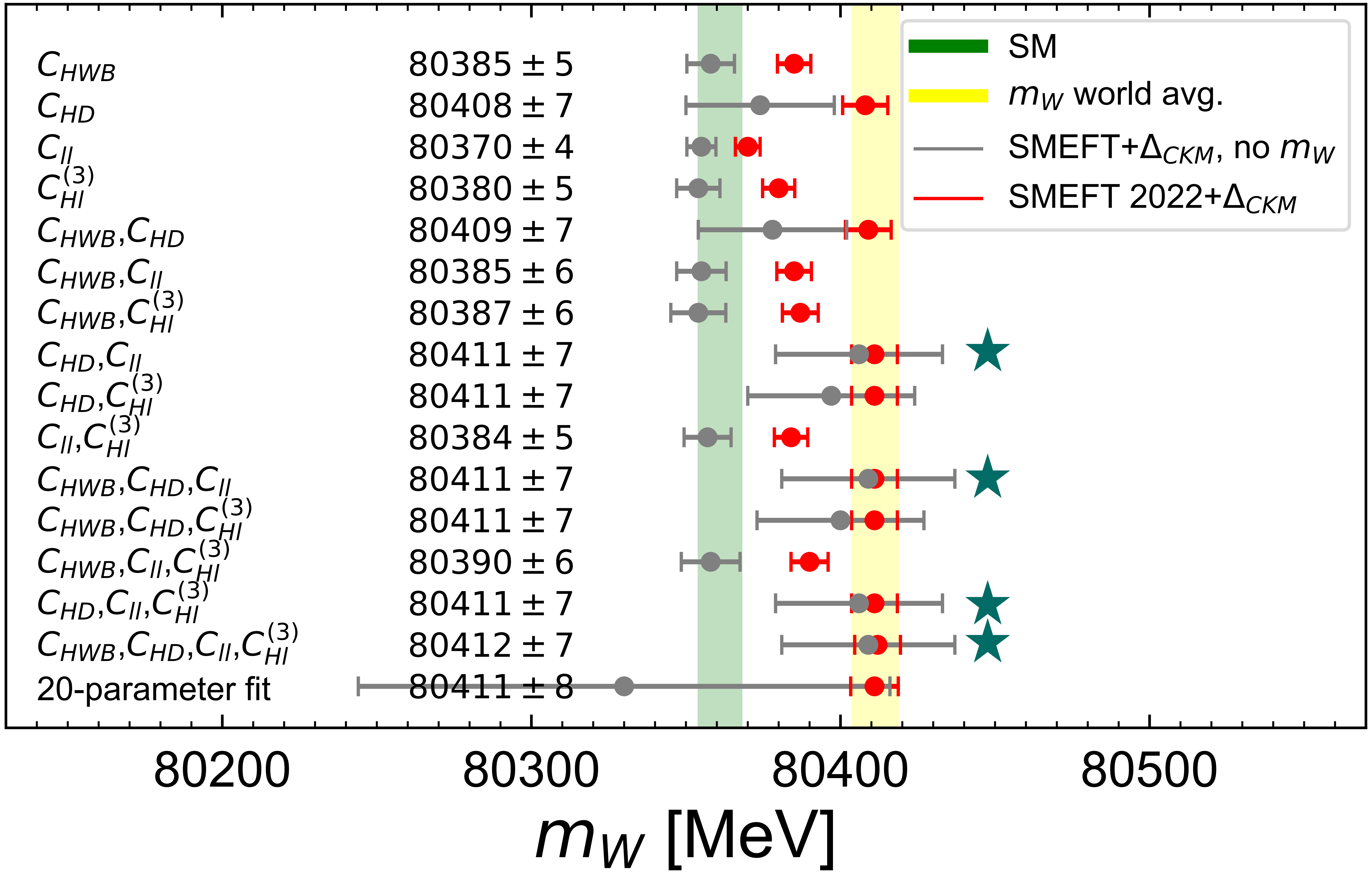
The combined 5-parameter fit (dashed) shows C_{HD} always bounded away from zero



m_W in the SMEFT with ΔCKM

No longer find a degeneracy between C_{HD}, C_{ll}

Indirect m_W predictions are compatible with the m_W world average in all fits involving C_{HD}



Probing single-field extensions of the SM

Single-field extensions of the SM matched to the SMEFT at tree-level, *1711.10391 de Blas et. al*

Model	C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S_1		-1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
B	-2						$-y_\tau$	$-y_t$	$-y_b$
Ξ	$-2\left(\frac{1}{M_\Xi}\right)^2$					$\frac{1}{2}\left(\frac{1}{M_\Xi}\right)^2$	$y_\tau\left(\frac{1}{M_\Xi}\right)^2$	$y_t\left(\frac{1}{M_\Xi}\right)^2$	$y_b\left(\frac{1}{M_\Xi}\right)^2$
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	$\frac{1}{2}$					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

$$\text{e.g. } N\text{:}\quad \frac{C_{Hl}^{(1)}}{\Lambda^2} = -\frac{C_{Hl}^{(3)}}{\Lambda^2} = \frac{1}{4}\frac{g_N^2}{M_N^2}$$

5 models shift m_W in the positive direction: N, E, B, Ξ, W_1

$$\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w}\frac{v^2}{4\Lambda^2}\left(\frac{\cos\theta_w}{\sin\theta_w}C_{HD} + \frac{\sin\theta_w}{\cos\theta_w}\left(4C_{Hl}^{(3)} - 2C_{ll}\right) + 4C_{HWB}\right)$$

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N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
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Ξ	$-2\left(\frac{1}{M_\Xi}\right)^2$					$\frac{1}{2}\left(\frac{1}{M_\Xi}\right)^2$	$y_\tau\left(\frac{1}{M_\Xi}\right)^2$	$y_t\left(\frac{1}{M_\Xi}\right)^2$	$y_b\left(\frac{1}{M_\Xi}\right)^2$
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W	$\frac{1}{2}$					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

Model	Spin	SU(3)	SU(2)	U(1)
N	$\frac{1}{2}$	1	1	0
E	$\frac{1}{2}$	1	1	-1
B	1	1	1	0
Ξ	0	1	3	0
W_1	1	1	3	1

5 models shift m_W in the positive direction: N, E, B, Ξ, W_1

$$\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w}\frac{v^2}{4\Lambda^2}\left(\frac{\cos\theta_w}{\sin\theta_w}C_{HD} + \frac{\sin\theta_w}{\cos\theta_w}\left(4C_{Hl}^{(3)} - 2C_{ll}\right) + 4C_{HWB}\right)$$

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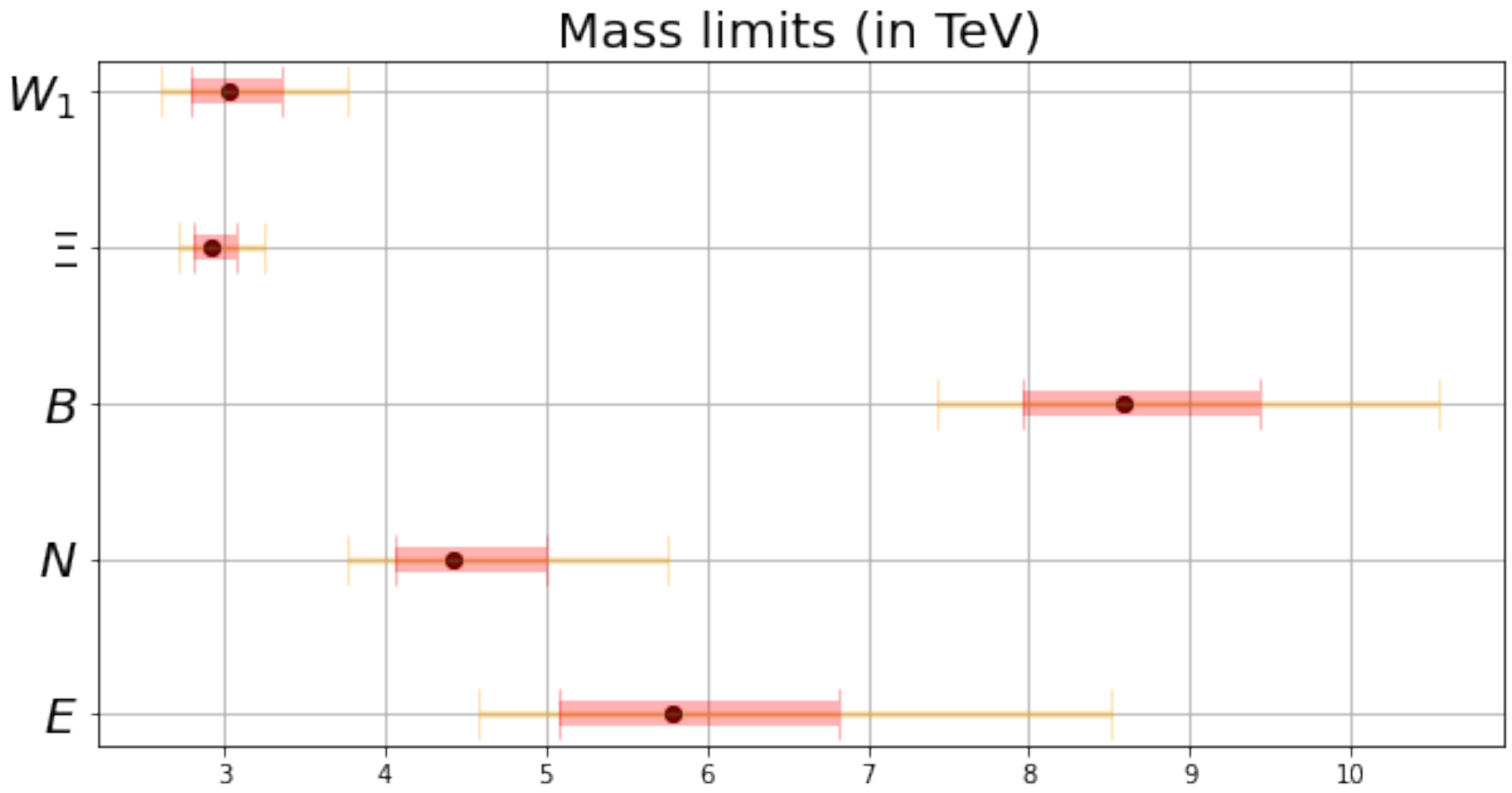


Constraints at 68% and 95% CL, assuming a coupling of *g=1*

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	8.6	[8.0, 9.4]	[7.4, 10.6]	[0.011, 0.016]
Ξ	6.4	2.9	[2.8, 3.1]	[2.7, 3.2]	[0.011, 0.016]
N	5.1	4.4	[4.1, 5.0]	[3.8, 5.8]	[0.040, 0.060]
E	3.5	5.8	[5.1, 6.8]	[4.6, 8.5]	[0.022, 0.039]

Conclusions

New physics parametrised by the dimension-6 SMEFT can account for a large enough shift in m_W without significant tension with other electroweak precision, Higgs and diboson data.

$$C_{HWB}, C_{HD}, C_{ll}, C_{Hl}^{(3)}$$

m_W can be accommodated within several single-field extensions of the SM with new particles whose masses are in the TeV range for couplings of order 1

$$N, E, B, \Xi, W_1$$

Low-energy measurements e.g. Δ_{CKM} provide complementary information on the SMEFT operators constrained by m_W

Thank you for listening!

S, T parameters

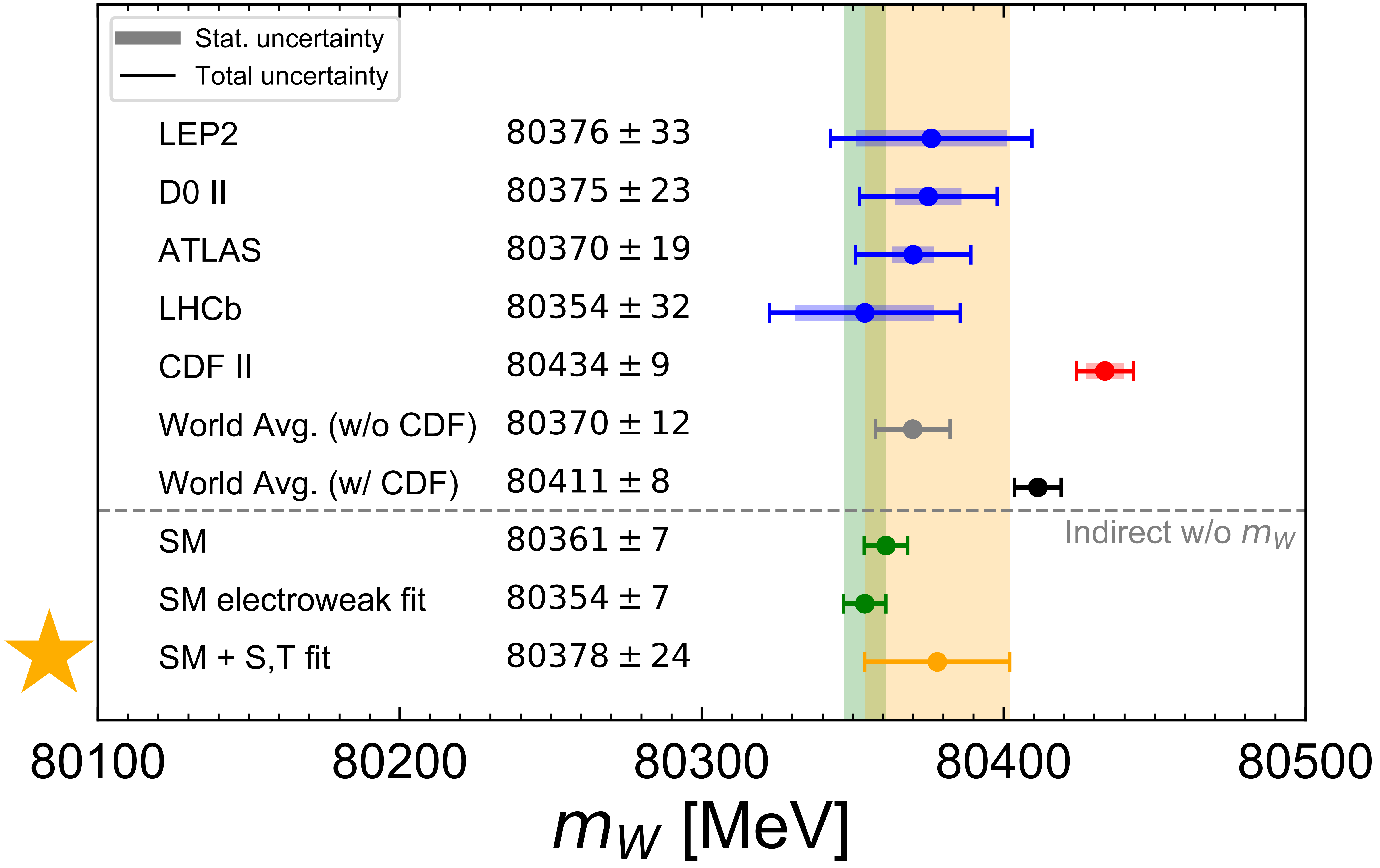
Relation to the electroweak oblique parameters *S, T*:

$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S$$

$$\frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1^2 g_2^2}{2\pi(g_1^2 + g_2^2)} T$$

SM + *S,T* electroweak fit:

greater compatibility with the W mass world average



S, T parameters

Clear pull away from the SM in the *T* direction

Fit to m_W data (purple) remains compatible with the fit to all other data (yellow)

$$\Delta m_W \in [0.04\%, 0.08\%]$$