

SMEFT Analysis of the W boson mass in light of the recent CDF measurement

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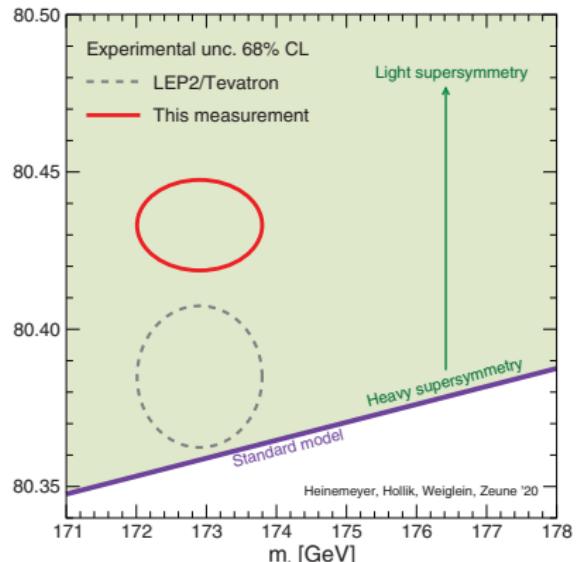
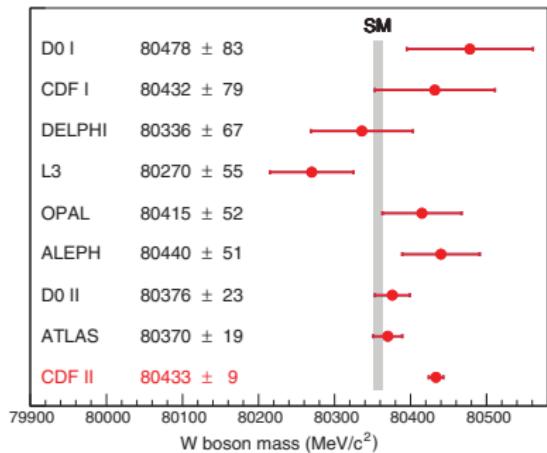


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Introduction

The physics case for the W mass

- The m_W mass measurement is one of the most important items of the SM precision program at colliders → See the talks of C. Hays (CDF), M. Ramos Pernas (LHCb) and S. Amoroso (CMS)
- The new CDF m_W mass measure has created a huge activity in the community, both in relation to the measurement itself and to the possible BSM implications



[CDF collaboration, Science 376 (2022) 6589, 170-176]

The CDF measurement and new physics models

- Many articles have been published discussing BSM perspectives, both from perspective of using explicit BSM models or a framework such as SMEFT

BSM Landscape

- SM+Singlet extension [Sakurai et al., 2204.04770]
- SM+Triplet extension [Addazi et al., 2204.10315; Ghost et al., 2205.05041; Kanemura et al., 2204.07511; Perez et al., 2204.07144]
- Superweak SM [Péli et al., 2204.07100]
- Nonlocal SM [Krasnikov, 2204.06327]
- Simple Extension of the SM [2205.08215]
- 2HDMs [Abouabid et al., 2204.12018; Ahn et al., 2204.06485; Applequist et al., 2205.03320; Arcadi et al., 2204.08406; Babu et al., 2204.05303; Bahl et al., 2204.05269; Botella et al., Fan et al., 2204.03693; Ghorbani et al., 2204.09001; Heo et al., 2204.06505; Kim 2205.01437; Kim et al., 2205.0170; Lee et al., 2204.10338; Song et al., 2204.04805; Zhu et al., 2204.03767; Zhu et al., 2204.04688]
- N2HDM [Biekötter et al., 2204.05975]
- GUT [Evans et al., 2205.03877; Senjanovic et al., 2205.05022; Wilson, 2204.07970]
- SUSY models [Athron et al., 2204.05285; Du et al., 2204.04286; Sun et al., 2204.06234; Tang et al., 2204.04356; Zheng et al., 2204.06541]

The CDF measurement and new physics models

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BSM Landscape

- Neutrinos [Arias-Aragon et al., 2204.04672; Batra et al., 2204.11945; Blennow et al. 2204.04559; Borah et al., 2204.08266; Chakraborty et al., 2206.11771; Cheng et al., 2204.05031; Chowdhury et al., 2204.08390; Coy et al., 2110.09126; Dong, 2205.04253; Dcruz et al., 2205.02217; Faraggi et al., 2204.11974; Ghoshal et al., 2204.07138; Heeck, 2204.10274; Liu et al., 2204.04834; Ma, 2205.09794; Popov et al., 2204.08568; Van Dong, 2205.04253; Yang et al., 2204.11871]
- String theory [Barman et al., 2205.01699; Basiouris et al., 2205.00758; Heckman et al., 2204.05302]
- Vector-like fermions [Cao et al., 2204.09477; Chowdhuri et al., 2205.03917; Crivellin et al. 2204.05962; Dermisek et al., 2204.13272; Kawamura et al., 2205.10480; Lee et al., 2204.05024; Li et al., 2205.02205; Nagato et al., 2204.07411]
- Extra vectors [Allanach et al., 2205.12252 ; Cai et al, 2204.11570; Di Luzio et al., 2204.05945; Endo et al., 2204.05965; Nagao et al., 2206.15256; Rizzo, 2206.09814; Thomas et al., 2205.01911; Zeng et al., 2204.09487]
- Leptoquarks [Bhaskar et al, 2204.09031; Cheung et al., 2204.05942; He, 2205.02088]
- Georgi-Machacek [Chen et al., 2204.12898; Du et al., 2204.05760; Mondal, 2204.07844]
- $U(1)_{L_{mu}-L_{\tau}}$ [Baek, 2204.09585]
- Little Higgs [Ramirez et al., 2205.10420]

The CDF measurement and new physics models

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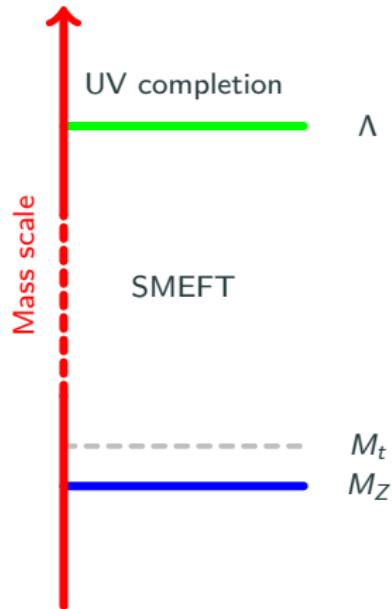
BSM Landscape

- Composite Higgs [Cacciapaglia et al., 2204.04514; Frandsen et al., 2207.01465]
- Composite vectors [Xue, 2205.14957]
- Dark sectors [Borah et al., 2204.09671; Cheng et al., 2204.10156; Du et al., 2204.09024; Kawamura et al., 2204.07022; Kim et al., 2205.04016; Wang et al., 2205.00783; Wojcik, 2205.11545; Zeng, 2203.09462 ; Zhang et al., 2204.08067]
- Axion models [Lazarides et al., 2205.04824]
- Colored scalars [Carpenter et al., 2204.08546]
- 3-3-1 [Van IJl et al., 2206.10100]
- $SU(2)_L \times SU(2)_R$ [Afoni, 2205.12237]
- Low-energy implications [Cirigliano et al., 2204.08440; Tran Tan et al., 2204.11991]
- EW fits (most with BSM interpretations; different levels of sophistication) [Athron et al., 2204.03996; Asadi et al., 2204.05283; Balkin et al., 2204.05992; De Blas et al., 2204.04204; Fan et al., 2204.04805; Lu et al., 2204.03796; Gu et al., 2204.05296; Paul et al., 2204.05267; Strumia 2204.04191] → See R. Kogler and M. Pierini talks
- (More) Global fits [EB et al. 2204.05260; D'Alise et al., 2204.03686; Gupta et al., 2204.13690]

Theoretical Framework

SM Effective Field Theory

- Assume that New Physics (NP) is sufficiently heavy so that there are no new dynamical degrees of freedom at the scale of the measurement(s) → particle content is the same as the SM
- Description of NP effects in terms higher-dimension operators → agnostic to the detail of NP models when fitting the data at the
- Model dependent matching of the SMEFT Lagrangian required for a complete physics insight
- We use the Warsaw basis in our study



$$\mathcal{L}_{\text{SMEFT}}^{\text{dim-6}} = \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

SMEFT and m_W

- At linear order in the Wilson coefficients, four dimension-6 operators can induce a shift in W mass

$$\begin{aligned}\mathcal{O}_{HWB} &\equiv H^\dagger \tau^I H W_{\mu\nu} B^{\mu\nu}, & \mathcal{O}_{HD} &\equiv \left(H^\dagger D^\mu H \right)^* \left(H^\dagger D_\mu H \right), \\ \mathcal{O}_{\ell\ell} &\equiv (\bar{\ell}_p \gamma_\mu \ell_r) (\bar{\ell}_s \gamma^\mu \ell_t), & \mathcal{O}_{H\ell}^{(3)} &\equiv \left(H^\dagger i \overleftrightarrow{D}_\mu H \right) (\bar{\ell}_p \tau^I \gamma^\mu \ell_r)\end{aligned}$$

- The shift in m_W is then given by

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

- In theory, SMEFT could in principle also influence the measurement process
- However, it has been found in [Bjørn and Trott, PLB 762 (2016) 426-431] that this effect is negligible

The setup

Fitmaker

The framework

- Python framework introduced in [Ellis et al. JHEP 04 (2021) 279]
- Used to perform a fit of Higgs, Electroweak, Higgs and top data using data from LHC Run 2
- Allows for a flexible implementations of constraints and various fit setups
- Fast analytical method for linear order fits; MCMC procedure to incorporate positivity priors in operator coefficients for specific BSM scenarios
- Available on Gitlab:
<https://gitlab.com/kenmimasu/fitrepo>

Fit strategy

- SMEFT predictions computed using MadGraph5_aMC@NLO with SMEFTsim and/or SMEFT@NLO
- Predictions used to extract the linear contribution a_i^X of a given Wilson coefficient

$$\mu_X \equiv \frac{X}{X_{SM}} = 1 + \sum_i a_i^X \frac{C_i}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- No theory uncertainty on the SMEFT prediction, assumed to be subdominant w.r.t. the SM ones
- Quadratic dim-6 or dim-8 contributions neglected

Experimental inputs

EW scheme

- $\{\alpha_{EW}, G_F, M_Z\}$
- $\alpha_{EW}^{-1} = 127.95$
- $G_F = 1.16638 \times 10^{-5} \text{ GeV}^{-2}$
- $m_Z = 91.1876 \text{ GeV}$

[Brivio et al. 2111.12515]

EWPOs

- $\Gamma_Z, \sigma_{\text{had.}}^0, R_I^0, A_{FB}^I, A_I, R_b^0, R_c^0, A_{FB}^b, A_{FB}^c, A_b, A_c, m_w$
- Three m_w values included in the fit, and assumed to be uncorrelated: m_w average from Tevatron+LEP as provided by CDF, and the LHCb and ATLAS measurements

Other input parameters

- $m_h = 125.09 \text{ GeV}$
- $m_T = 173.2 \text{ GeV}$
- $m_\mu = 0.106 \text{ GeV}$
- $m_\tau = 1.77 \text{ GeV}$
- $m_c = 0.907 \text{ GeV}$
- $m_b = 3.237 \text{ GeV}$

Diboson

- $W^+ W^-$ cross-sections and angular distributions at LEP
- fiducial differential cross-section in leading lepton p_T by ATLAS at the LHC and ATLAS and CMS fiducial differential cross-section measurements of the Z-boson p_T in leptonic $W^\pm Z$ production.
- Differential distribution in $\Delta\phi_{jj}$ for Zjj
- Total: 118 measurements

Experimental inputs

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Higgs

- Combination of Higgs signal strengths by ATLAS and CMS for Run 1
- For Run 2 both signal strengths and STXS measurements are used
- Total: 72 measurements

- More information on the Higgs and diboson datasets in [Ellis et al., JHEP 04 (2021) 279]

Results

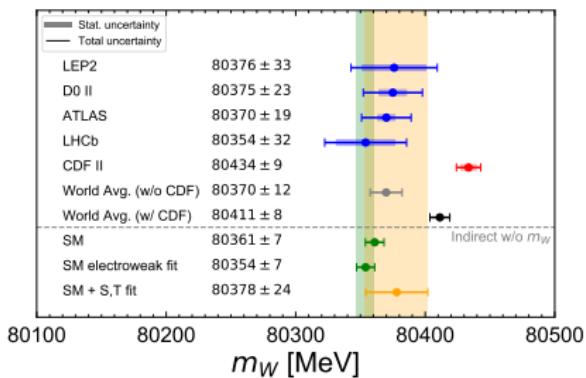
S & T fit

- Common parametrization of NP effects in the terms of the oblique parameters S & T

- We can express S & T in terms of dimension-6 operators

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

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



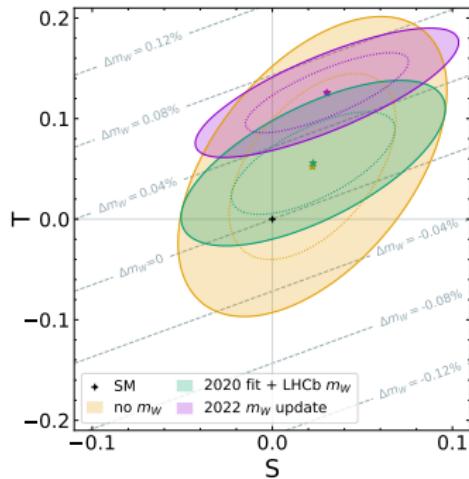
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$SU(3)^5$ SMEFT fit: EWPO + Diboson + Higgs

- To reduce the number of operators, we assume a $SU(3)^5$ flavor symmetry and consider 20 operators in the analysis
- It was shown in [Ellis et al. JHEP 04 (2021) 279] that since correlations between the top sector and bosonic data are small, then including top data or breaking the flavor symmetry down to $SU(2)^2 \times SU(3)^2$ should yield similar results

These operators are mostly constrained by

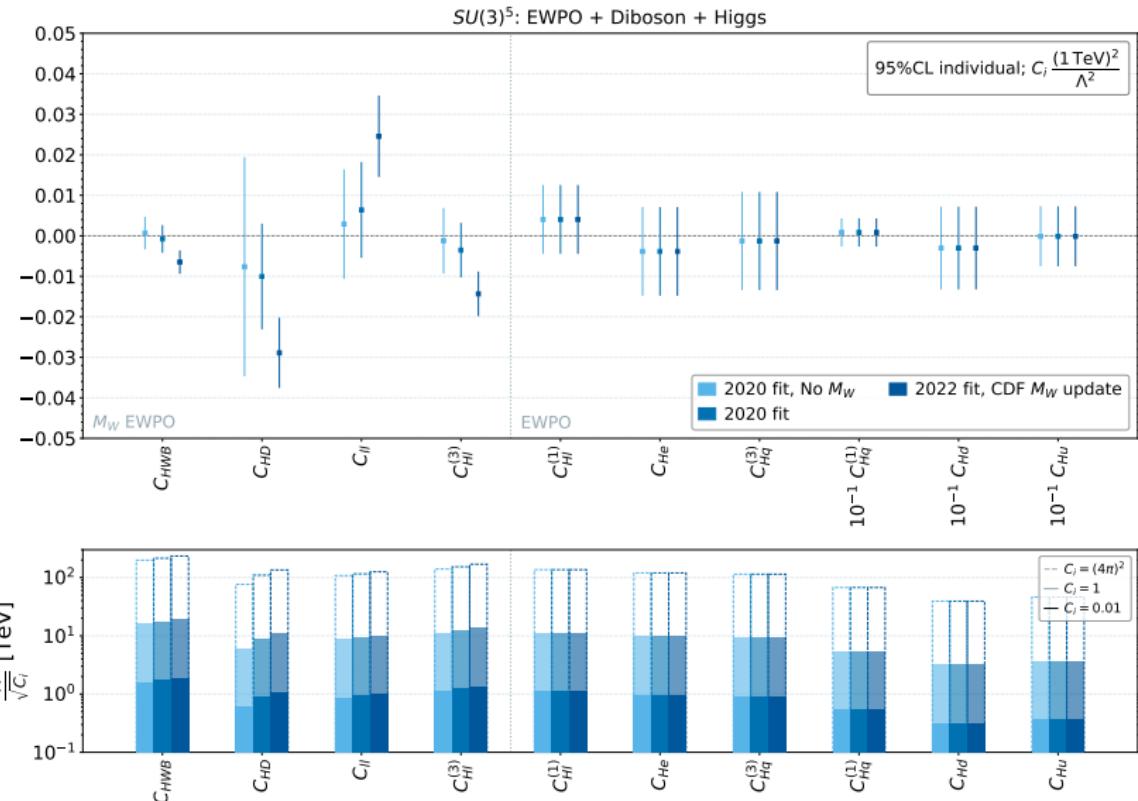
- **EWPOs**: constrained by Electroweak Precision Observables
- **Bosonic**: Higgs and diboson measurements
- **Yukawa**: operators that induce shifts in the Yukawa couplings

$$\text{EWPOs} \rightarrow \mathcal{O}_{HWB}, \mathcal{O}_{HD}, \mathcal{O}_{II}, \mathcal{O}_{HI}^{(3)}, \mathcal{O}_{HI}^{(1)}, \mathcal{O}_{He}, \mathcal{O}_{Hq}^{(3)}, \mathcal{O}_{Hq}^{(1)}, \mathcal{O}_{Hd}, \mathcal{O}_{Hu}$$

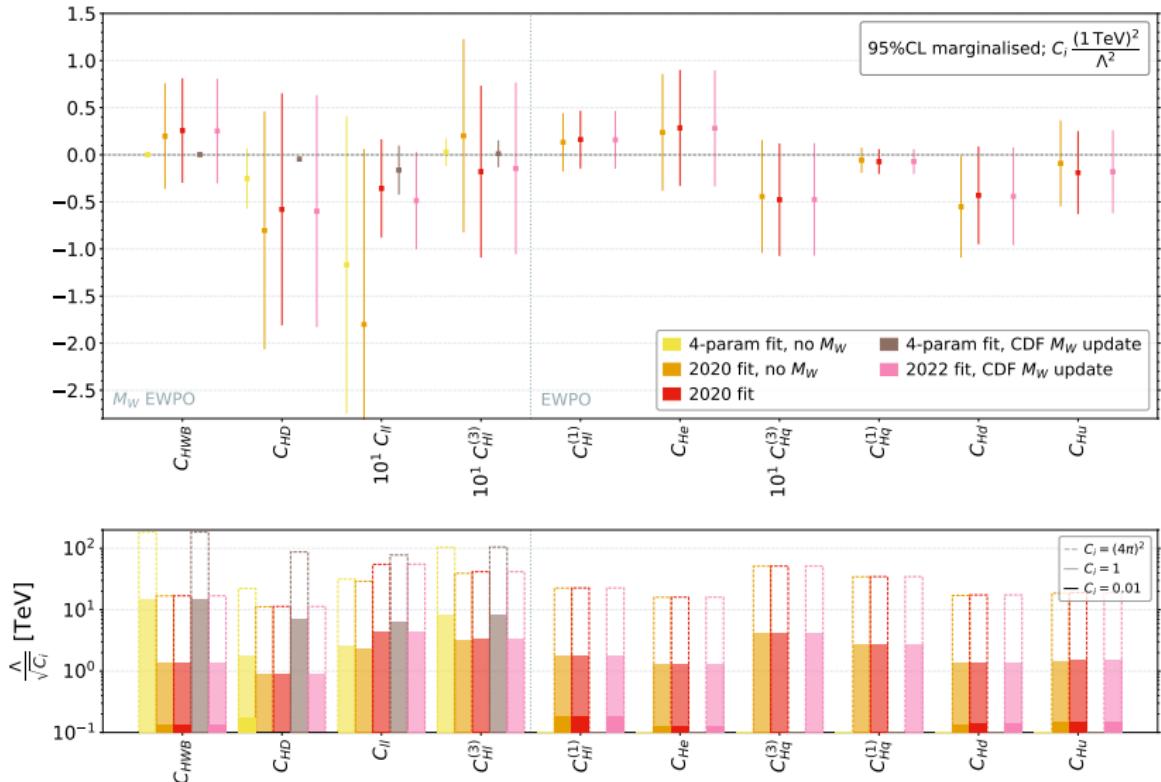
$$\text{Bosonic} \rightarrow \mathcal{O}_{H\square}, \mathcal{O}_{HG}, \mathcal{O}_{HW}, \mathcal{O}_{HB}, \mathcal{O}_W, \mathcal{O}_G$$

$$\text{Yukawa} \rightarrow \mathcal{O}_{\tau H}, \mathcal{O}_{\mu H}, \mathcal{O}_{b H}, \mathcal{O}_{t H}$$

Fit result – individual coefficients

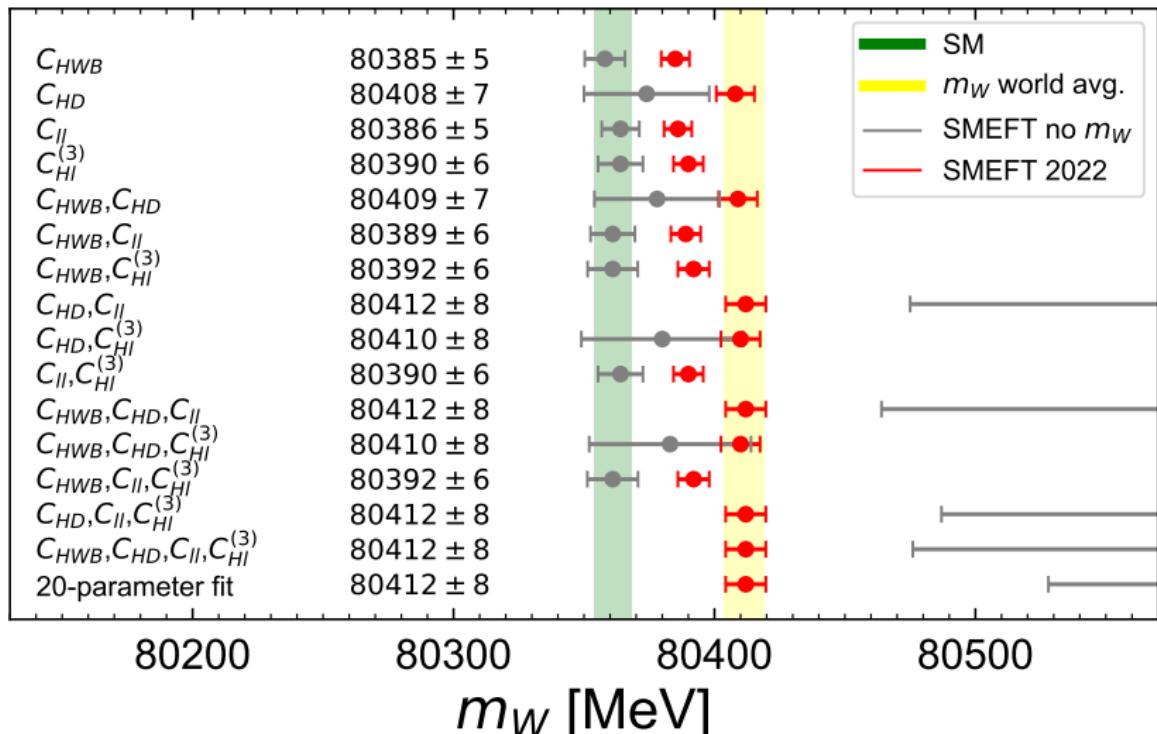


Fit result – marginalised coefficients



m_W – indirect determination vs measurement

- All possible fits that include the four operators contributing to δm_W^2



The role of low-energy constraints

β -decay, CKM unitarity and the W mass in SMEFT

- The consistency of β -decay measurements with the unitarity of the CKM matrix imposes a significant constraint on a specific combination of dimension-6 operators that are relevant for m_W [Blennow et al., 2204.04559, Cirigliano et al., 2204.08440]
- We can express the quantity $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 - 1$ in terms of dim-6 operators

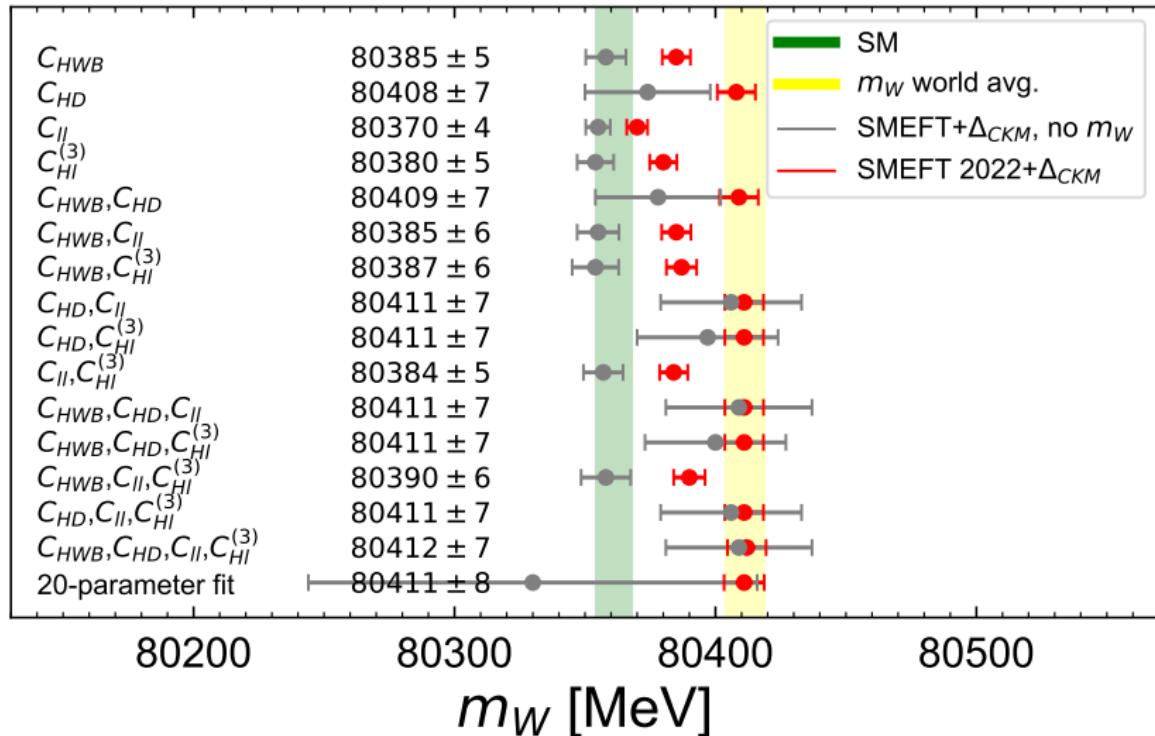
$$\Delta_{CKM} = 2 \frac{v^2}{\Lambda^2} \left[C_{Hq}^{(3)} - C_{H\ell}^{(3)} + C_{\ell\ell} - C_{\ell q}^{(3)} \right]$$

- Measurements of $0^+ \rightarrow 0^+$ nuclear transitions and kaon decays indicate that

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

- We include this constraint in our fit, with a more thorough study left to a future work

m_W – indirect determination vs measurement



UV physics: single field extensions of the SM

Single field extensions and m_W

- Consider single field extensions of the SM that can contribute at tree level to m_W , assuming that only a single coupling to the Higgs is present (catalogue given in [J. De Blas et al., JHEP 03 (2018) 109])

Model	Spin	SU(3)	SU(2)	U(1)	Parameters
S_1	0	1	1	1	(M_S, κ_S)
Σ	$\frac{1}{2}$	1	3	0	$(M_\Sigma, \lambda_\Sigma)$
Σ_1	$\frac{1}{2}$	1	3	-1	$(M_{\Sigma_1}, \lambda_{\Sigma_1})$
N	$\frac{1}{2}$	1	1	0	(M_N, λ_N)
E	$\frac{1}{2}$	1	1	-1	(M_E, λ_E)
B	1	1	1	0	(M_B, \hat{g}_H^B)
B_1	1	1	1	1	(M_{B_1}, λ_{B_1})
Ξ	0	1	3	0	(M_Ξ, κ_Ξ)
W_1	1	1	3	1	$(M_{W_1}, \hat{g}_{W_1}^\phi)$
W	1	1	3	0	(M_W, \hat{g}_W^H)

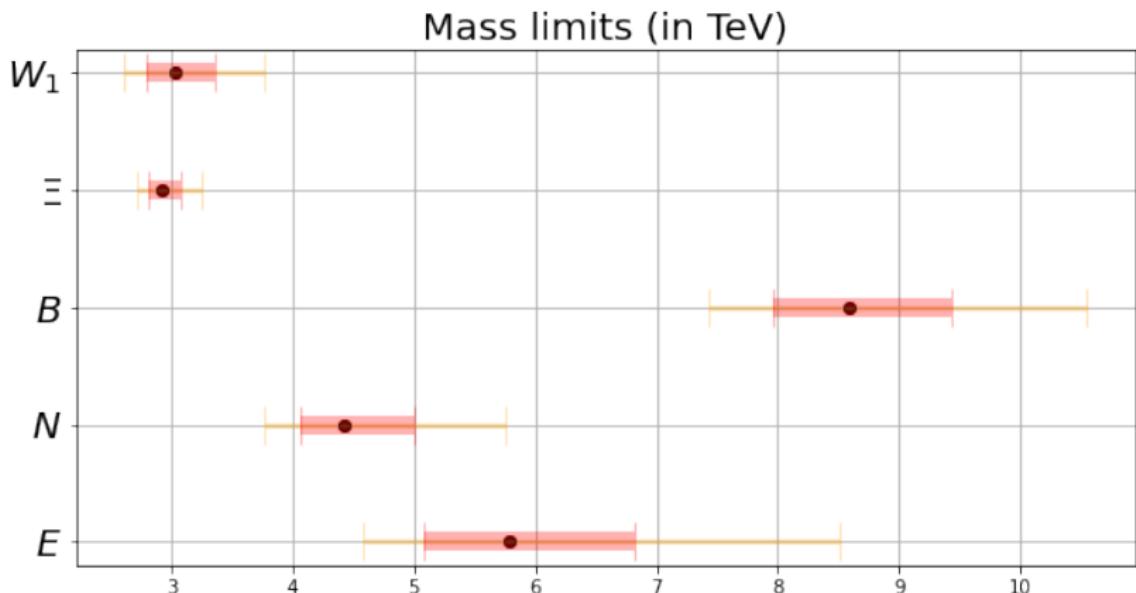
Single field extensions and m_w

Model	C_{HD}	C_{II}	$C_{HI}^{(3)}$	$C_{HI}^{(1)}$	C_{He}	$C_{H\square}$	$C_{\tau H}$	C_{tH}	C_{bH}
S_1		-1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$y_\tau \frac{1}{4}$		
Σ_1			$\frac{1}{16}$	$-\frac{3}{16}$			$y_\tau \frac{1}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$y_\tau \frac{1}{2}$		
B_1	1					$-\frac{1}{2}$	$-y_t \frac{1}{2}$	$-y_t \frac{1}{2}$	$-y_b \frac{1}{2}$
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	$-\frac{1}{4}$					$-\frac{1}{8}$	$-y_t \frac{1}{8}$	$-y_t \frac{1}{8}$	$-y_b \frac{1}{8}$
W	$\frac{1}{2}$					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

- No single-field models contribute at tree level to C_{HWB}
- Only S_1 contributes to C_{II}
- Five single-field models contribute to C_{HD} , and four to $C_{HI}^{(3)}$ (these models also contribute to other operators)
- Models grayed-out can not explain the observed m_w value (wrong sign contribution)

Mass range for the preferred models

- Mass range obtained assuming unit coupling



Conclusions and outlook

Conclusions and outlook

Outcome

- We have shown that a large m_W value as implied by the CDF measurement is compatible with new-physics as parameterized by dimension-6 operators, without any tension with Higgs, diboson and EW precision data
- Fit qualities are good
- Several single-field extensions of the SM could explain this measurement

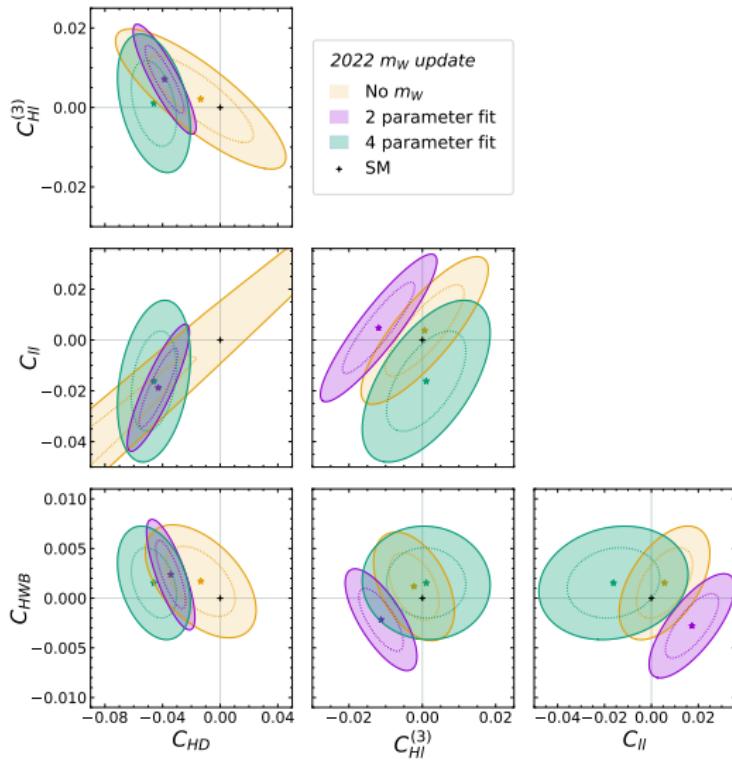
Future prospects

- Inclusion of SMEFT operator running
- Study of more complex and more motivated UV models

EWPO, H diboson	Previous m_W	Combined m_W	Parameter Count	N_{dof}	χ^2/dof	$p\text{-value}$
✓			20	182	0.92	0.76
✓	✓		20	185	0.93	0.75
✓		✓	20	185	0.97	0.59
✓			4	198	0.93	0.76
✓	✓		4	201	0.93	0.75
✓		✓	4	201	0.97	0.60

Backup slides

2D planes – correlations

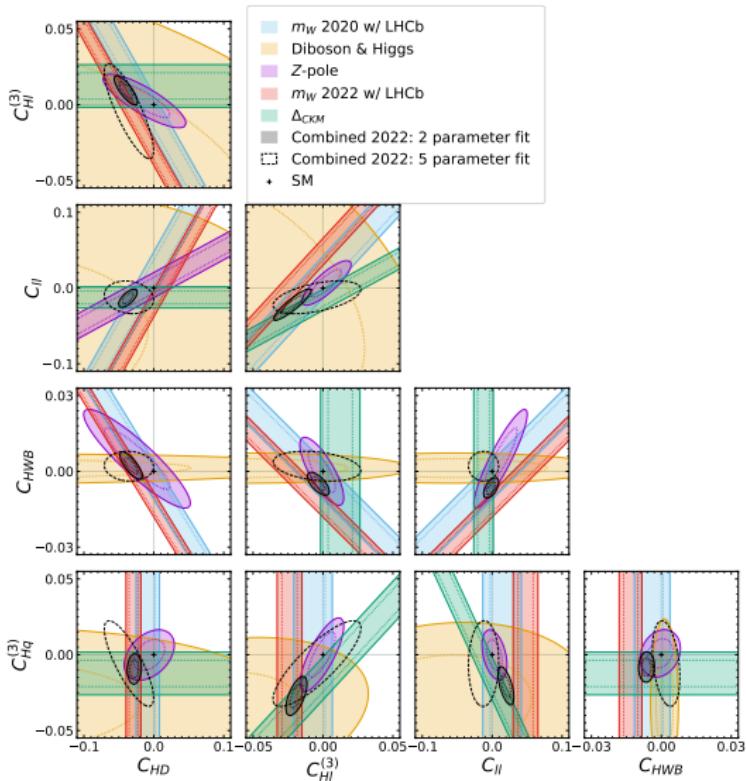


Fit qualities

EWPO, H diboson	Previous m_W	Combined m_W	Parameter Count	N _{dof}	χ^2/dof	p-value
✓			20	182	0.92	0.76
✓	✓		20	185	0.93	0.75
✓		✓	20	185	0.97	0.59
✓			4	198	0.93	0.76
✓	✓		4	201	0.93	0.75
✓		✓	4	201	0.97	0.60

- Results show for three choices: without any m_w measurements; with the pre-CDF m_w combinations; combination including the CDF result
- In all cases we have a $\chi^2/\text{dof} < 1$ and p-values $> 0.5 \rightarrow$ good description of the data in all cases

2D planes – correlations



Fit qualities

EWPO, H diboson	Previous m_W	Combined m_W	Δ_{CKM}	Parameter Count	N_{dof}	χ^2/dof	$p\text{-value}$
✓			✓	20	183	0.94	0.71
✓	✓		✓	20	186	0.93	0.74
✓		✓	✓	20	186	0.98	0.56
✓			✓	4	199	0.93	0.74
✓	✓		✓	4	202	0.93	0.75
✓		✓	✓	4	202	0.97	0.62

- Results show for three setup: without any m_W measurements; with the pre-CDF m_W combinations; combination including the CDF result
- As before, in all cases we have a $\chi^2/\text{dof} < 1$ and $p\text{-values} > 0.5 \rightarrow$ good description of the data in all cases

Mass and coupling range for the preferred models

- Mass range obtained assuming unit coupling
- Coupling range obtained assuming 1 TeV mass

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]