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

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24 June 2022

KIAS workshop on physics beyond the Standard Model in light of the CDF W boson mass anomaly

online

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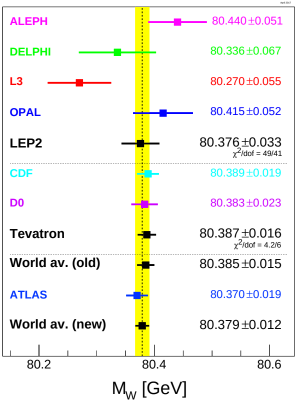
[2204.05260]

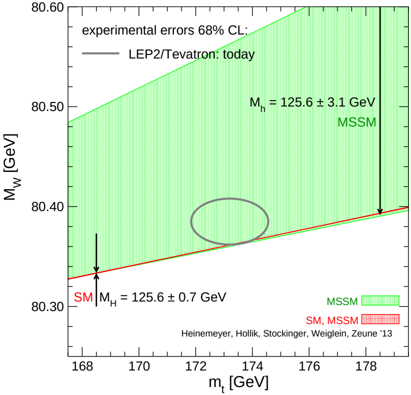
Introduction

The physics case for the W mass

- The M_W mass measurement is one of the important items of the SM precision program at colliders
- The value of M_W is important to understand the consistency of the SM and to constrain new physics



[PDG 2021]



[1311.1663]

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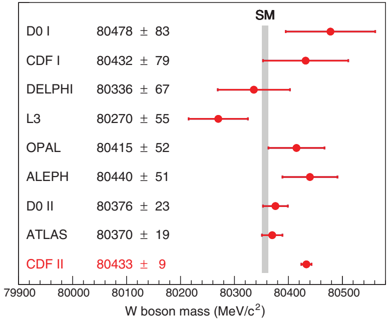
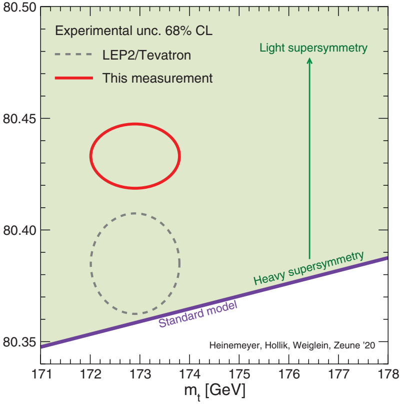


[CDF collaboration, Science 376 (2022) 6589, 170-176]



The CDF measurement and new physics models

- The new CDF measurement has created a huge interest in the community
- Still open questions on the measurement itself → see J. Isaacson's talk
- $\mathcal{O}(xx)$ articles have been published discussing BSM perspectives

Explicit models

- MRSSM [Athron et al. 2204.05285] – See D. Stöckinger's talk
- 2HDMs [J. Kim et al. 2205.0170] – See J. Song talk
- Dark sector with a Stueckelberg-Higgs portal [2204.09024] – See Z. Liu's talk
- NMSSM [Pang et al. 2204.04356]
- RH neutrinos [Blennow et al. 2204.04559]

EFT/generic analyses

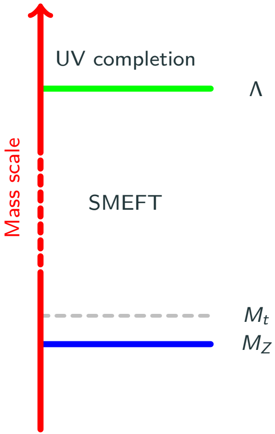
- SMEFT – See R. Gupta's talk [R. Gupta 2204.13690]
- SMEFT – See T. Liu's talk
- Higgs couplings – See S. Hong's talk
- EW fit/SMEFT [De Blas et al., 2204.04204; Strumia 2204.04191, Lu et al. 2204.03796...]

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) $\rightarrow$ particle content is the same as the SM
- Description of NP effects in terms higher-dimension operators $\rightarrow$ 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

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

- The shift in M_W is then given by

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

- 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

- $\{\alpha_{EW}, G_F, M_Z\}$
  $\alpha_{EW}^{-1} = 127.95$
  $G_F = 1.16638 \times 10^{-5}\ \text{GeV}^{-2}$
  $m_Z = 91.1876$ GeV
  [Brivio et al. 2111.12515]

Other input parameters

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

EWPOs

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

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

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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

Results

S & T fit

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

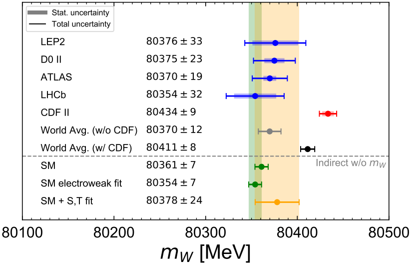
$$\frac{\alpha S}{4 s_W^2 c_W^2} = \left[\frac{\delta \Pi_{ZZ}(M_Z^2) - \delta \Pi_{ZZ}(0)}{M_Z^2} \right] - \frac{(c_W^2 - s_W^2)}{s_W c_W} \, \delta \Pi'_{Z\gamma}(0) - \delta \Pi'_{\gamma\gamma}(0)$$

$$\alpha T = \frac{\delta \Pi_{WW}(0)}{M_W^2} - \frac{\delta \Pi_{ZZ}(0)}{M_Z^2}$$

- 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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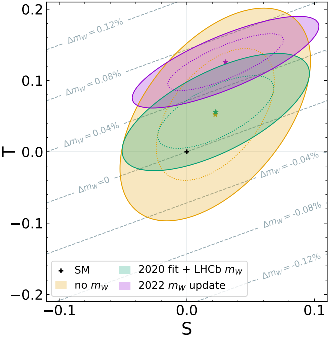


$SU(3)^5$ SMEFT fit: EWPO + Diboson + Higgs

- 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

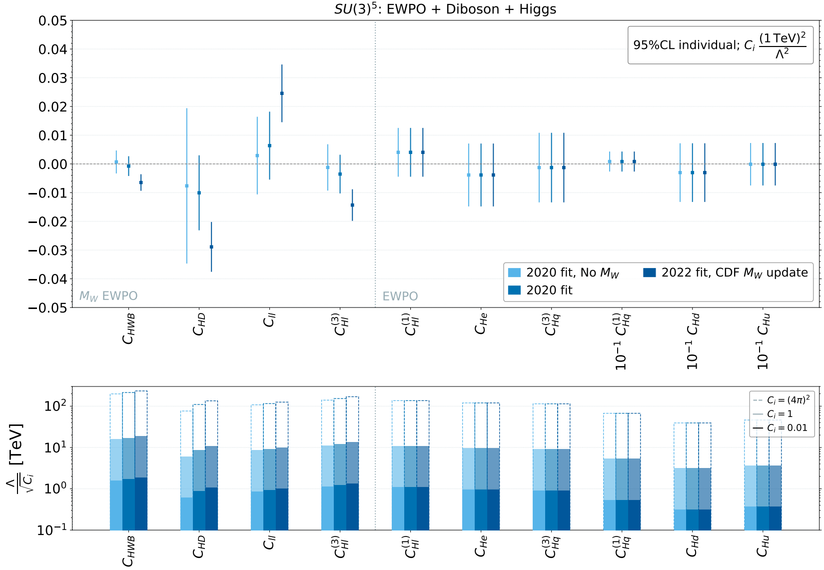
- **EWPOs**: constrained by Electroweak Precision Observables
- **Bosonic**: Higgs and diboson measurements
- **Yukawa**: operators that induce shifts in the Yukawa couplings

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

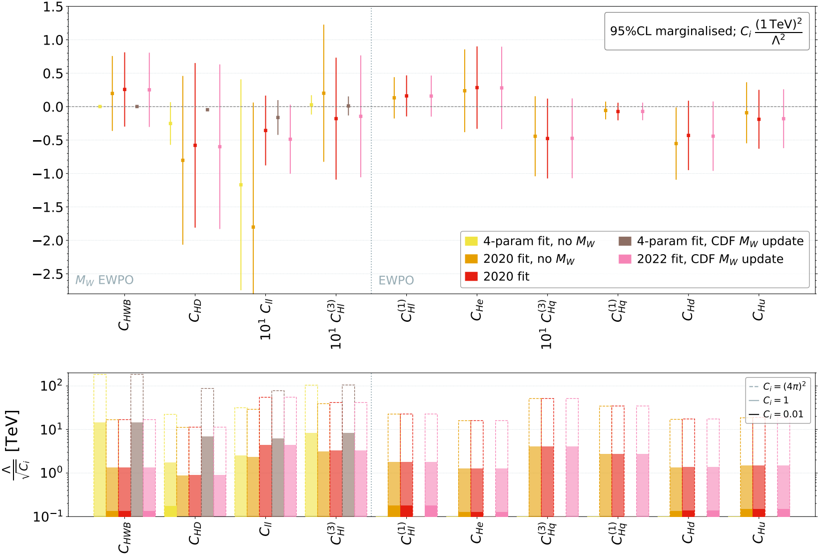
Bosonic $\rightarrow$ $\mathcal{O}_{H\Box}\,, \mathcal{O}_{HG}\,, \mathcal{O}_{HW}\,, \mathcal{O}_{HB}\,, \mathcal{O}_{W}\,, \mathcal{O}_{G}$

Yukawa $\rightarrow$ $\mathcal{O}_{\tau H}\,, \mathcal{O}_{\mu H}\,, \mathcal{O}_{bH}\,, \mathcal{O}_{tH}$

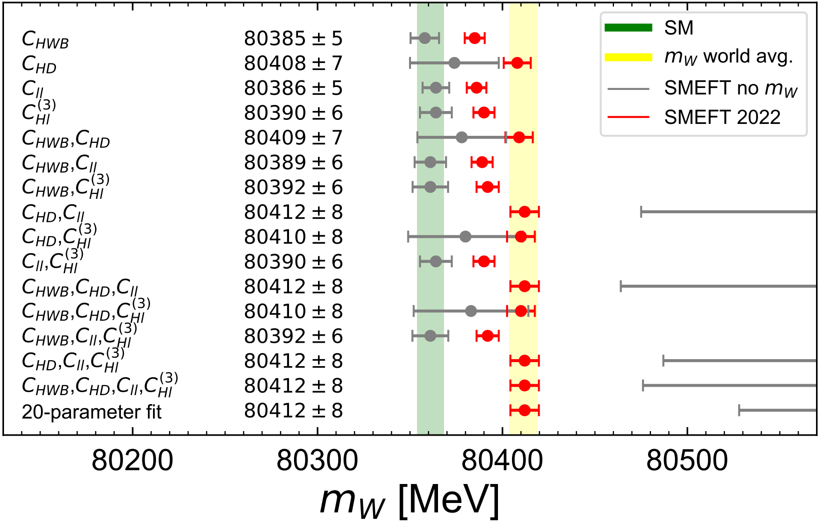
Fit result – individual coefficients



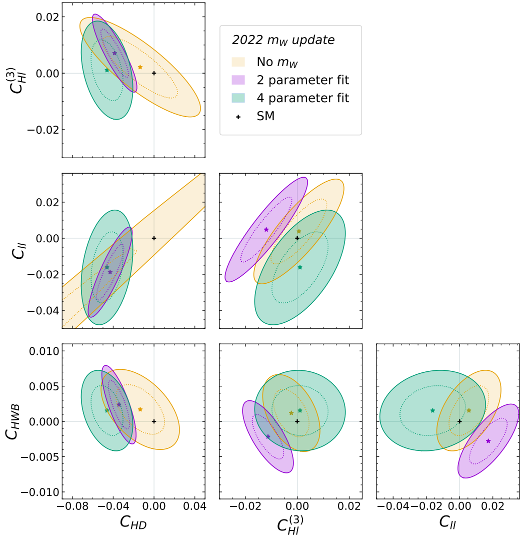
Fit result – marginalised coefficients



M_W – preferred range from the fits



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

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

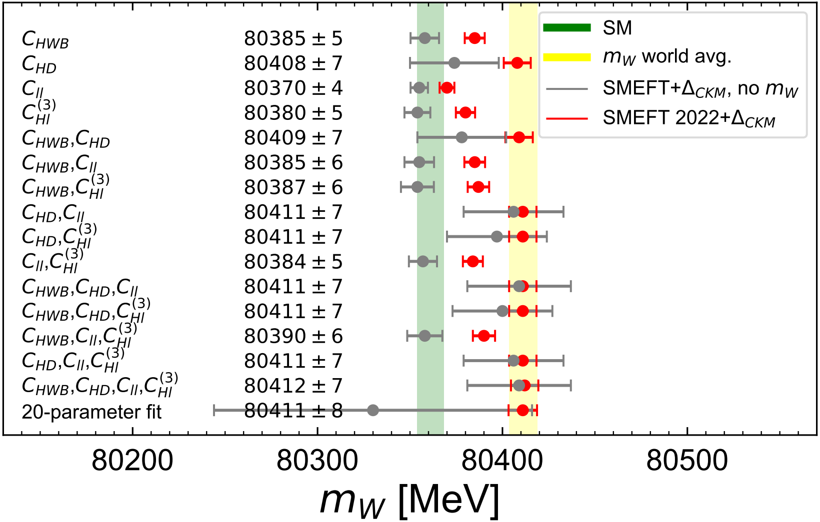
$$\Delta_{CKM} = 2\frac{v^2}{\Lambda^2}\left[C_{Hq}^{(3)} - C_{H\ell}^{(3)} + C_{\ell\ell} - C_{\ell q}^{(3)}\right]$$

- Measurements of $0^+ \to 0^+$ 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 – preferred range from the fits



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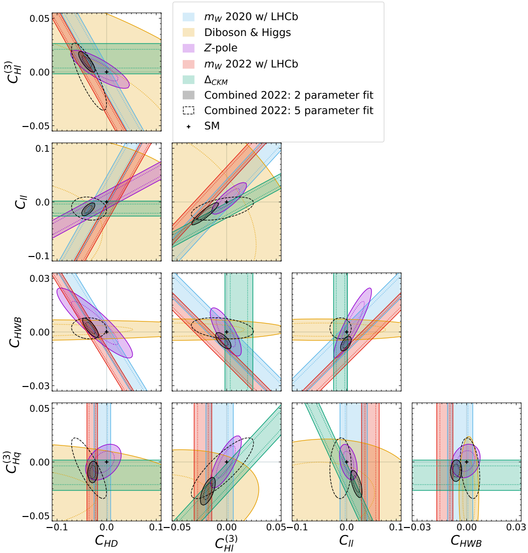

Fit qualities

EWPO, H diboson	Previous m_W	Combined m_W	Δ_{CKM}	Parameter Count	$\mathrm{N_{dof}}$	χ^2/dof	p-value
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✓	✓		✓	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 $\chi^2/\mathrm{dof} < 1$ and p-values $> 0.5 \rightarrow$ good description of the data in all cases

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	$(M_S,\ \kappa_S)$
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	$(M_{W_1}, \hat{g}^\phi_{W_1})$
W	1	1	3	0	$(M_W, \hat{g}_W^H)$

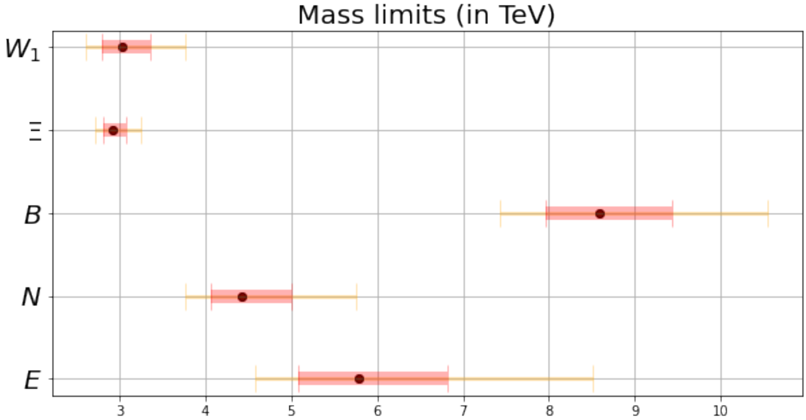
Single field extensions and M_W

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	$\frac{1}{2}$					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

- No single-field models contribute at tree level to C_{HWB}
- Only S1 contributes to C_{ll}
- Five single-field models contribute to C_{HD} , and four to $C_{Hl}^{(3)}$ (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



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]

Conclusions and outlook

Conclusions and outlook

Study 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 (see R. Gupta talk)
- Study of more complex and more motivated UV models

EWPO, H diboson	Previous m_W	Combined m_W	Parameter Count	$N_{\rm dof}$	$\chi^2/{\rm dof}$	p-value
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