SMEFT Analysis of m_W

Status of the Standard Model

CDF measurement of m_W

Reminder of the SMEFT approach

SMEFT analysis of m_W

Favoured BSM scenarios

How to detect them?

John Ellis

KING'S College LONDON

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Where are we now?

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L E_R	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$ $e^-_R \ , \ \mu^-_R \ , \ \tau^-_R$	$(\mathbf{1},\mathbf{2},-1)$ $(\mathbf{1},\mathbf{1},-2)$
Q_L U_R D_R	$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L$ $u_R \ , \ c_R \ , \ t_R$ $d_R \ , \ s_R \ , \ b_R$	$(\mathbf{3},\mathbf{2},+1/3)$ $(\mathbf{3},\mathbf{1},+4/3)$ $(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

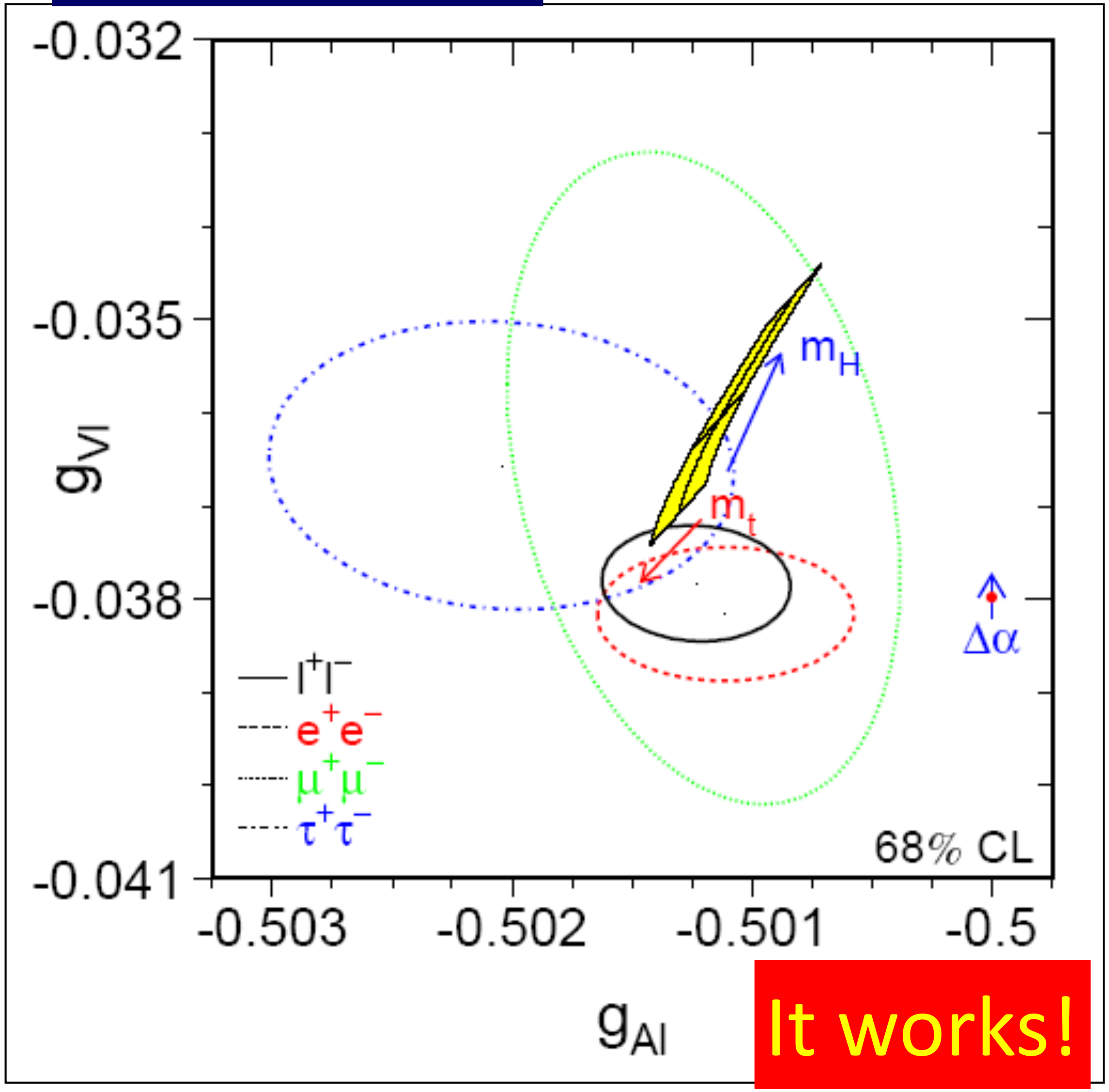
$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} && \text{gauge interactions} \\ &+ i\bar{\psi} \not{D} \psi + h.c. && \text{matter fermions} \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions} \\ &+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential} \end{aligned}$$

Tested < 0.1% before LHC

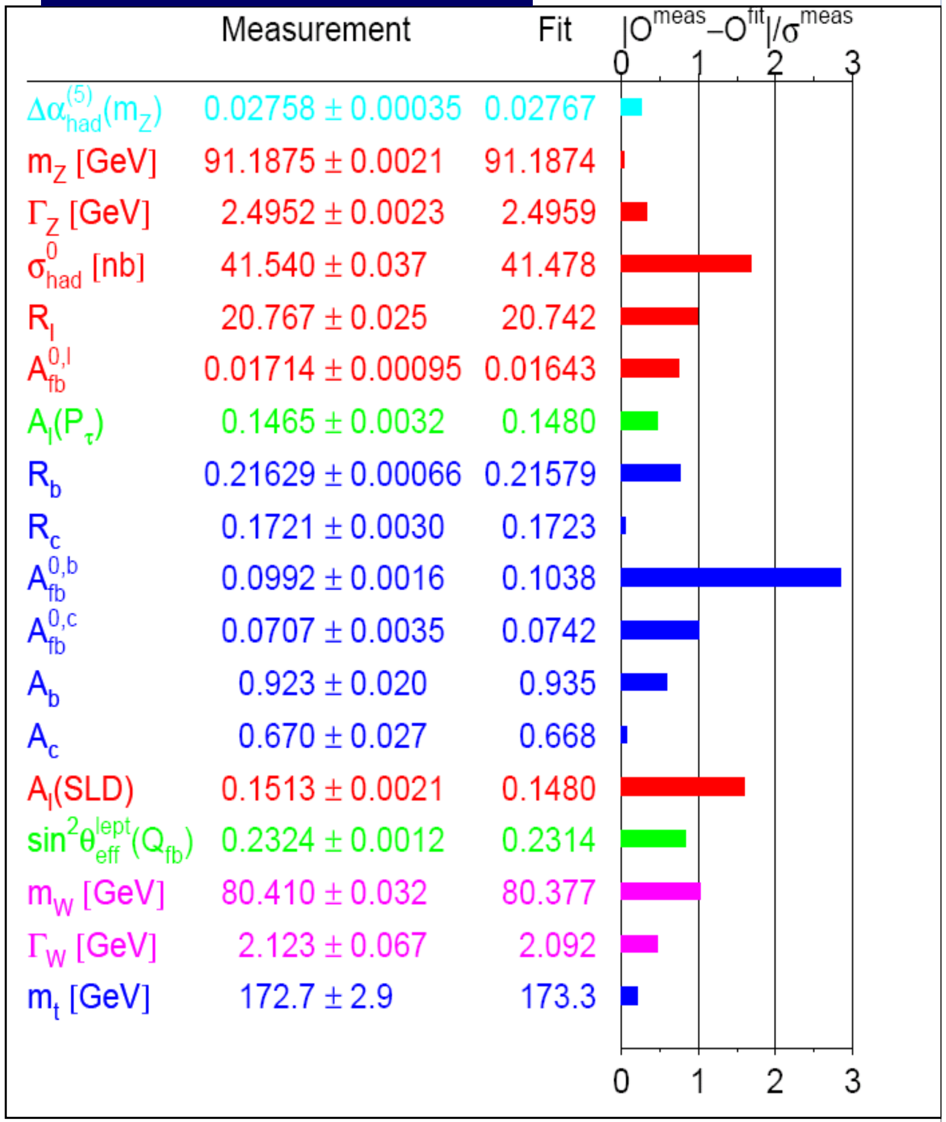
Testing now in progress

Precision Tests of the Standard Model

Lepton couplings

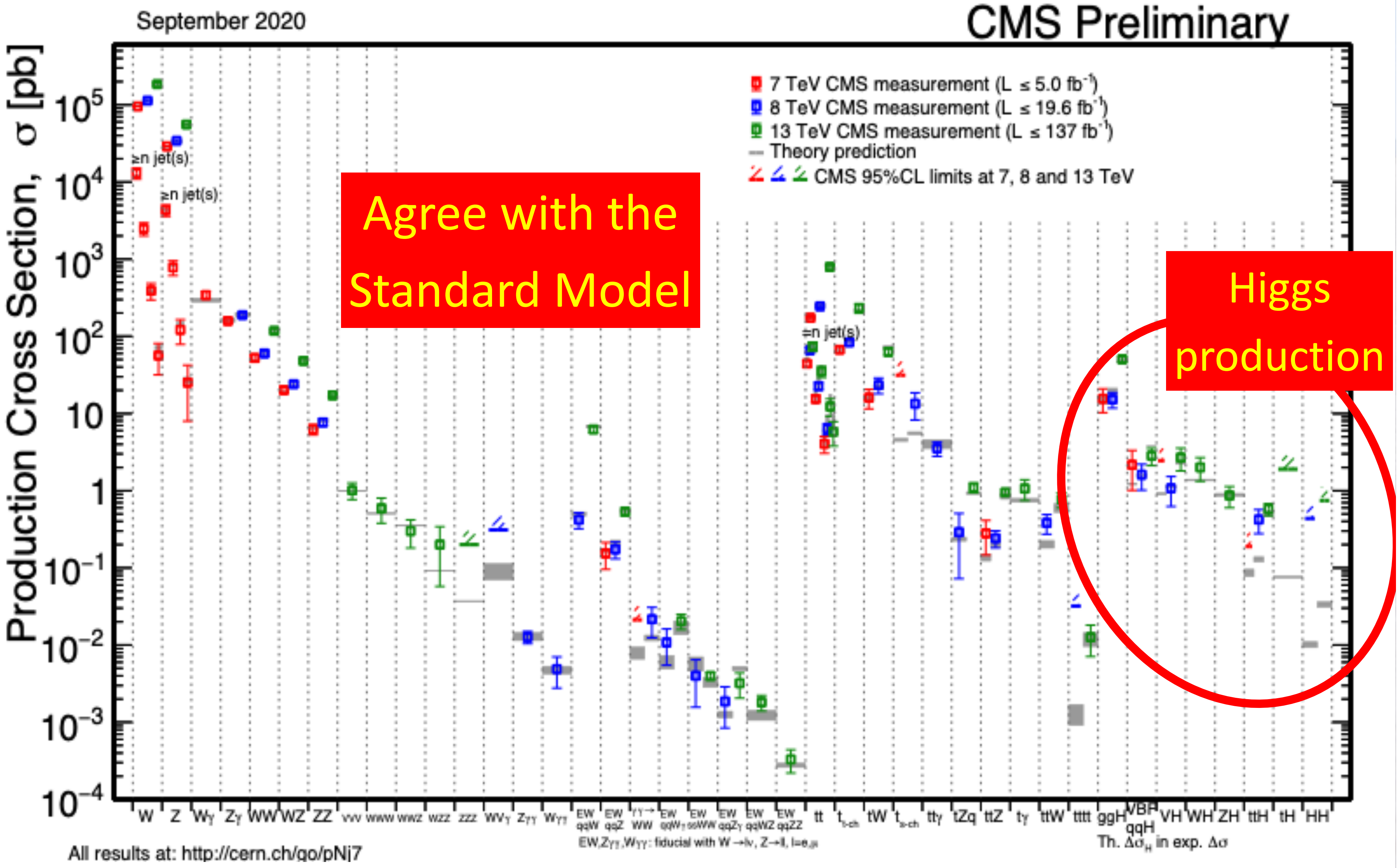


Pulls in global fit



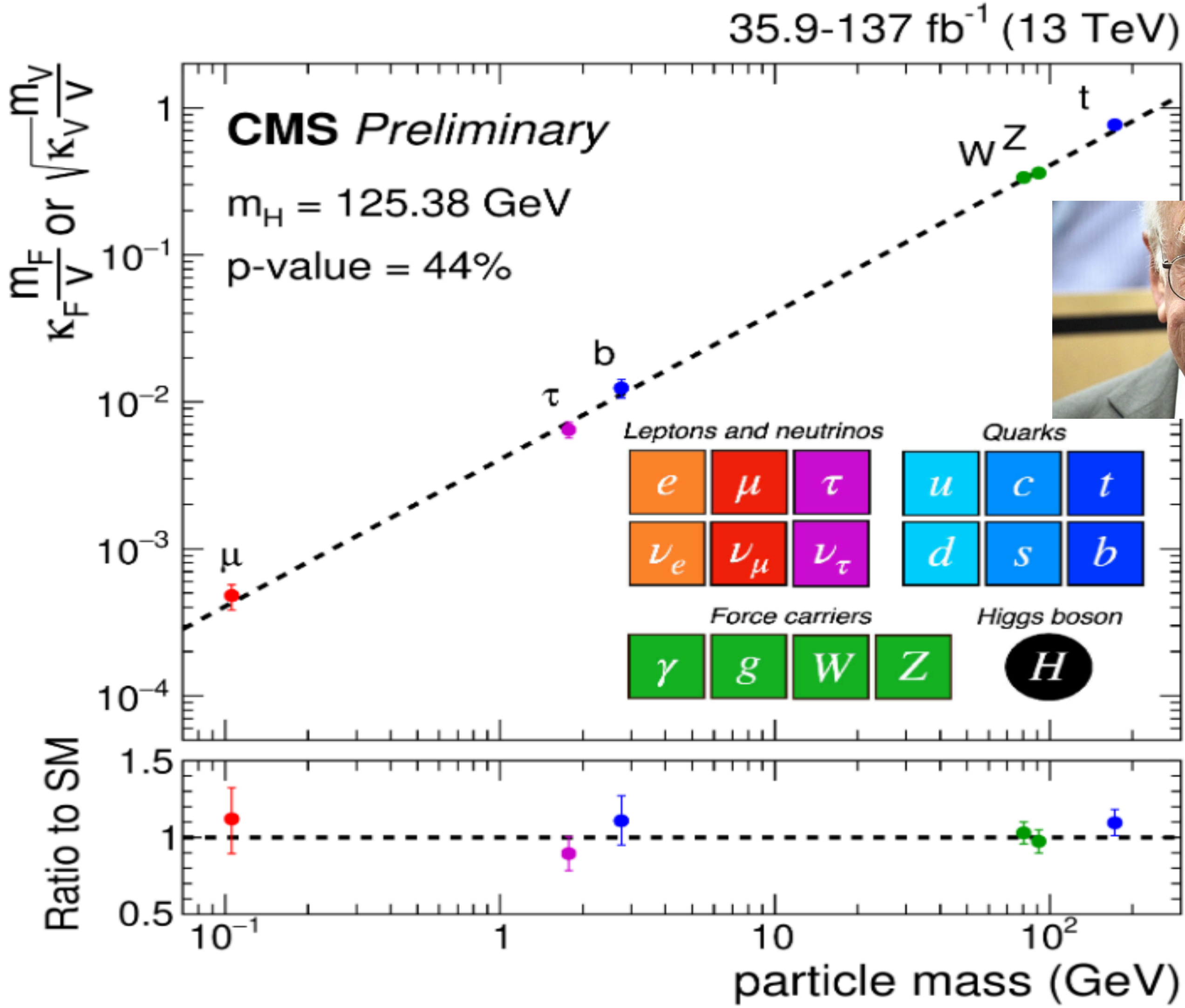
It works!

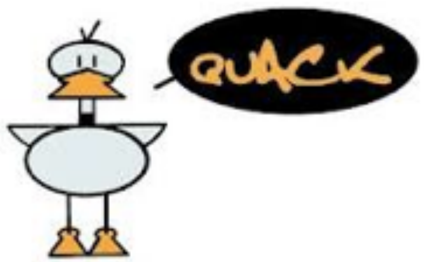
LHC Measurements



It Walks and Quacks like a Higgs

- Couplings scale ~ mass, with scale ~ v





Global fit

CDF Collaboration, Science 376 (2022) p170

PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration†‡, T. Aaltonen[1,2], S. Amerio[3,4], D. Amidei[5], A. Anastassov[6], A. Annovi[7], J. Antos[8,9], G. Apollinari[6], J. A. Appel[6], T. Arisawa[10], A. Artikov[11], J. Asaadi[12], W. Ashmanskas[6], B. Auerbach[13], A. Aurisano[12], F. Azfar[14], W. Badgett[6], T. Bae[15,16,17,18,19,20,21], A. Barbaro-Galtieri[22], V. E. Barnes[23], B. A. Barnett[24], P. Barria[25,26], P. Bartos[8,9], M. Bauce[3,4], F. Bedeschi[25], S. Behari[6], G. Bellettini[25,27], J. Bellinger[28], D. Benjamin[29], A. Beretvas[6], A. Bhatti[30], K. R. Bland[31], B. Blumenfeld[24], A. Bocci[29], A. Bodek[32], D. Bortoletto[23], J. Boudreau[33], A. Boveia[34], L. Brigliadori[35,36], C. Bromberg[37], E. Brucken[1,2], J. Budagov[11]§, H. S. Budd[32], K. Burkett[6], G. Busetto[3,4], P. Bussey[38], P. Butti[25,27], A. Buzatu[38], A. Calamba[39], S. Camarda[40], M. Campanelli[41], B. Carls[42], D. Carlsmith[28], R. Carosi[25], S. Carrillo[43]§, B. Casal[44], M. Casarsa[45], A. Castro[35,36], P. 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Giakoumopoulou[57], K. Gibson[33], C. M. Ginsburg[6], N. Giokaris[57]§, P. Giromini[7], V. Glagolev[11], D. Glenzinski[6], M. Gold[58], D. Goldin[12], A. Golossanov[6], G. Gomez[44], G. Gomez-Ceballos[59], M. Goncharov[59], O. González López[55], I. Gorelov[58], A. T. Goshaw[29], K. Goulianos[30], E. Gramellini[35], C. Grosso-Pilcher[34], J. Guimaraes da Costa[46], S. R. Hahn[6], J. Y. Han[32], F. Happacher[7], K. Hara[60], M. Hare[61], R. F. Harr[52], T. Harrington-Taber[6], K. Hatakeyama[31], C. Hays[14], J. Heinrich[62], M. Herndon[28], A. Hocker[6], Z. Hong[12], W. Hopkins[6], S. Hou[49], R. E. Hughes[63], U. Husemann[64], M. Hussein[37], J. Huston[37], G. Introzzi[25,65,66], M. Iori[56,67], A. Ivanov[50], E. James[6], D. Jang[39], B. Jayatilaka[6], E. J. Jeon[15,16,17,18,19,20,21], S. Jindariani[6], M. Jones[23], K. K. Joo[15,16,17,18,19,20,21], S. Y. Jun[39], T. R. Junk[6], M. Kambeitz[68], T. Kamon[15,16,17,18,19,20,21,12], P. E. Karchin[52], A. Kasmi[31], Y. Kato[69], W. 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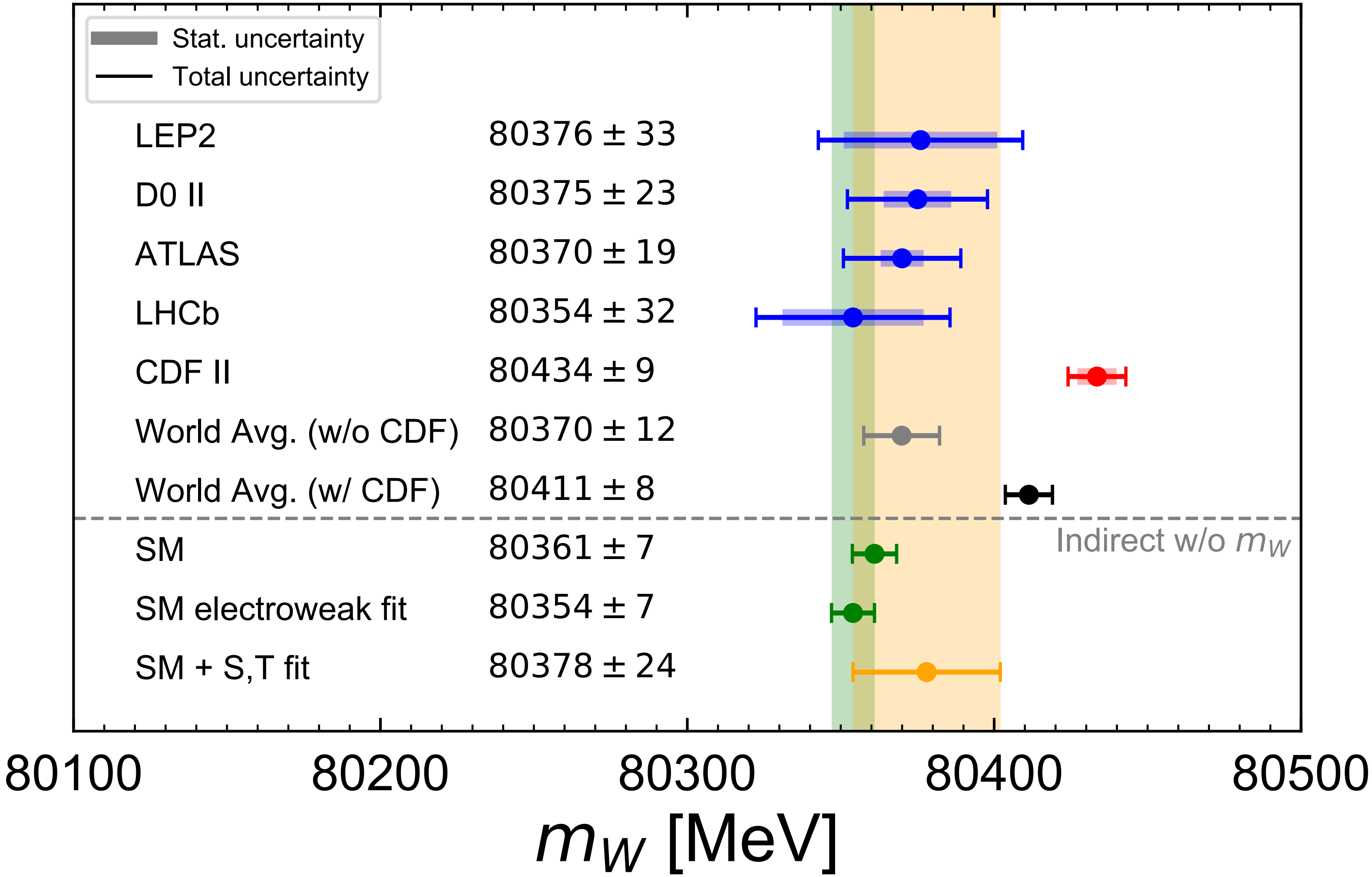
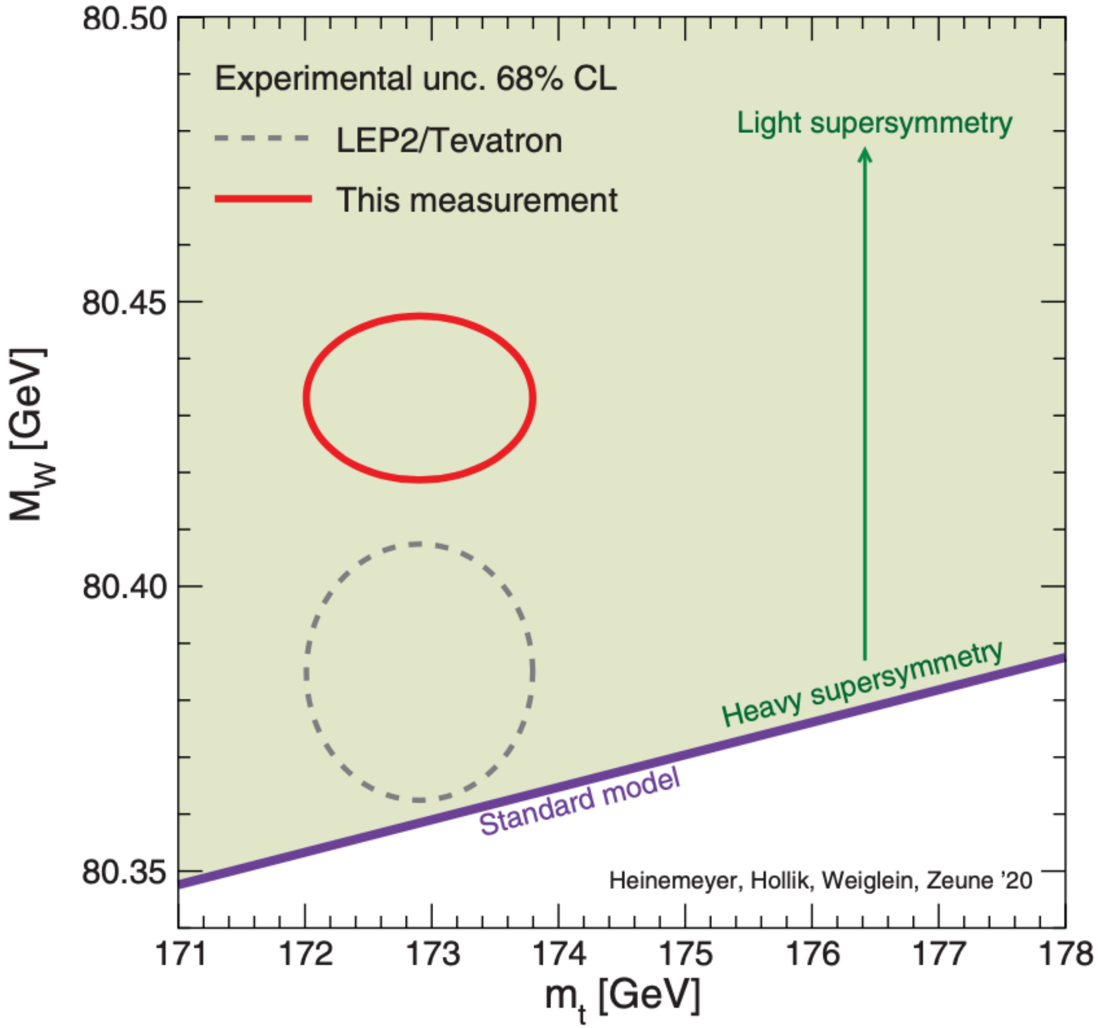
CDF Measurement of m_W

compared with previous measurements



Tension: 7-σ discrepancy with Standard Model?

CDF Measurement of the Mass of the W Boson



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

Biggest uncertainties: lepton energy, p_T model, parton distributions, backgrounds

CDF Collaboration, Science 376 (2022) p170

CDF Measurement of the Mass of the W Boson

Table 1. Individual fit results and uncertainties for the M_W measurements. The fit ranges are 65 to 90 GeV for the m_T fit and 32 to 48 GeV for the p_T^ℓ and p_T^ν fits. The χ^2 of the fit is computed from the expected statistical uncertainties on the data points. The bottom row shows the combination of the six fit results by means of the best linear unbiased estimator (*66*).

Distribution	*W* boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80{,}429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^\ell(e)$	$80{,}411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^\nu(e)$	$80{,}426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu,\nu)$	$80{,}446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^\ell(\mu)$	$80{,}428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^\nu(\mu)$	$80{,}428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

Small differences for measurements with electrons and muons

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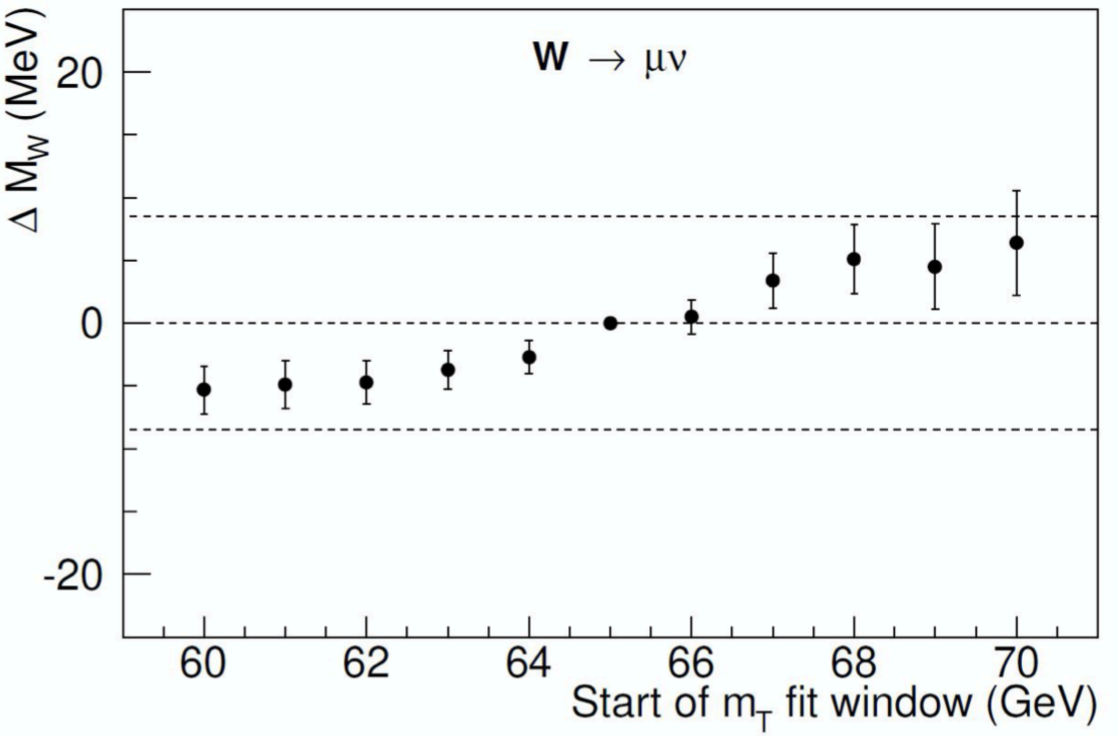
Dependence of W Mass on m_T Fit Window



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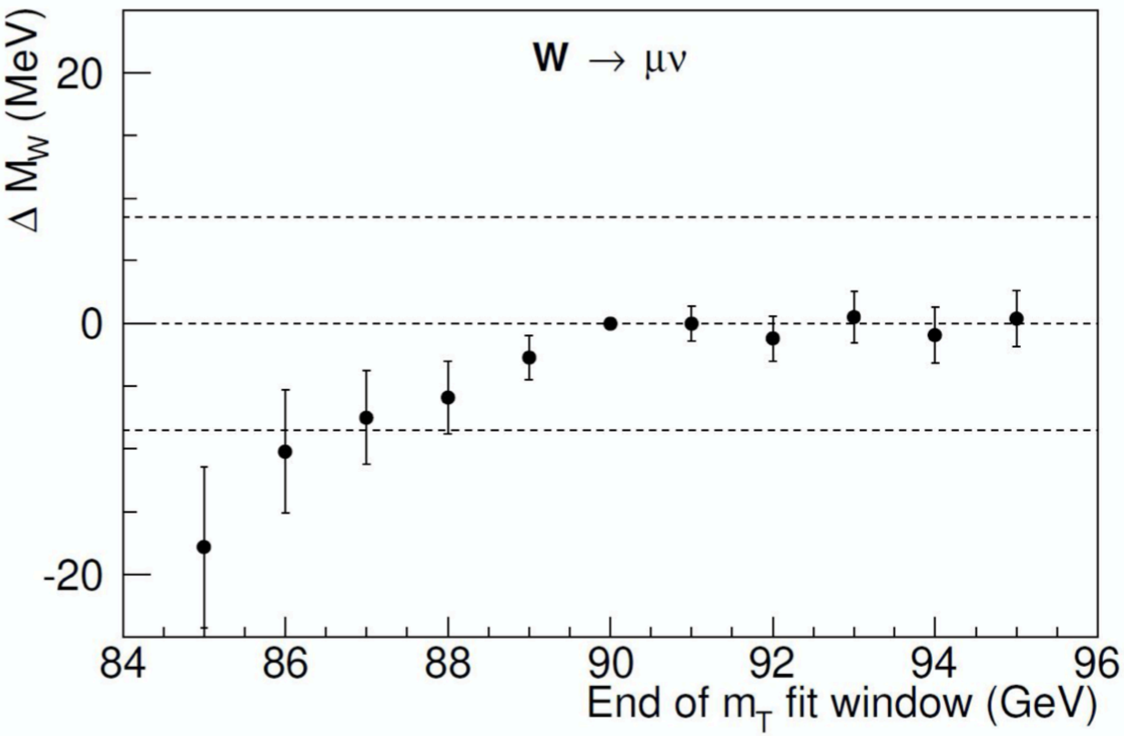

- Smaller mass in muon channel if lower range of m_T in fit
- Smaller mass possible if number of “one-legged” Z bosons underestimated

Tomaso Rodrigo

Accuracy of Muon Momentum Measurement?

- Momentum calibration using $Z, J/\Psi, \Upsilon$
- Larger uncertainty at smaller p_T^μ ?

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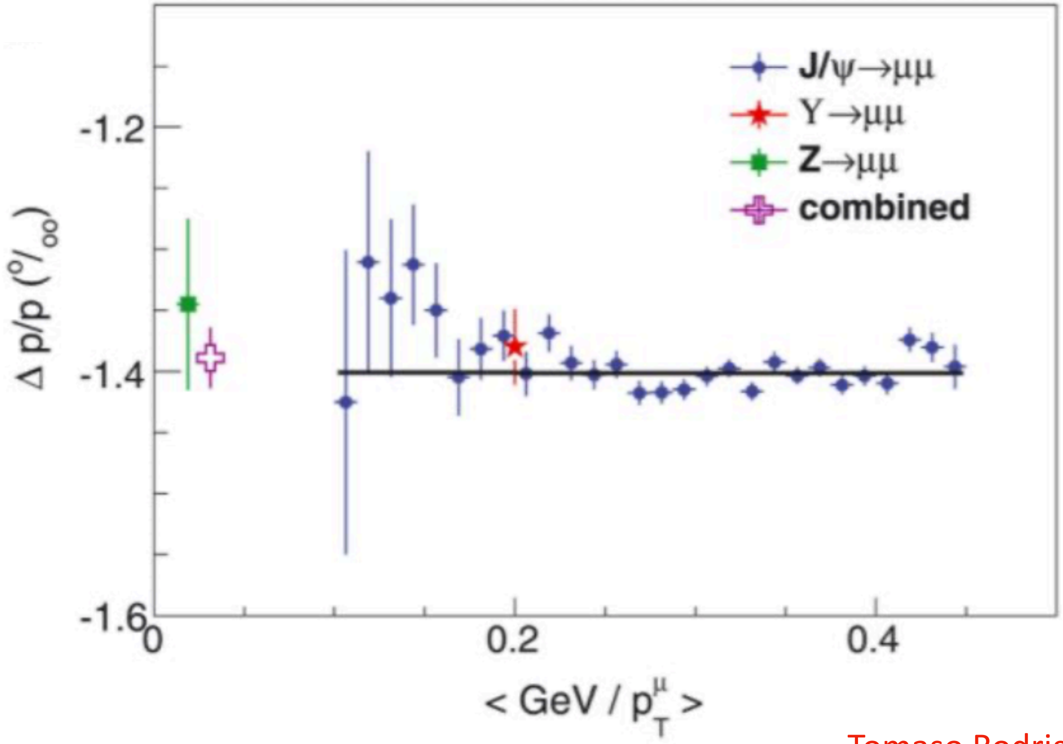
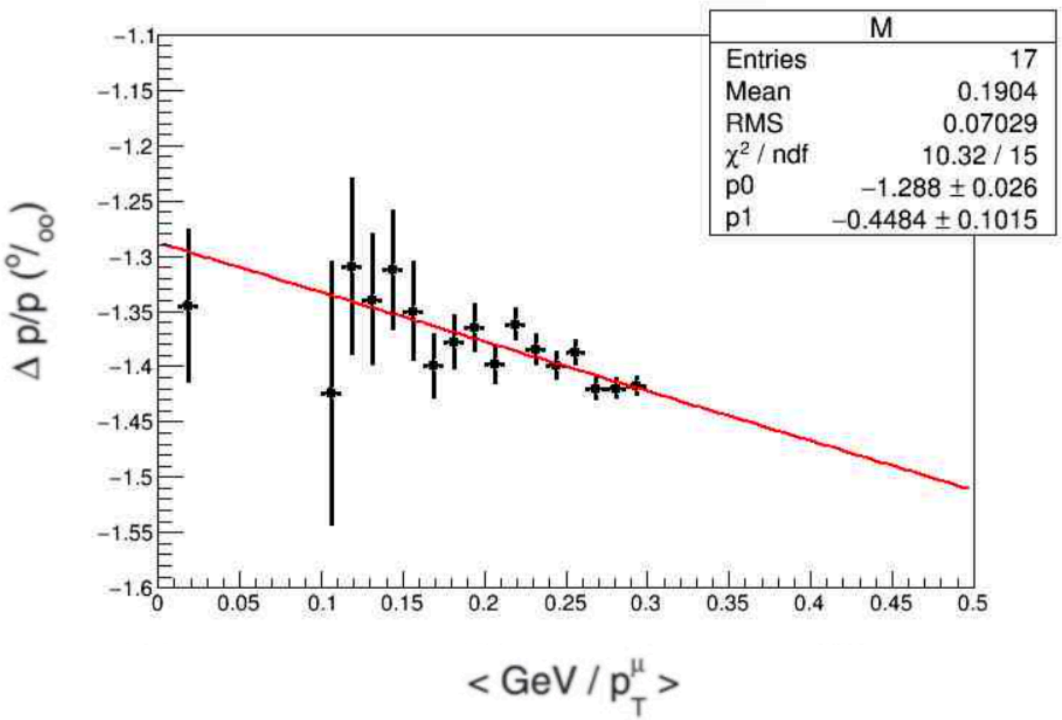


Tomaso Rodrigo



Model for W Boson Production and Decay

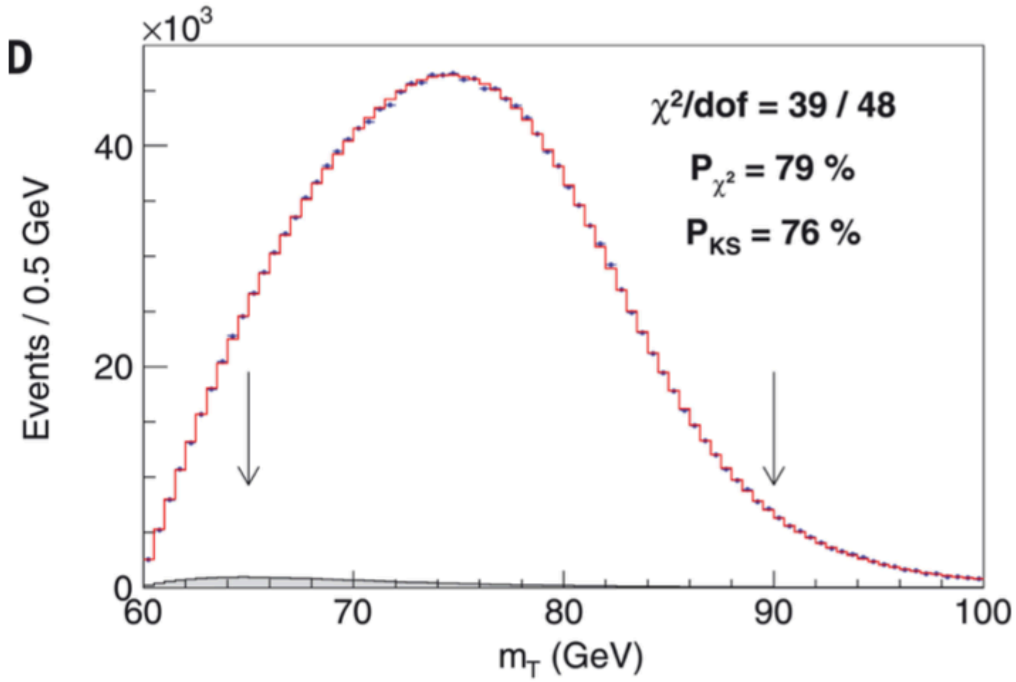
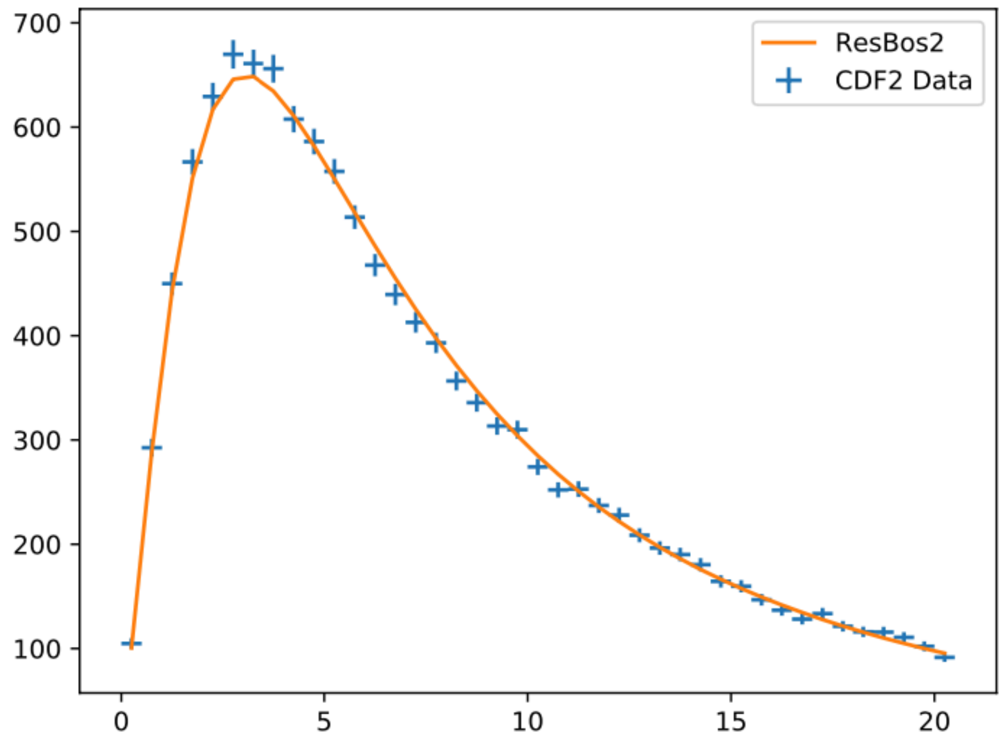


Figure reproduced from CDF-II measurement (Science 376, 170).

- Can't measure invariant mass directly due to neutrino
- Look at sensitive observables
  - $M_T = \sqrt{2\left(p_T^\ell p_T^\nu - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu}\right)}$
  - p_T^ℓ
  - p_T^ν with $(\vec{p}_T^{\,\nu} = -\vec{p}_T^{\,\ell} - \vec{u}_T)$
- Requires precise theory calculation
- Fit theory templates with varying M_W

Model for W Boson Production and Decay

- Perturbative series has terms proportional to $\alpha_s^n \log^{2n}\left(\frac{p_T^2}{M_W^2}\right)$
- As $p_T^W \to 0$ the series no longer converges
- Need to include corrections to all orders by resumming the series

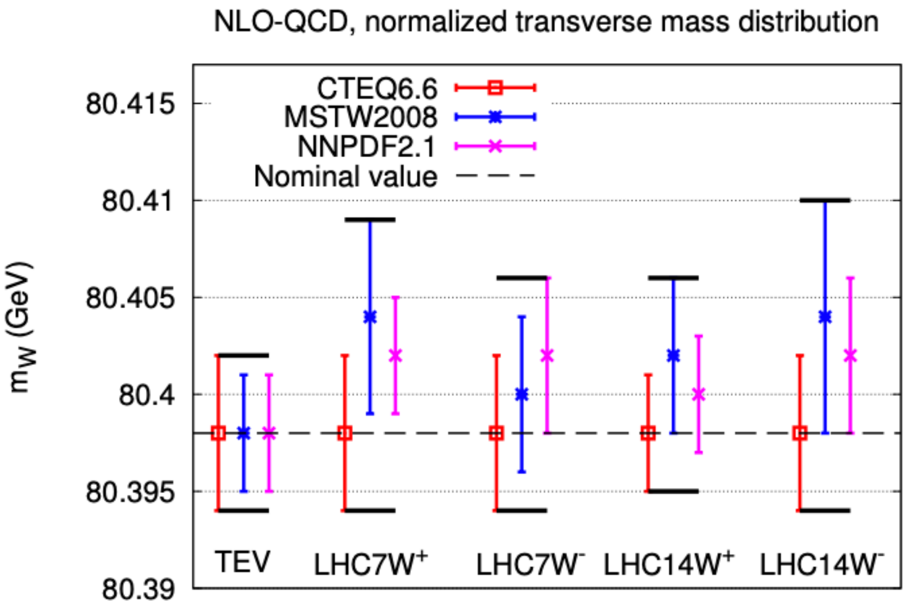


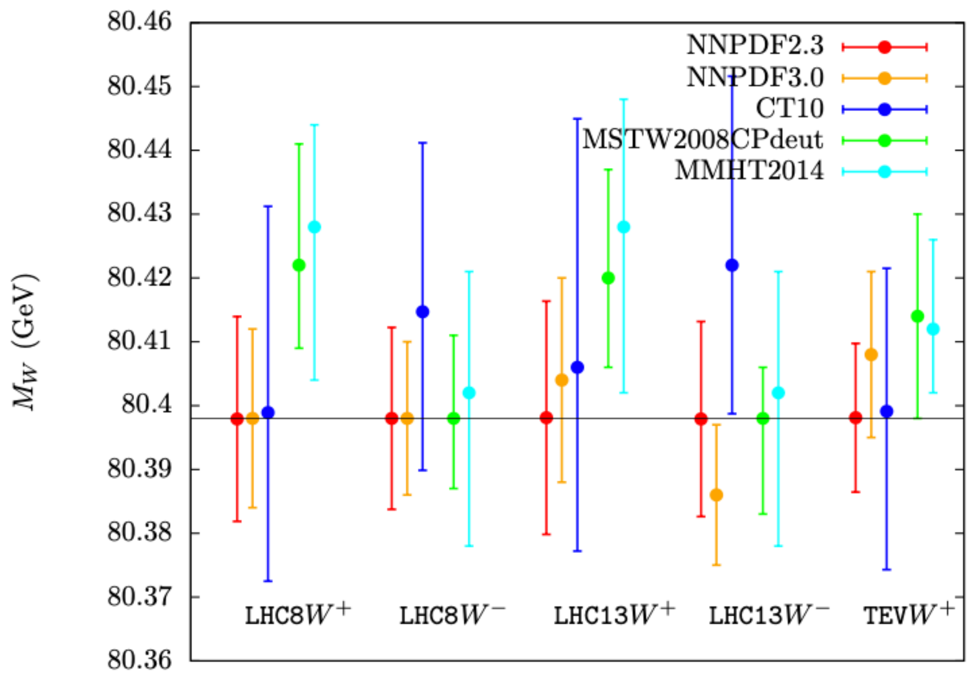
Status of Perturbative Calculations

Order	Boundary Condition	Anomalous Dimension γ_i (non-cusp)	Γ_{cusp}, β	Fixed Order Matching
LL	1	-	1-loop	-
NLL	1	1-loop	2-loop	-
NLL' (+ NLO)	α_s	1-loop	2-loop	α_s
NNLL (+ NLO)	α_s	2-loop	3-loop	α_s
NNLL' (+ NNLO)	α_s^2	2-loop	3-loop	α_s^2
N^3LL (+ NNLO)	α_s^2	3-loop	4-loop	α_s^2
N^3LL' (+ N^3LO)	α_s^3	3-loop	4-loop	α_s^3
N^4LL' (+ N^3LO)	α_s^3	4-loop	5-loop	α_s^3

- ■ Accuracy used by CDF
- ■ Current accuracy available in ResBos code
- ■ All terms known to this accuracy

Sensitivity to Parton Distributions





Larger uncertainties when p_T^ℓ is used than with m_T

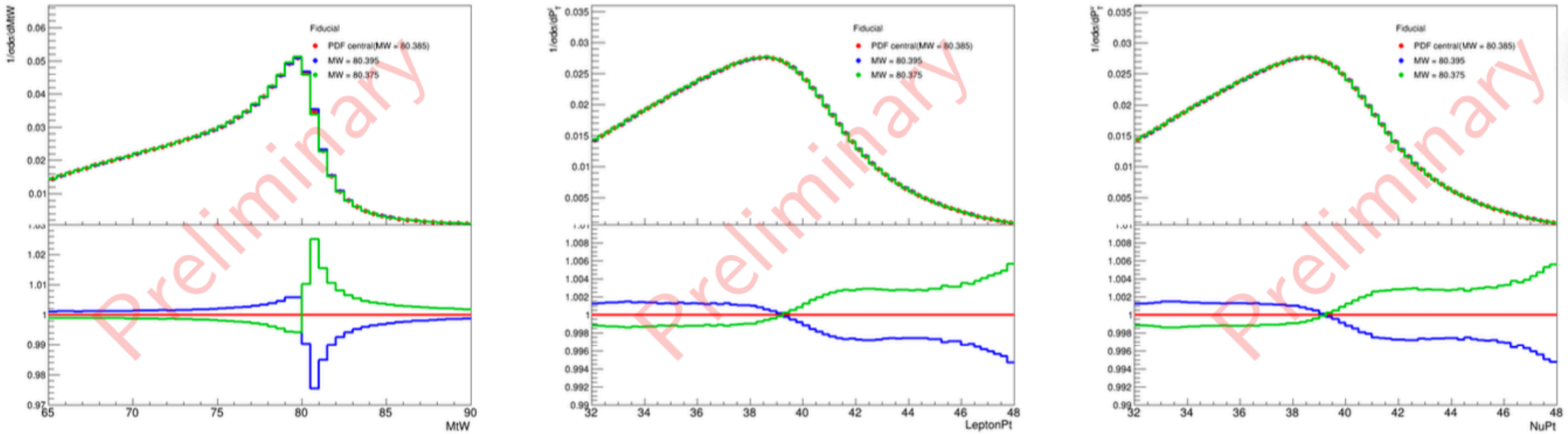
$\mathcal{O}(10)$ MeV variations possible

Larger at LHC than at Tevatron?

Different for $m_{W^\pm}$?

Sensitive to flavour-dependence in quark p_T

Sensitivity to Modelling



Disclaimers:

- Results are all preliminary
- Extraction of M_W uncertainty requires detailed fitting of templates
- Need to appropriately emulate data-driven approach from CDF

Prospects for LHC Measurement?

- Higher LHC energy implies more hadronic background per event
- Higher LHC luminosity generates more pile-up events
- Special low-pile-up run of HL-LHC?

Prospects for LHC Measurement?

- Higher LHC energy implies more hadronic background per event
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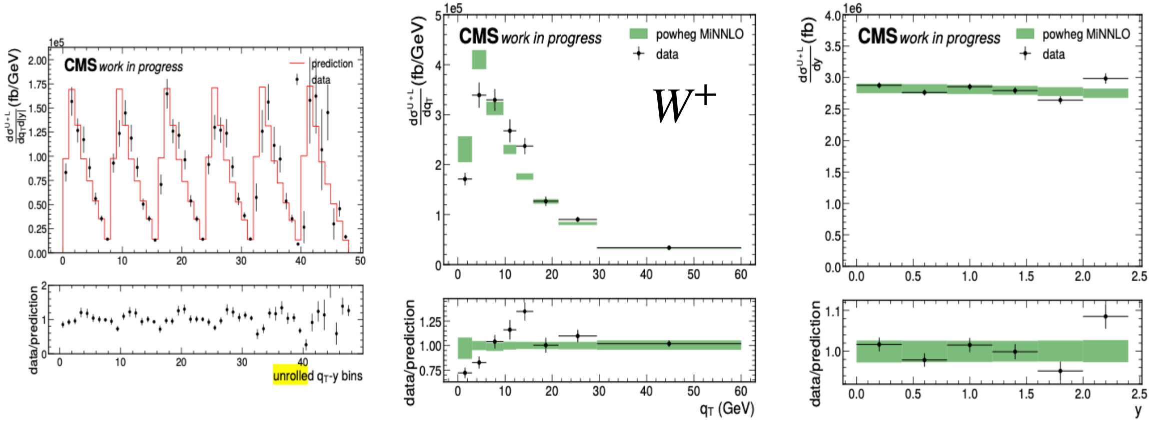
- **Stop Press!**

Manca & Rolandi, arXiv:2104.14015

- Study in CMS of potential sensitivity measuring the W double differential cross section in (p_T^μ, y)
- $\Delta m_W^\pm = 11.2, 16.1$ MeV, combined $\Delta m_W = 9$ MeV
- Not $\ni \Delta p_\mu$ scale, FSR



Theoretical Interpretations of W Mass

taking CDF measurement at face value

70 pairs and counting!

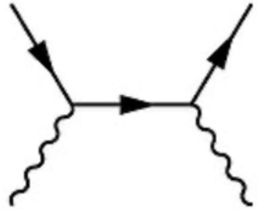
3667	DM	Zhu
3693	Inert H	Fan
3797	EWPO	Lu
3996	Relation to g-2	Athron
4183	Axion, chameleon	Yuan
4191	EWPO	Strumia
4202	SUSY	Yang
4204	EWPO	de Blas
4286	SUSY GMSB	Du
4356	SUSY NMSSM	Tang
4514	non-standard H	Cacciapaglia
4559	RH neutrinos	Blennow
4710	SUSY NMSSM	Cao
5031	Seesaw triplet	Cheng
5085	2HDM	Song
5260	SMEFT	Bagnaschi
5267	Custodial symm	Paul
5269	2HDM	Bahl
5283	S&T	Asadi
5284	Higgs physics	Di Luzio
5285	FlexibleSUSY	Athron
5296	S&T, SMEFT	Gu
5302	D3-Brane	Heckman
5303	2HDM	Babu
5728	2HDM	Heo
5760	Georgi-Machacek	Du
5942	Leptoquark	Cheung
5962	VL quarks	Crivellin
5965	Single-field	Endo
5975	2HDM + singlet	Biekötter
5992	SMEFT	Balkin
6327	Non-local SM	Krasnikov
6485	2HDM	Ahn
6505	2HDM	Han
6541	RPV MSSM	Zheng
7022	Lepton portal DM	kawamura
7144	Triplet H	Fileviez

7970	GUT, finite group	Wilson
8067	Extra U(1)	Zhang
8266	Seesaw	Borah
8390	Zee model	Chowdhury
8406	2HDM	Arcadi
8440	Beta decay	Cirigliano
8546	Oblique	Carpenter
8568	Seesaw	Popov
9001	2HDM	Ghorbani
9029	Stueckelberg	Du
9031	Leptoquarks	Bhaskar
9376	Triplet	Batra
9477	VLQ	Cao
9487	Extra U(1)	Zeng
9585	Extra U(1)	Baek
9671	DM fermions	Borah
10130	SMEFT	da Silva
10156	Dark photon	Cheng
10274	Triplet seesaw	Heeck
10375	FOPT triplet	Addazi
10338	2HDM	Lee
11570	Extra U(1)	Cai
11755	2HDM	Benbrik
11871	nu-lepton collider	Yang
11945	Scotogenic DM	Batra
11991	Atomic PV	Tran Tan
12018	2HDM	Abouabid
12453	Colour-octet	Gisbert
12898	Georgi-Machacek	Chen
13027	Extra U(1)	Zhou
13690	RG running	Gupta
2205.00758	Flipped SU(5)	Basiouris
783	DM	Wang

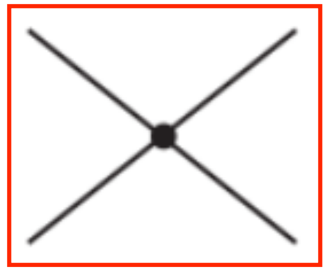
Effective Field Theories (EFTs)

a long and glorious History

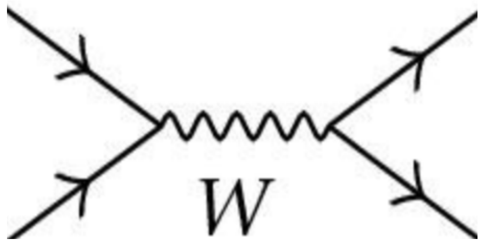
- 1930's: "Standard Model" of QED had d=4



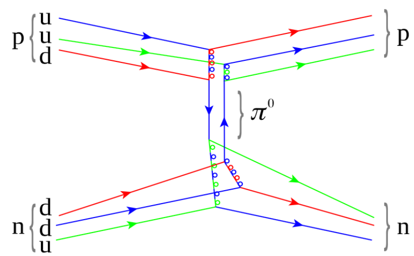
- **Fermi's four-fermion theory of the weak force**



- Dimension-6 operators: form = S, P, V, A, T?
  – Due to exchanges of massive particles?



- V-A ➔ massive vector bosons ➔ gauge theory



- Yukawa's meson theory of the strong N-N force
  – Due to exchanges of mesons? ➔ pions
- Chiral dynamics of pions: (∂π∂π)ππ clue ➔ QCD

Standard Model Effective Field Theory

a more powerful way to analyze the data

- Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
- Look for additional interactions between SM particles due to exchanges of heavier particles
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other experiments
- **Model-independent way to look for physics beyond the Standard Model (BSM) - and identify it?**

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Summary of Analysis Framework

- Include all leading dimension-6 operators?

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions
- Work to linear order in operator coefficients, i.e. $\mathcal{O}(1/\Lambda^2)$
- Use G_F, M_Z, α as input parameters

Dimension-6 SMEFT Operators

- Including 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate SU(3)^5 symmetry
- Important when including top observables

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar l_p e_r H)$
$\mathcal{O}_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar q_p d_r H)$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\,\widetilde G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar l_p\sigma^{\mu\nu}e_r)HB_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\,\widetilde W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\,\widetilde B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde WB}$	$H^\dagger\tau^I H\,\widetilde W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$\mathcal{O}_{ll}$	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$		

JE, Madigan, Mimasu, Sanz & You,
arXiv:2012.02779

Dimension-6 SMEFT Operators

- Including 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate $SU(3)^5$ symmetry
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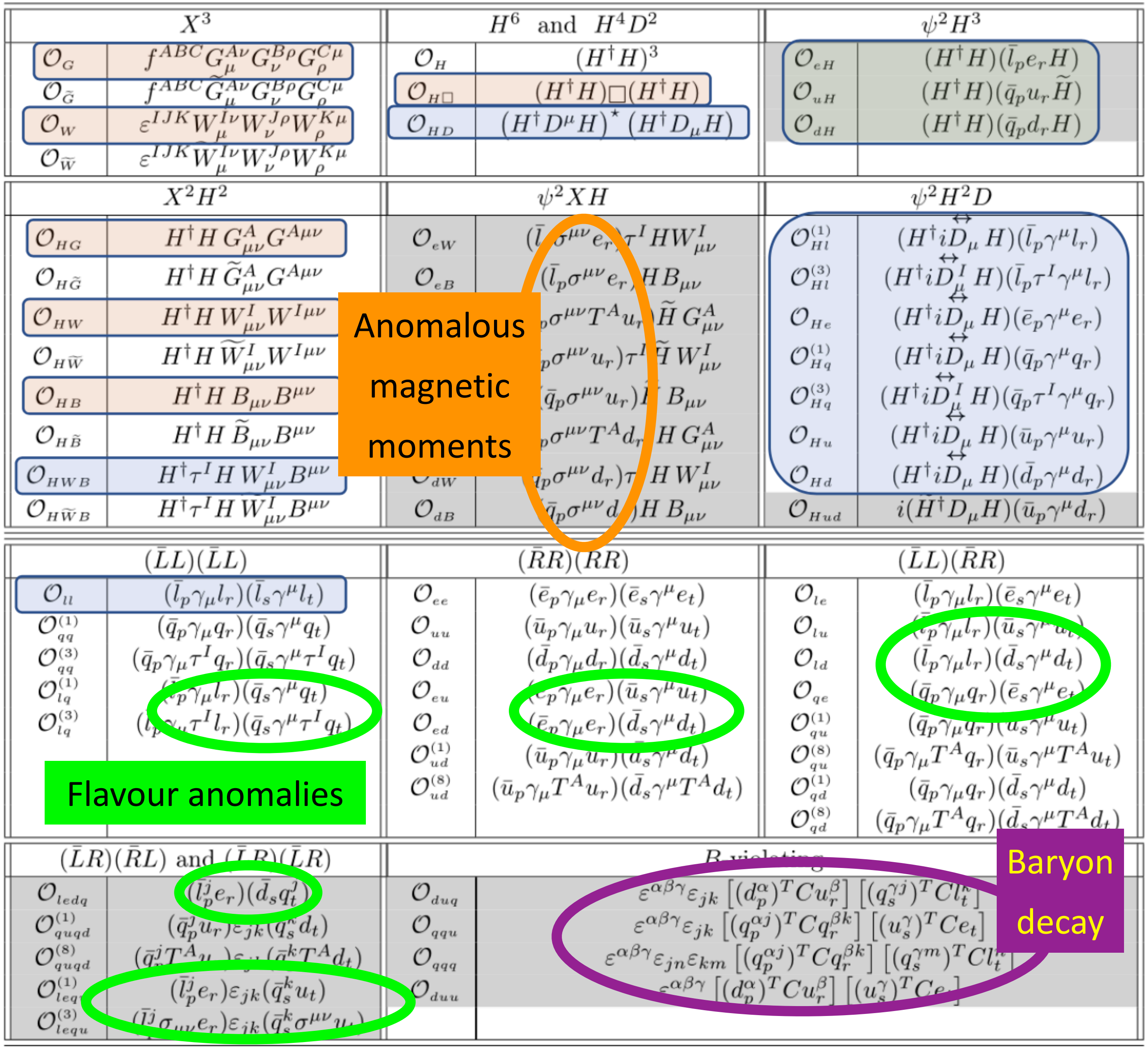


X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}^{(1)}_{lq}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(3)}_{lq}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}^{(1)}_{qd}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$\mathcal{O}^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$\mathcal{O}^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$		

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Operators included in Global Fit

- 20 operators in flavour-universal SU(3)^5 fit

EWPO:	$\mathcal{O}_{HWB}\,,\,\mathcal{O}_{HD}\,,\,\mathcal{O}_{ll}\,,\,\mathcal{O}_{Hl}^{(3)}\,,\,\mathcal{O}_{Hl}^{(1)}\,,\,\mathcal{O}_{He}\,,\,\mathcal{O}_{Hq}^{(3)}\,,\,\mathcal{O}_{Hq}^{(1)}\,,\,\mathcal{O}_{Hd}\,,\,\mathcal{O}_{Hu}\,,$
Bosonic:	$\mathcal{O}_{H\Box}\,,\,\mathcal{O}_{HG}\,,\,\mathcal{O}_{HW}\,,\,\mathcal{O}_{HB}\,,\,\mathcal{O}_{W}\,,\,\mathcal{O}_{G}\,,$
Yukawa:	$\mathcal{O}_{\tau H}\,,\,\mathcal{O}_{\mu H}\,,\,\mathcal{O}_{bH}\,,\,\mathcal{O}_{tH}\,.$

- 34 operators in top-specific SU(2)^2 x SU(3)^3 fit

Indicating which sectors constrain which operators

EWPO:	$\mathcal{O}_{HWB}\,,\,\mathcal{O}_{HD}\,,\,\mathcal{O}_{ll}\,,\,\mathcal{O}_{Hl}^{(3)}\,,\,\mathcal{O}_{Hl}^{(1)}\,,\,\mathcal{O}_{He}\,,\,\mathcal{O}_{Hq}^{(3)}\,,\,\mathcal{O}_{Hq}^{(1)}\,,\,\mathcal{O}_{Hd}\,,\,\mathcal{O}_{Hu}\,,$	
Bosonic:	$\mathcal{O}_{H\Box}\,,\,\mathcal{O}_{HG}\,,\,\mathcal{O}_{HW}\,,\,\mathcal{O}_{HB}\,,\,\mathcal{O}_{W}\,,\,\mathcal{O}_{G}\,,$	
Yukawa:	$\mathcal{O}_{\tau H}\,,\,\mathcal{O}_{\mu H}\,,\,\mathcal{O}_{bH}\,,\,\mathcal{O}_{tH}\,,$	
Top 2F:	$\mathcal{O}_{HQ}^{(3)}\,,\,\mathcal{O}_{HQ}^{(1)}\,,\,\mathcal{O}_{Ht}\,,\,\mathcal{O}_{tG}\,,\,\mathcal{O}_{tW}\,,\,\mathcal{O}_{tB}\,,$	
Top 4F:	$\mathcal{O}_{Qq}^{3,1}\,,\,\mathcal{O}_{Qq}^{3,8}\,,\,\mathcal{O}_{Qq}^{1,8}\,,\,\mathcal{O}_{Qu}^{8}\,,\,\mathcal{O}_{Qd}^{8}\,,\,\mathcal{O}_{tQ}^{8}\,,\,\mathcal{O}_{tu}^{8}\,,\,\mathcal{O}_{td}^{8}\,.$	(2.12)

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Operators included in Global Fit

- 20 operators in flavour-universal $SU(3)^5$ fit

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

Bosonic: $\mathcal{O}_{H\Box}\,, \mathcal{O}_{HG}\,, \mathcal{O}_{HW}\,, \mathcal{O}_{HB}$

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

Positive contributions to m_W

Indicating which sectors constrain which operators

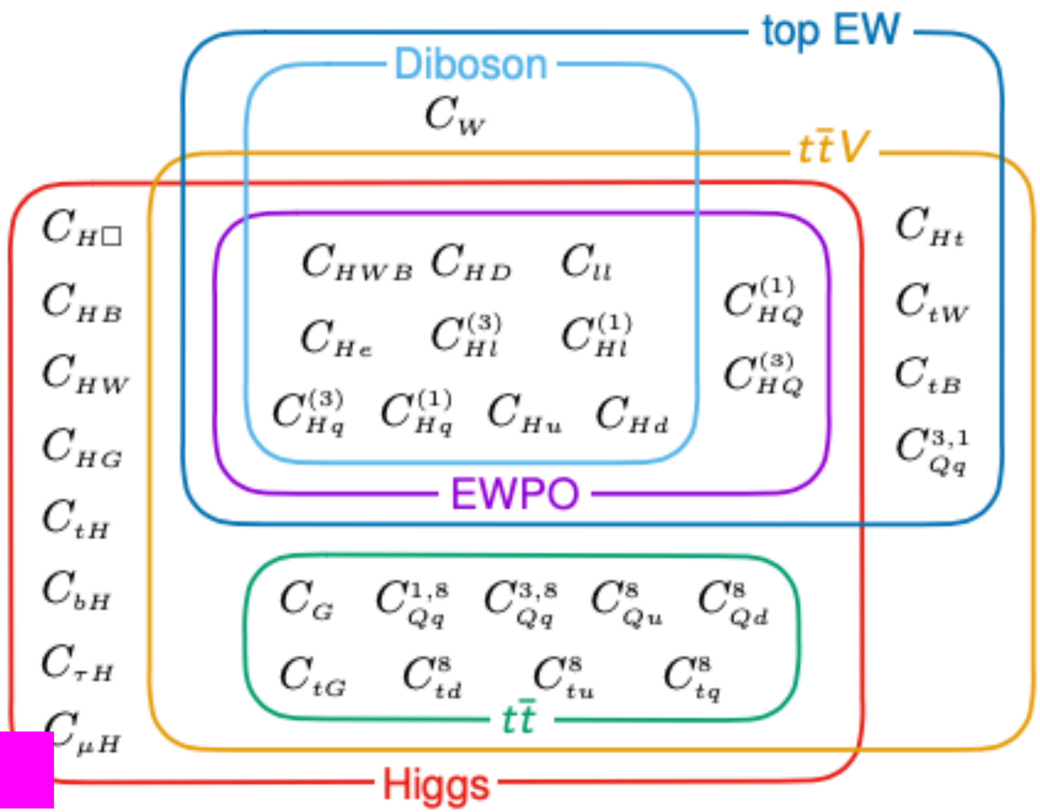
- 34 operators in top-specific $SU(2)^2$ x SU(3) fit

$$
\begin{array}{ll}
\text{EWPO:} & \mathcal{O}_{HWB}\,, \mathcal{O}_{HD}\,, \mathcal{O}_{ll}\,, \mathcal{O}_{Hl}^{(3)}\,, \mathcal{O}_{Hl}^{(1)}\,, \mathcal{O}_{He}\,, \mathcal{O}_{Hq}^{(3)}\,, \mathcal{O}_{Hq}^{(1)}\,, \mathcal{O}_{Hd}\,, \mathcal{O}_{Hu}\,, \\
\text{Bosonic:} & \mathcal{O}_{H\Box}\,, \mathcal{O}_{HG}\,, \mathcal{O}_{HW}\,, \mathcal{O}_{HB}\,, \mathcal{O}_{W}\,, \mathcal{O}_{G}\,, \\
\text{Yukawa:} & \mathcal{O}_{\tau H}\,, \mathcal{O}_{\mu H}\,, \mathcal{O}_{bH}\,, \mathcal{O}_{tH}\,, \\
\text{Top 2F:} & \mathcal{O}_{HQ}^{(3)}\,, \mathcal{O}_{HQ}^{(1)}\,, \mathcal{O}_{Ht}\,, \mathcal{O}_{tG}\,, \mathcal{O}_{tW}\,, \mathcal{O}_{tB}\,, \\
\text{Top 4F:} & \mathcal{O}_{Qq}^{3,1}\,, \mathcal{O}_{Qq}^{3,8}\,, \mathcal{O}_{Qq}^{1,8}\,, \mathcal{O}_{Qu}^{8}\,, \mathcal{O}_{Qd}^{8}\,, \mathcal{O}_{tQ}^{8}\,, \mathcal{O}_{tu}^{8}\,, \mathcal{O}_{td}^{8}\,.
\end{array} \tag{2.12}
$$

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Global SMEFT Fit
to Top, Higgs, Diboson, Electroweak Data

- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level



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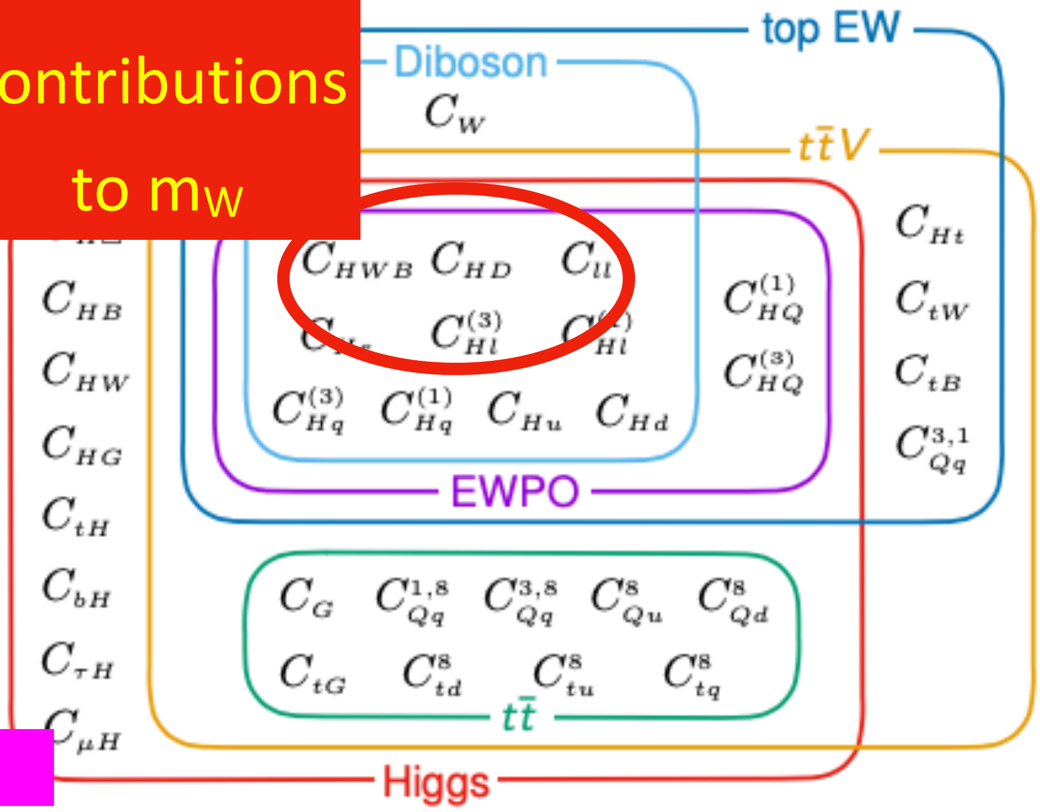
Positive contributions to m_W



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Data included in Global Fit

EW precision observables

Precision electroweak measurem...
Γ_Z, $\sigma^0_{\text{had.}}$, R^0_ℓ, A^ℓ_{FB}, A_ℓ(SLD), A...
Combination of CDF and D0 W...
LHC run 1 W boson mass meas...

Diboson LEP & LHC

W^+W^- angular distribution me...
W^+W^- total cross section meas... final states for 8 energies
W^+W^- total cross section meas... $qqqq$ final states for 7 energies
W^+W^- total cross section mea... & $qqqq$ final states for 8 energies
ATLAS W^+W^- differential cr... $p_T > 120$ GeV overflow bin
ATLAS W^+W^- fiducial differe... $\frac{d\sigma}{dp^T_{\ell_1}}$
ATLAS $W^\pm Z$ fiducial differential cross section in the ℓ^+... $\frac{d\sigma}{dp^T_Z}$
CMS $W^\pm Z$ normalised fiducial differential cross section... channel, $\frac{1}{\sigma}\frac{d\sigma}{dp^T_Z}$
ATLAS Zjj fiducial differential cross section in the $\ell^+\ell^-$...

LHC Run 1 Higgs

ATLAS and CMS LHC Run 1 combination of Higgs sig...
Production: ggF, VBF, ZH, WH & ttH
Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ & $b\bar{b}$
ATLAS inclusive $Z\gamma$ signal strength measurement

LHC Run 2 Higgs

ATLAS combination ... including ratios of bra...
Signal strengths|coars...
CMS LHC combinatic... Production: ggF, VB... Decay: $\gamma\gamma$, ZZ, W^+W...
CMS stage 1.0 STXS ... 13 parameter fit | 7 pa...
CMS stage 1.0 STXS
CMS stage 1.1 STXS
CMS differential cross... tion in the $WW^* \to \ell$... $\frac{d\sigma}{dn_{\text{jet}}}$ | $\frac{d\sigma}{dp^T_H}$
ATLAS $H \to Z\gamma$ sign...
ATLAS $H \to \mu^+\mu^-$ si...

Tevatron & Run 1 top	n_{obs}	Ref.
Tevatron combination of differential $t\bar{t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar{t}})$.	4	[7]
ATLA... $\frac{d\sigma}{dm_{t\bar{t}}}$		
ATLA... $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS ... $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS ... dilept...		
ATLA... dilept...		
ATLA... $A_C(m$...		
CMS ... $\frac{d\sigma}{dm_{t\bar{t}}dy}$		
ATLA... decay.		
ATLA... f_0, f_L		
CMS ... f_0, f_L		
ATLA...		
CMS ...		
ATLA... $\frac{d\sigma}{dp^T_t}$		
CMS ...		
CMS ... $\frac{d\sigma}{dp^T_{t+\bar{t}}}$		
CMS ... $\sigma_t \mid \sigma_{\bar{t}} \mid \sigma_{t+\bar{t}} \mid R_t$.		
ATLAS s-channel single-top cross section measurement.		
CMS tW cross section measurement.		
ATLAS tW cross section measurement in the single lepto...		
ATLAS tW cross section measurement in the dilepton channel.	1	[35]

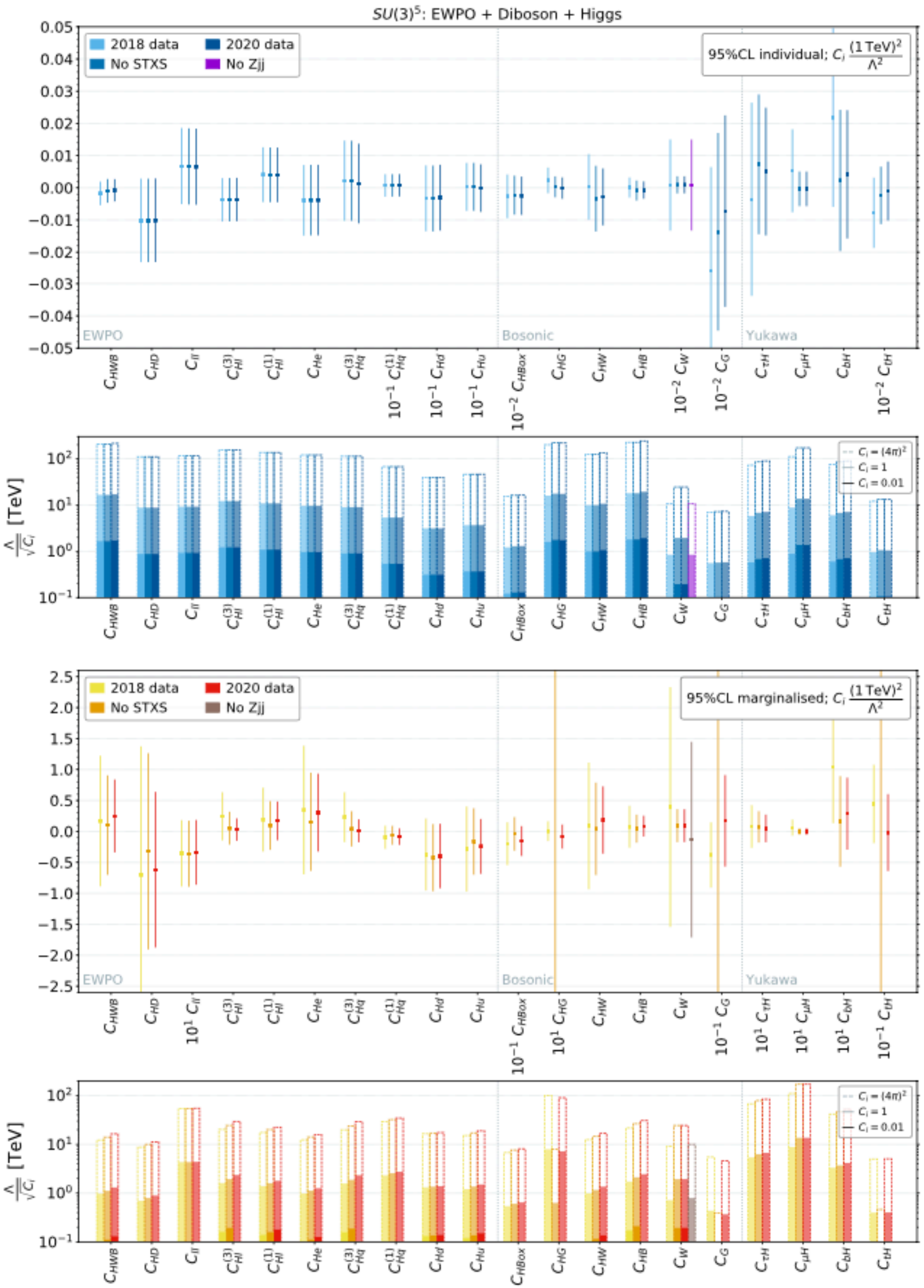
Run 2 top	n_{obs}	Ref.
CMS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	6	[36, 231]
CMS $t\bar{t}$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	10	[37]
ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$.	5	[38]
ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	2	[39]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	1|1	[40]
CMS $t\bar{t}Z$ differential distributions. $\frac{d\sigma}{dp^T_Z}$ | $\frac{d\sigma}{d\cos\theta^*}$	4|4	[41]
CMS measurement of differential cross sections and charge ratios for t-channel single-top quark production. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $R_t\,(p^T_{t+\bar{t}})$	5|5	[42]
CMS measurement of t-channel single-top and anti-top cross sections. σ_t, $\sigma_{\bar{t}}$, $\sigma_{t+\bar{t}}$ & R_t.	4	[43]
CMS measurement of the t-channel single-top and anti-top cross sections. $\sigma_t \mid \sigma_{\bar{t}} \mid \sigma_{t+\bar{t}} \mid R_t$.	1|1|1|1	[44]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $\frac{d\sigma}{d\lvert y_{t+\bar{t}}\rvert}$	4|4	[45]
ATLAS tW cross section measurement.		
CMS tZ cross section measurement.		
CMS tW cross section measurement.		
ATLAS tZ cross section measurement.		
CMS tZ ($Z \to \ell^+\ell^-$) cross section measurement...		

341 measurements included in global analysis

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

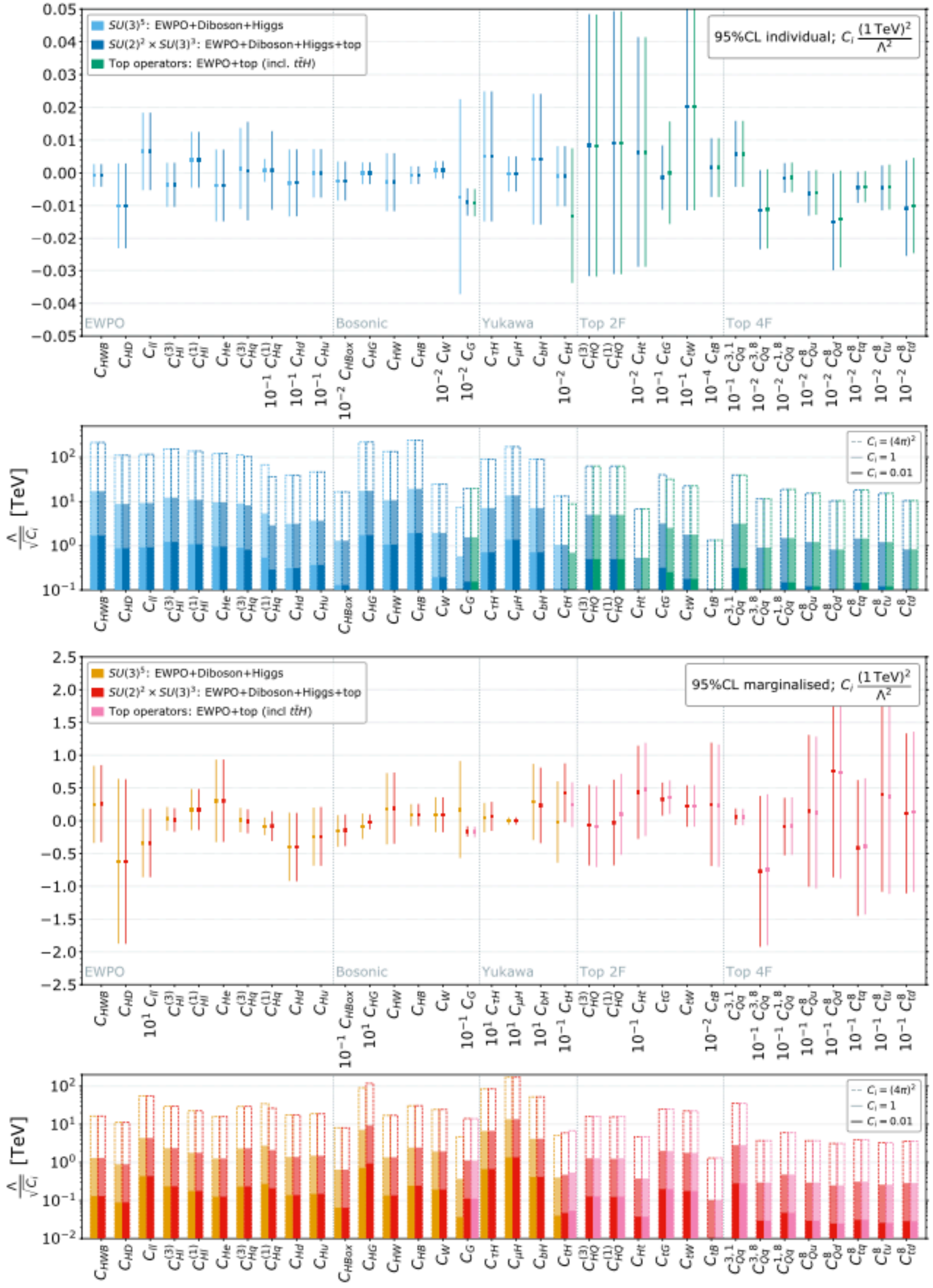
Dimension-6 Constraints with Flavour-Universal SU(3)^5 Symmetry

- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Dimension-6 Constraints with Top-Specific SU(2)^2 x SU(3)^3

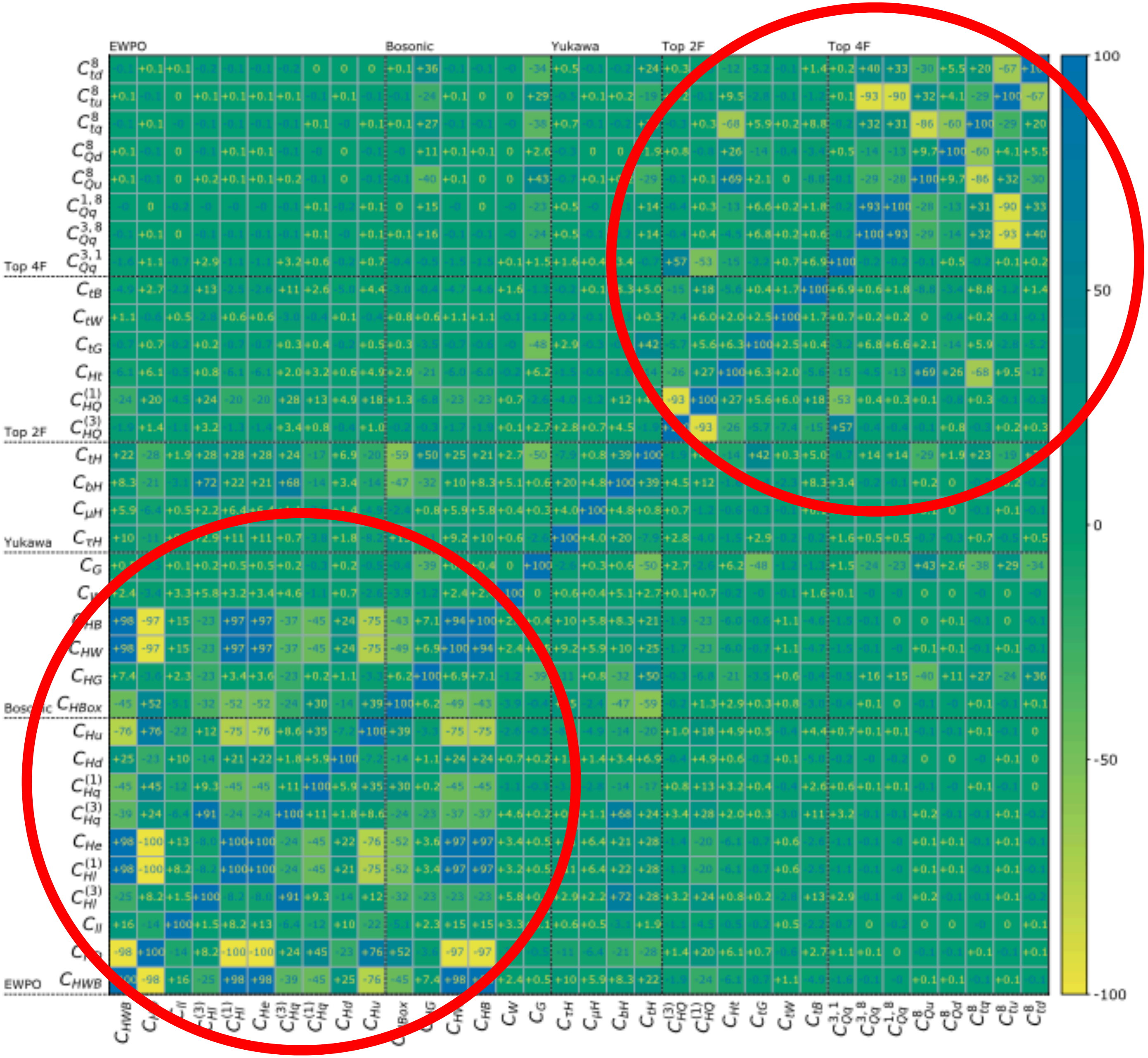


- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Correlation Analysis

- EWPO and boson sectors correlated
- Also within top sector
- Weaker correlations between sectors



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Single-Field Extensions of the Standard Model

Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
W_1	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$

Spin zero

Vector

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Contributions to SMEFT Coefficients

Spin zero

Spin zero

Vector

Spin zero

Vector

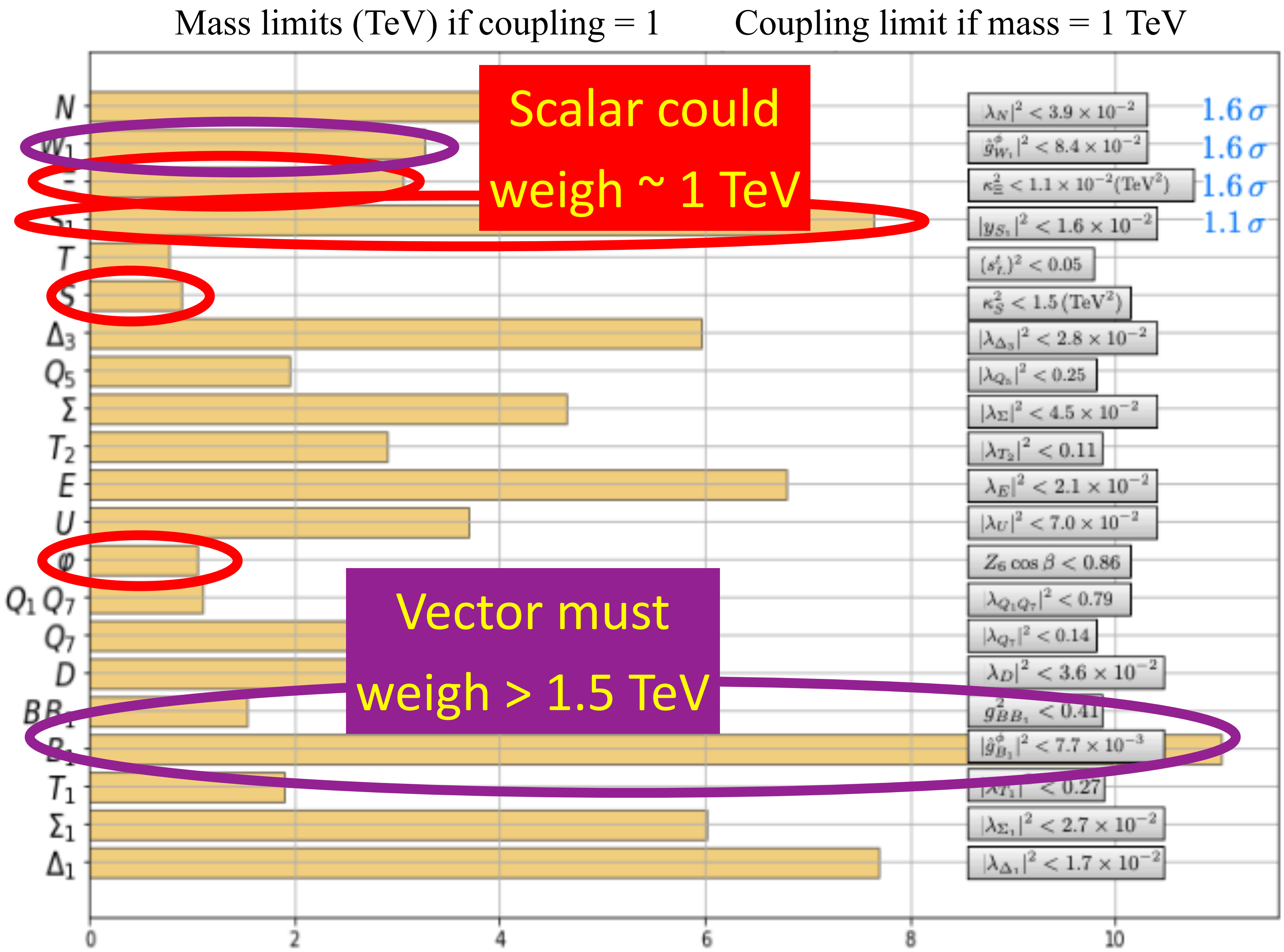
Model	C_{HD}	C_{ll}	C^3_{Hl}	C^1_{Hl}	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						-1			
S_1		1							
Σ			$\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$						1	y_τ	y_t	y_b
$\{Q_1, Q_7\}$								y_t	

Model	C_{HG}	C^3_{Hq}	C^1_{Hq}	$(C^3_{Hq})_{33}$	$(C^1_{Hq})_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}
U		$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$	
D		$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$
Q_5							$-\frac{1}{2}$		$\frac{y_b}{2}$
Q_7						$\frac{1}{2}$		$\frac{y_t}{2}$	
T_1		$-\frac{5}{8}$	$-\frac{3}{16}$	$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$
T_2		$-\frac{5}{8}$	$\frac{3}{16}$	$-\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$
T	$-\frac{M_T^2}{v^2}\frac{\alpha_s(0.02)}{8\pi}$			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$	

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Constraints on Single-Field BSM Scenarios

- No significant pulls away from SM
- Any single-field extension of SM must have mass scale > 800 GeV if coupling = 1



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

SMEFT Constraints on Light Stops

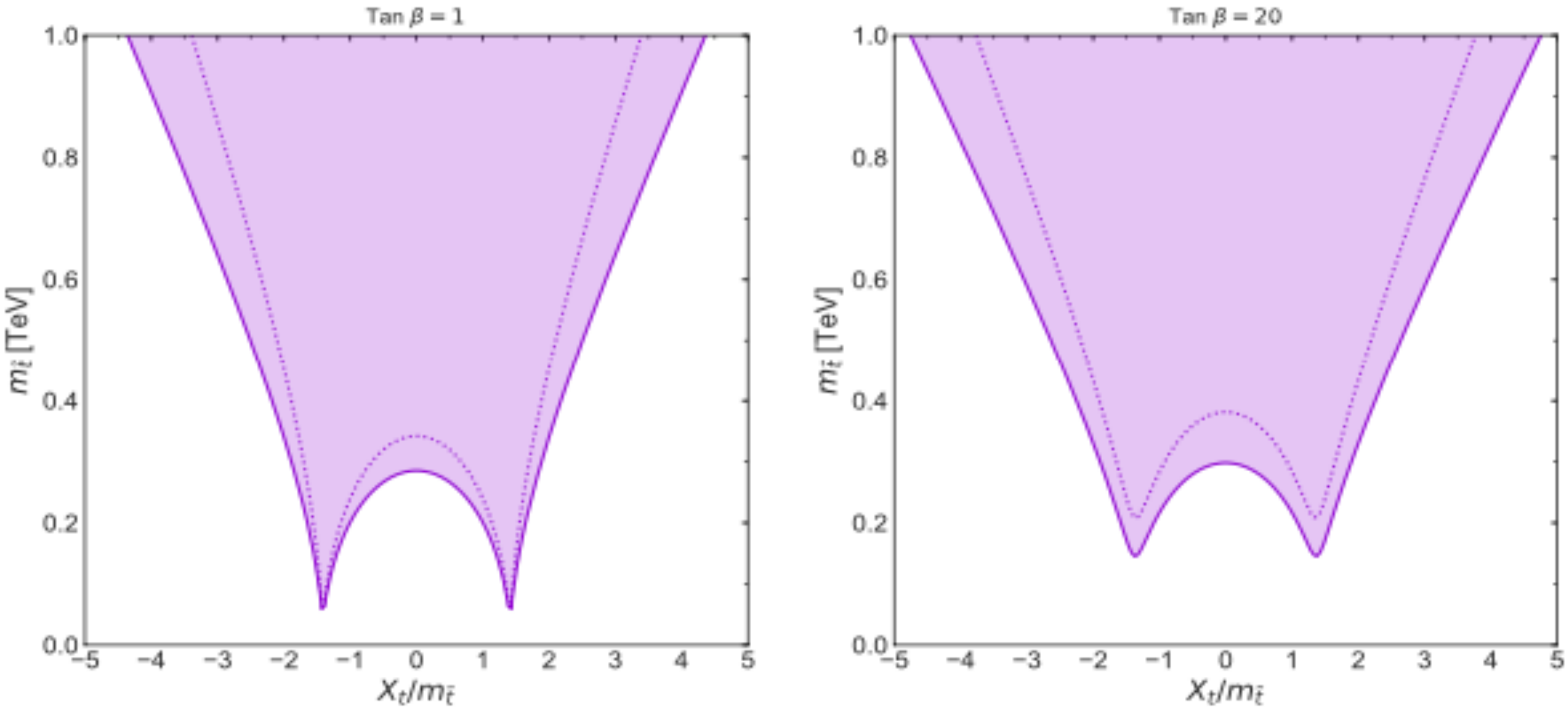
From quantum loop corrections:

$$C_{HG} = \frac{g_s^2}{12}\frac{h_t^2}{(4\pi)^2}\left[\left(1+\frac{1}{12}\frac{c_{2\beta}g'^2}{h_t^2}\right)-\frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\right],$$

$$C_{HB} = \frac{17g'^2}{144}\frac{h_t^2}{(4\pi)^2}\left[\left(1+\frac{31}{102}\frac{c_{2\beta}g'^2}{h_t^2}\right)-\frac{38}{85}\frac{X_t^2}{m_{\tilde{t}}^2}\right],$$

$$C_{HW} = \frac{g^2}{16}\frac{h_t^2}{(4\pi)^2}\left[\left(1-\frac{1}{6}\frac{c_{2\beta}g'^2}{h_t^2}\right)-\frac{2}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\right],$$

$$C_{HWB} = -\frac{gg'}{24}\frac{h_t^2}{(4\pi)^2}\left[\left(1+\frac{1}{2}\frac{c_{2\beta}g^2}{h_t^2}\right)-\frac{4}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\right],$$

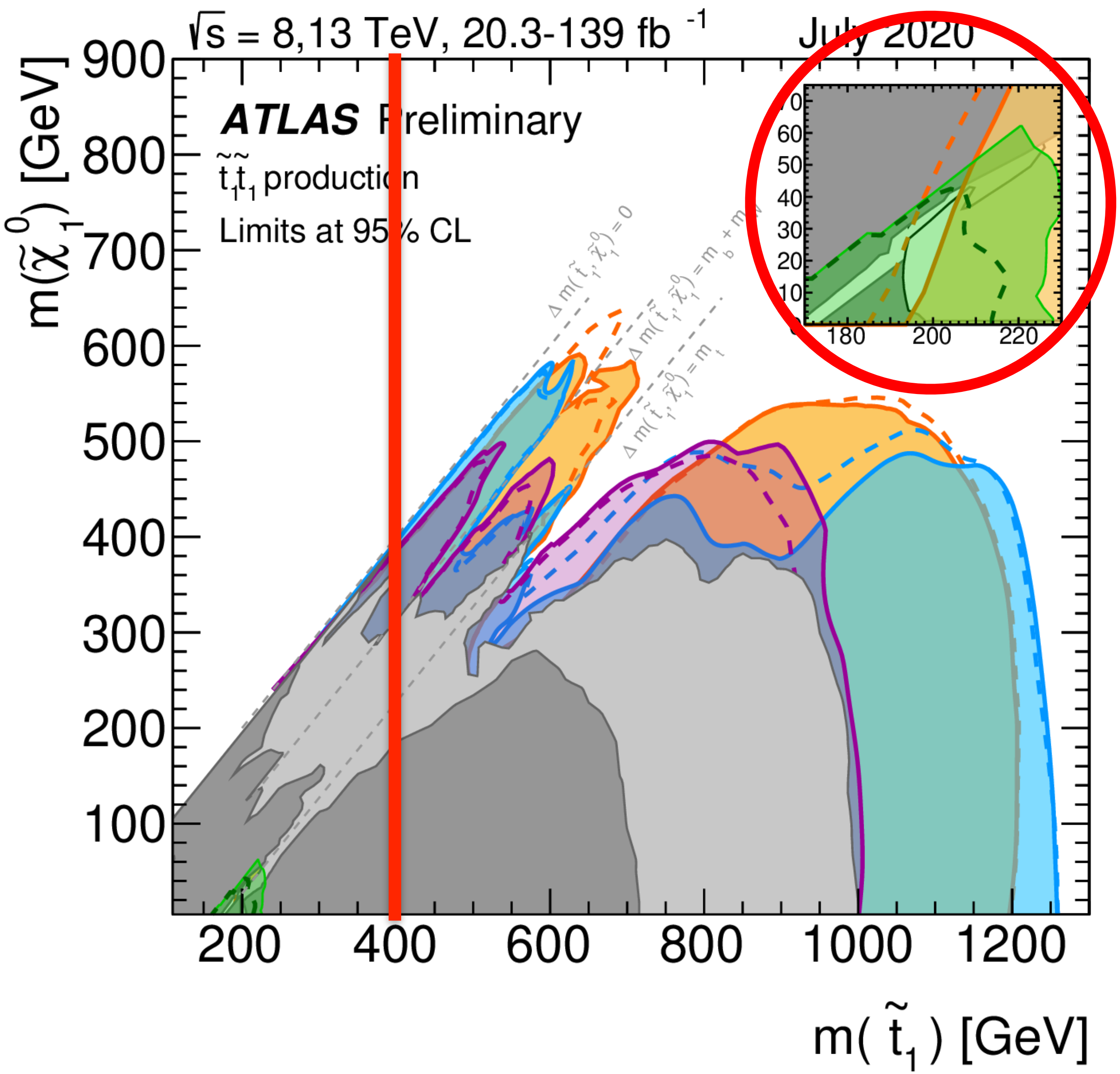


(Almost) model-independent lower limit on stop squark mass

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

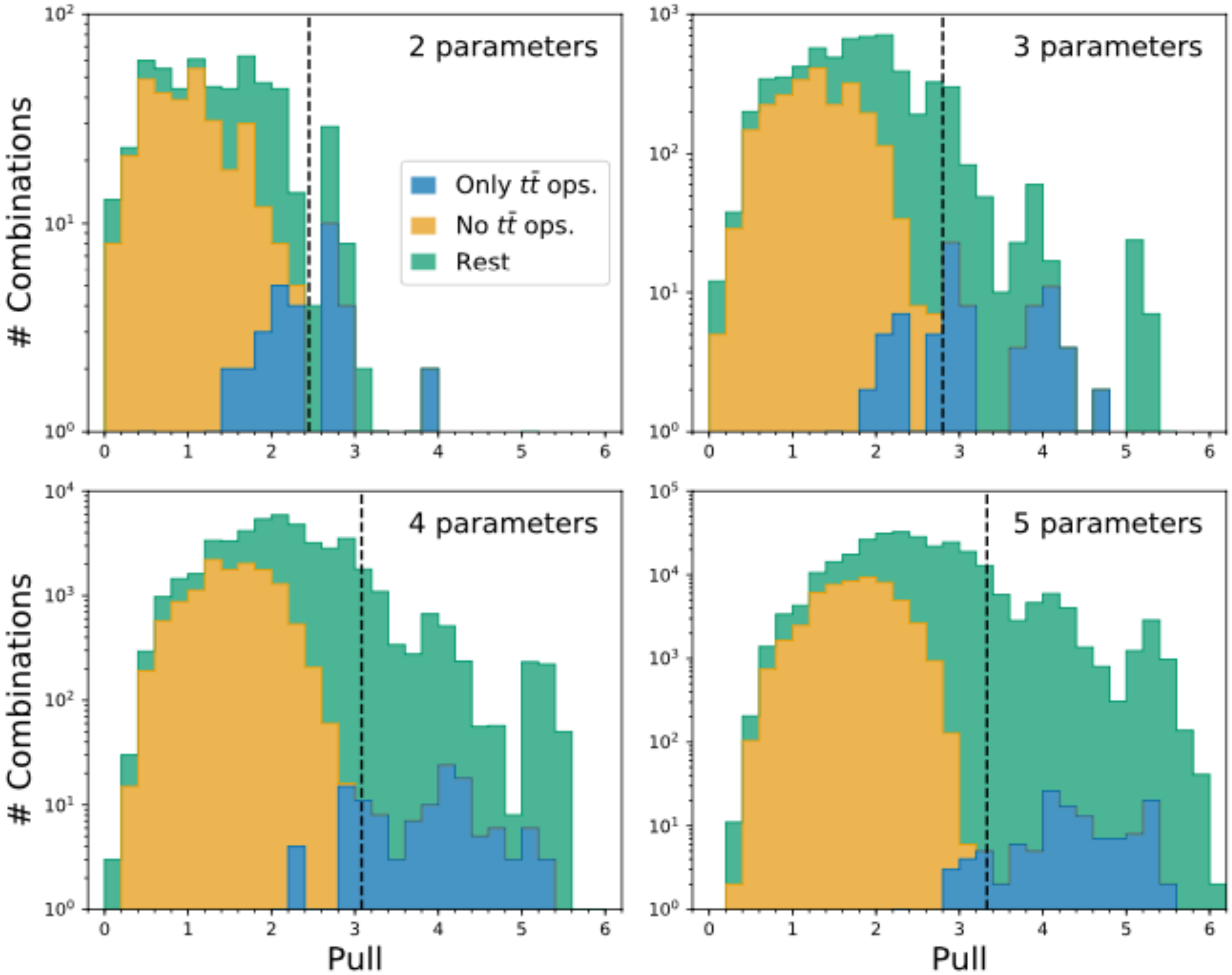
Direct Search Constraints on Light Stops

- Patchwork of many model-dependent searches
- Indirect constraint excludes low-mass region (almost) model-independently



Model-Independent BSM Survey

- General combinations of operators
- **Top-less sector fits SM very well**
- Top sector does not fit so well
- Overall, pulls not excessive
- **No hint of BSM**



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

SMEFT Operators that can Contribute to W Mass

- Relevant SMEFT operators

$$\mathcal{O}_{HWB} \equiv H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_{HD} \equiv \left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$$

$$\mathcal{O}_{\ell\ell} \equiv \left(\bar{\ell}_p \gamma_\mu \ell_r\right)\left(\bar{\ell}_s \gamma^\mu \ell_t\right), \quad \mathcal{O}^{(3)}_{H\ell} \equiv \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{\ell}_p \tau^I \gamma^\mu \ell_r\right)$$

- Contributions to W mass

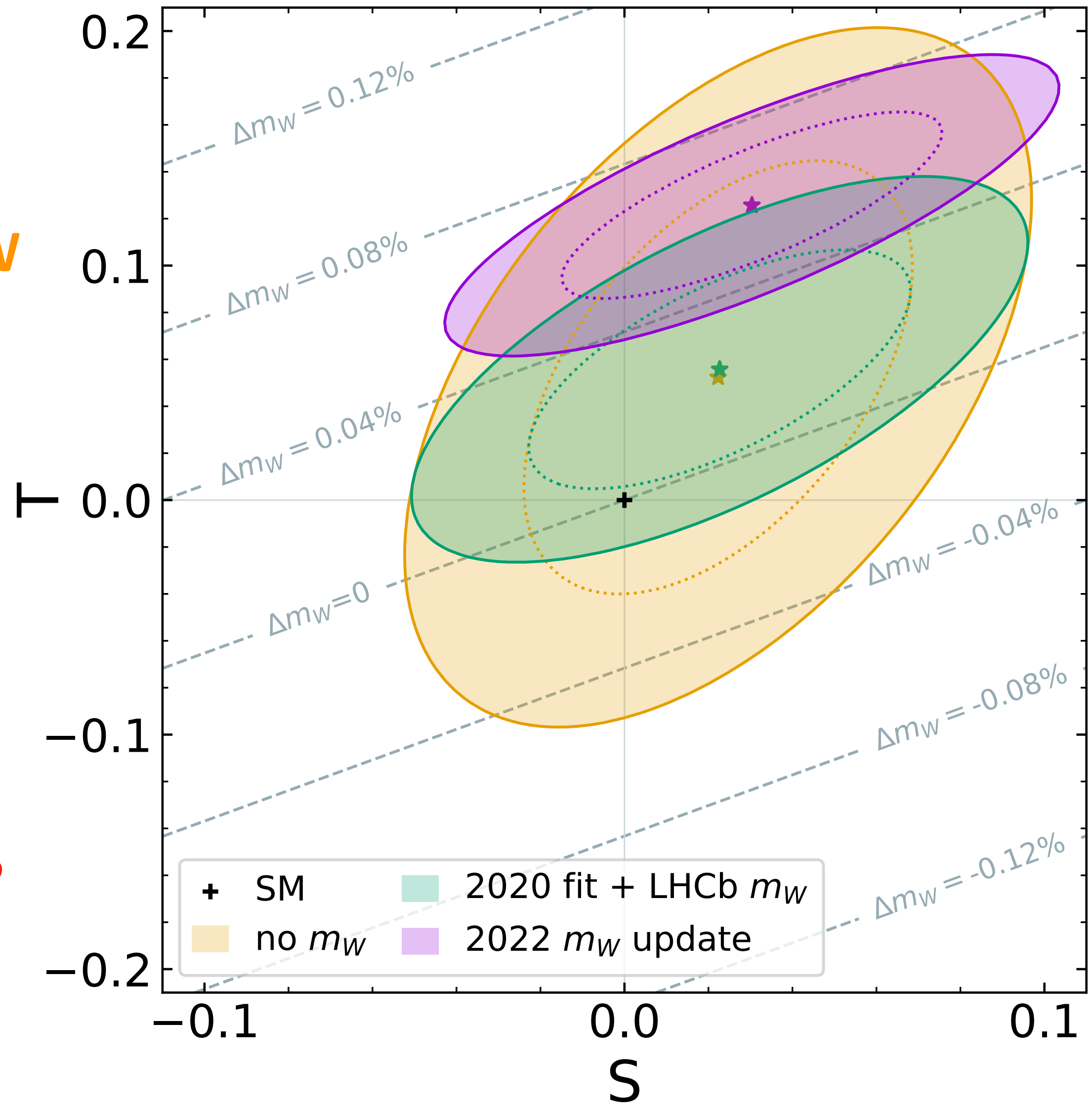
$$\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w}\frac{v^2}{4\Lambda^2}\left(\frac{\cos\theta_w}{\sin\theta_w} C_{HD} + \frac{\sin\theta_w}{\cos\theta_w}\left(4C^{(3)}_{Hl} - 2C_{ll}\right) + 4C_{HWB}\right)$$

- Contributions to *S* and *T* oblique parameters

$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S \quad , \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T$$

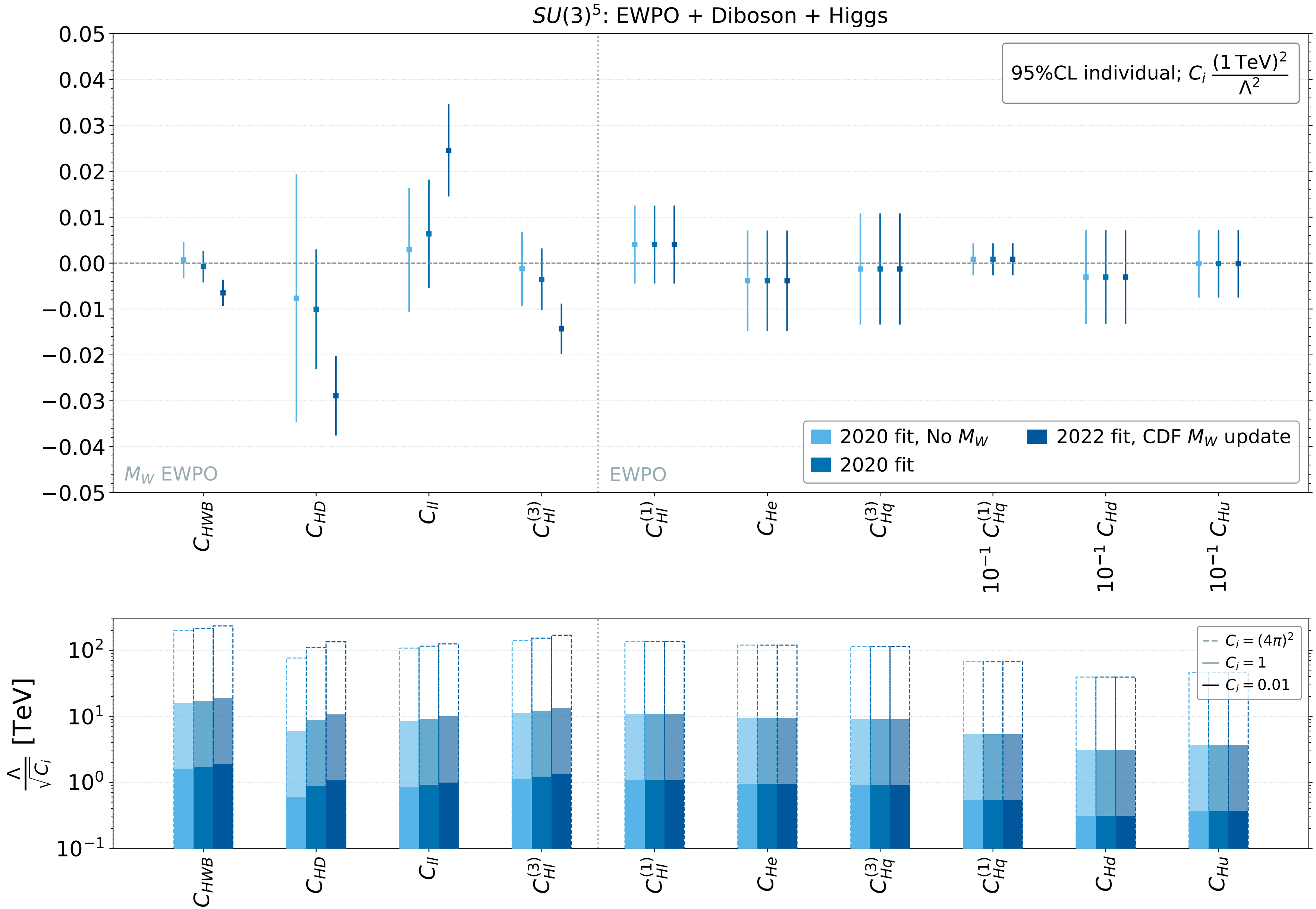
SMEFT Fits to S and T Parameters

- SM prediction
- **SMEFT fit without m_W**
- SMEFT fit to 2020 data + LHCb m_W
- SMEFT fit including CDF mW
- Little effect on S, pulls T away from SM



Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

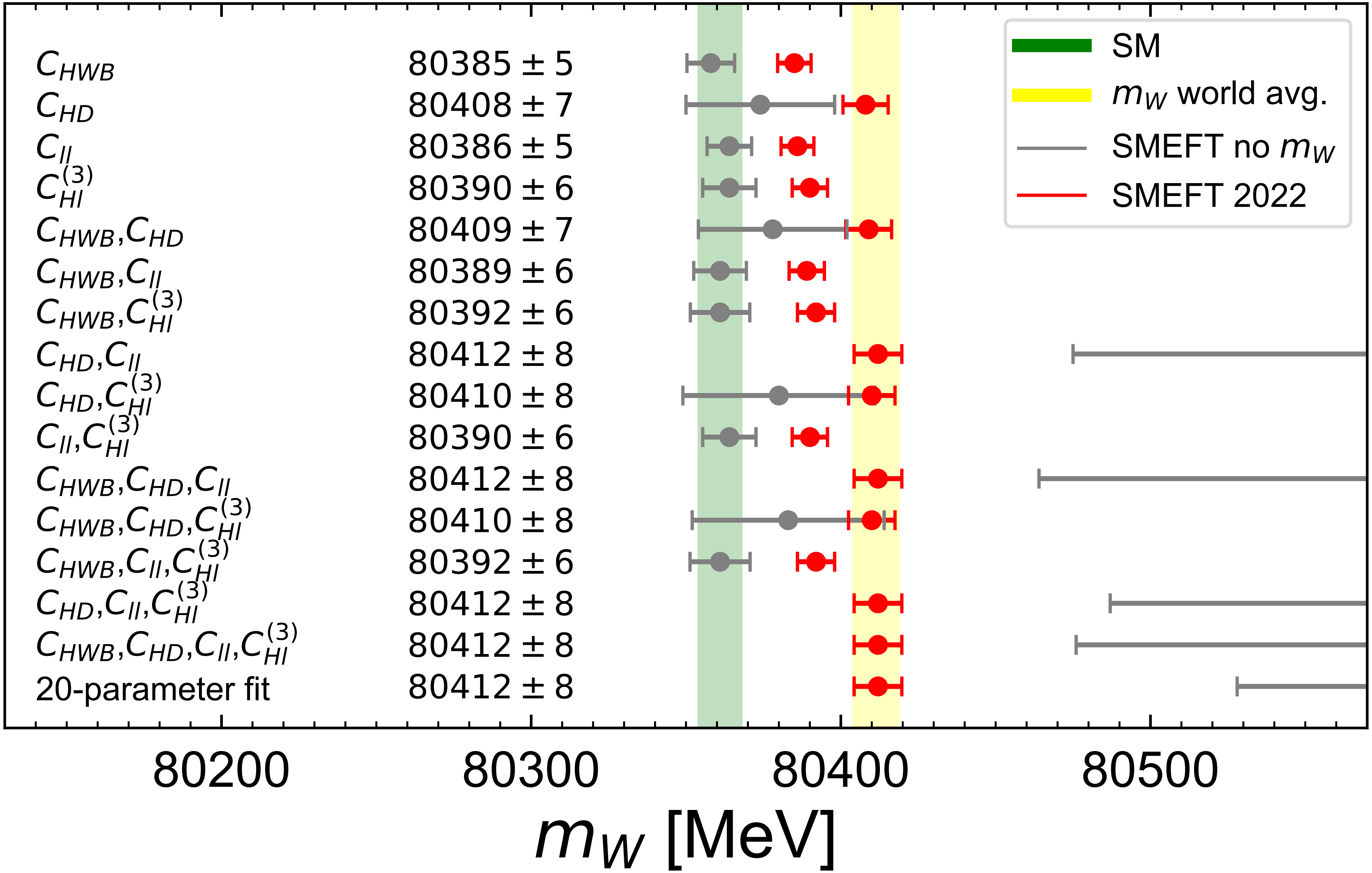
SMEFT Fit with the Mass of the W Boson



Non-zero coefficients for any of four operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

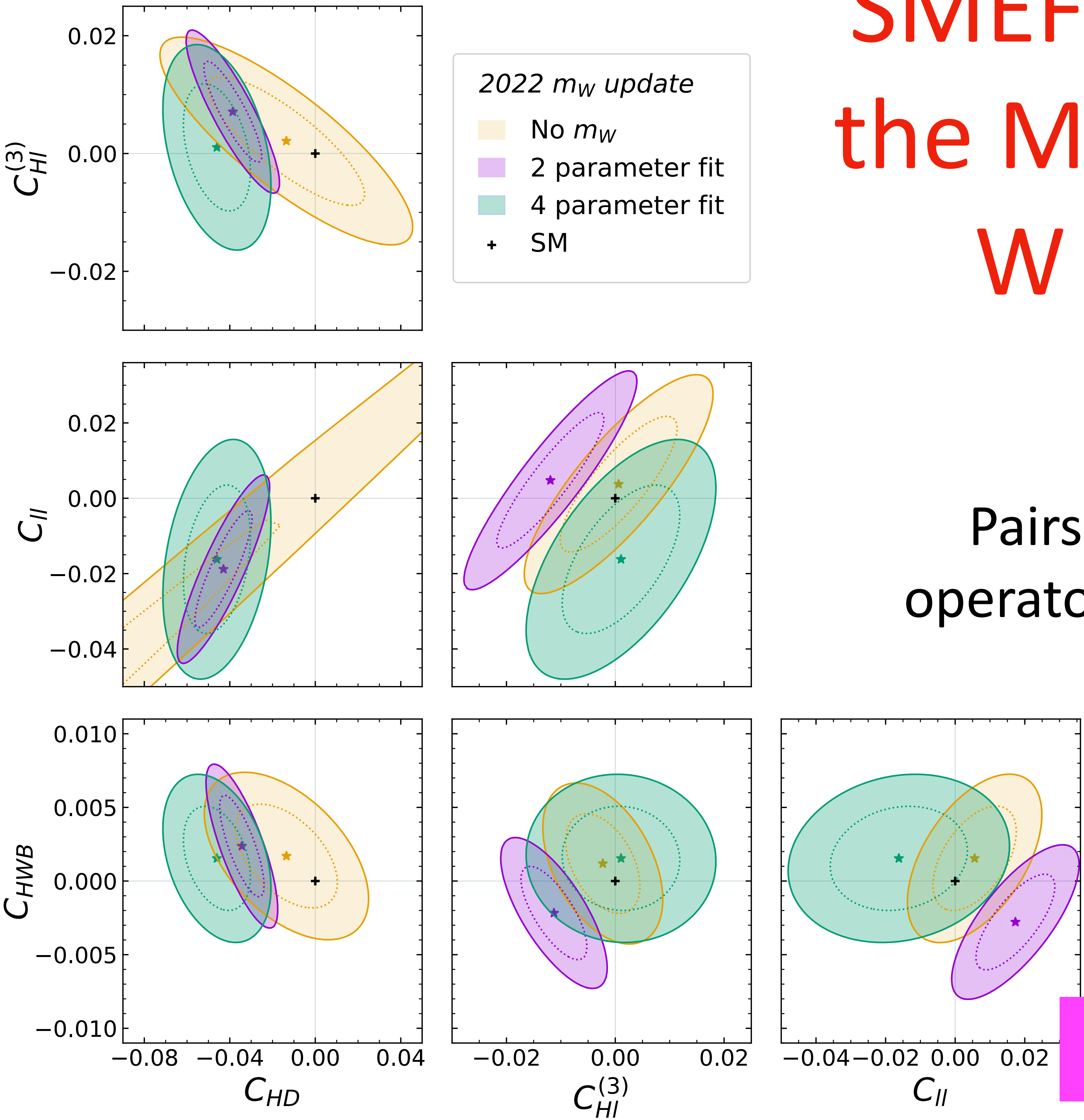
SMEFT Fits with the Mass of the W Boson



Subsets of four operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

SMEFT Fit with the Mass of the W Boson



Pairs of four SMEFT operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Models that can Contribute to W Mass

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	$(M_{W_1},\hat{g}_{W_1}^{\varphi})$
W	1	1	3	0	$(M_W,\hat{g}_W^H)$

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Models that can Contribute to W Mass

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					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	$\frac{1}{2}$					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

Operators contributing to m_W

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Models that can Contribute to W Mass

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

Wrong sign

Operators contributing to m_W

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Models that can Contribute to W Mass

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			X ~~$\frac{1}{16}$~~	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			X ~~$\frac{1}{16}$~~	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	X					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
B	-2						$-y_\tau$	$-y_t$	$-y_b$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	X					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

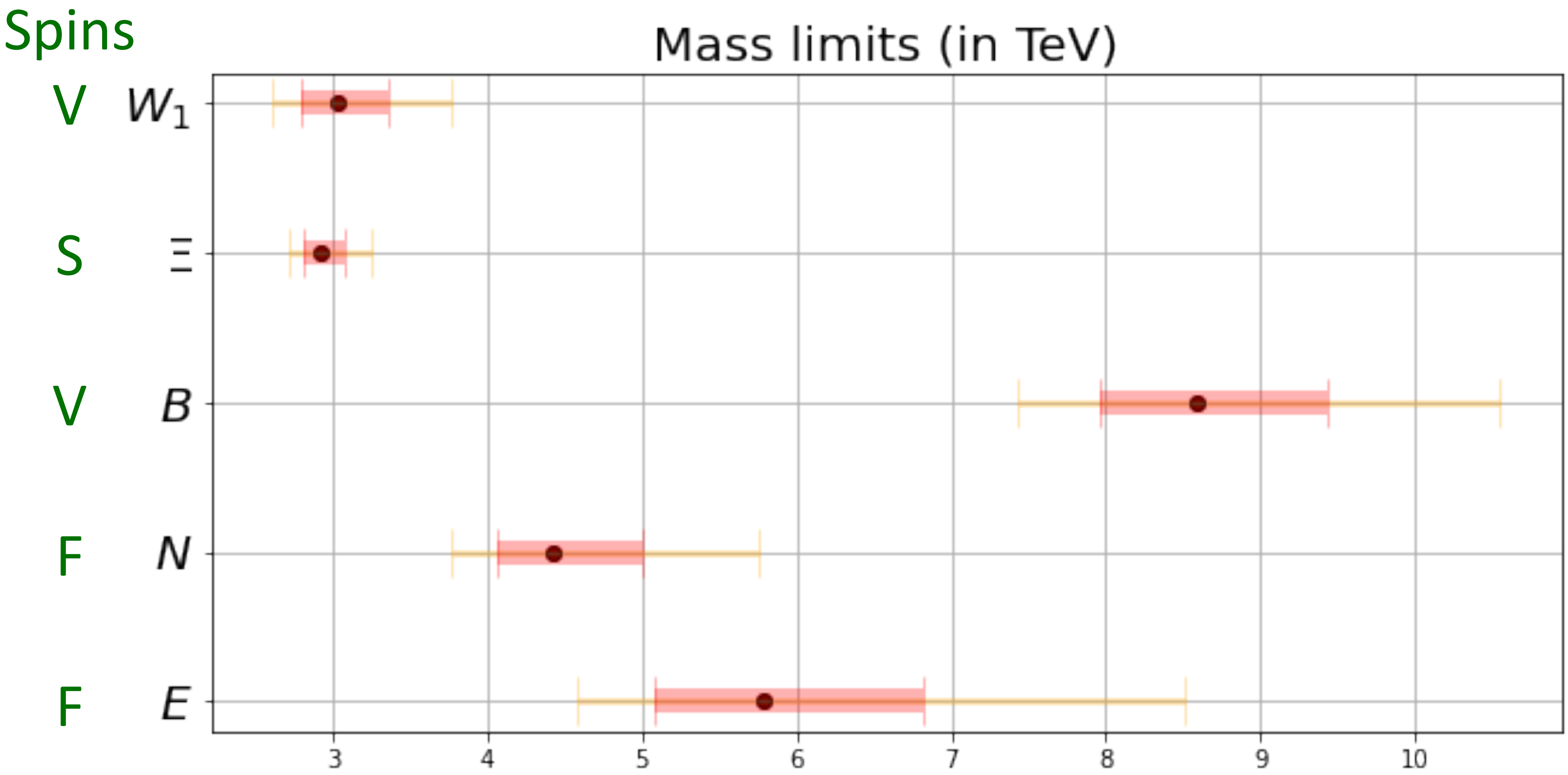
Wrong sign

Right sign

Operators contributing to m_W

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Models Fitting the Mass of the W Boson



68 and 95% CL ranges of masses assuming unit couplings

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Models Fitting the Mass of the W Boson

Spins	Model	Pull	Best-fit mass (TeV)	1-σ mass range (TeV)	2-σ mass range (TeV)	1-σ coupling^2 range
V	W_1	6.4	3.0	[2.8, 3.6]	[2.6, 3.8]	[0.09, 0.13]
S	B	6.4	8.6	[8.0, 9.4]	[2.7, 3.2]	[0.011, 0.017]
V	Ξ	6.4	2.9	[2.8, 3.1]	[2.7, 3.2]	[0.011, 0.017]
F	N	5.1	4.4	[4.1, 5.0]	[3.8, 5.8]	[0.040, 0.060]
F	E	3.5	5.8	[5.1, 6.8]	[4.6, 8.5]	[0.022, 0.039]

Best-fit, 68 and 95% CL ranges of masses assuming unit couplings

68% CL ranges of couplings for 1 TeV

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

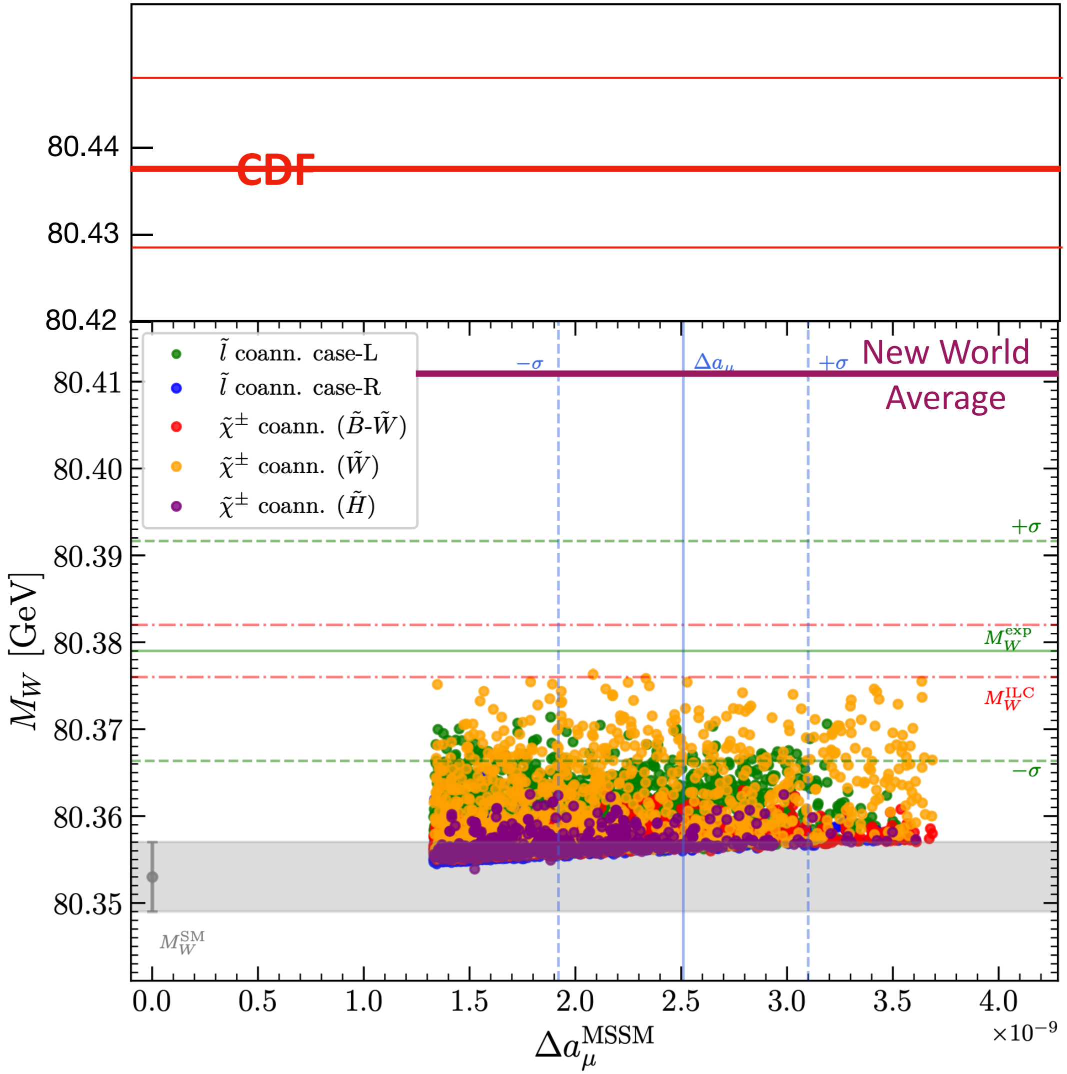
Searching for Models Fitting the Mass of the W Boson

- W: Isotriplet vector boson, mass ~ 3 TeV x coupling, electroweak production, accessible at LHC?
- B: Singlet vector boson, mass ~ 8 TeV x coupling, phenomenology depends on fermion couplings, too heavy for LHC?
- Ξ: Isotriplet scalar boson, mass ~ 3 TeV x coupling, detectable in LHC searches for heavy Higgs bosons?
- N: Isosinglet neutral fermion, mass ~ 4 TeV x coupling, similar to (right-handed) singlet neutrino
- E: Isosinglet charged fermion, mass ~ 6 TeV x coupling, similar to (right-handed) singlet electron

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

W Mass in Supersymmetry?

- Survey of possible contributions from electroweak particles
- Can reach old world average, but not CDF or new world average
- Additional contribution from stops?



Bagnaschi, Chakraborti, Heinemeyer, Saha & Weiglein, arXiv:2203.15710

Quo Vadis m_W?

- The jury is still out concerning the experimental measurement
  - Tension with SM, previous measurements

    "Extraordinary claims require extraordinary evidence"

- Nevertheless, much theoretical speculation (70 papers!)
- 4 SMEFT operators can increase m_W
- Prospects for the LHC?
- 3 SMEFT operators generated by single field extensions of the SM at tree level
  - Vector bosons W or B, scalar boson Ξ, fermions N, E
- Could also be important loop effects (supersymmetry?)

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260