Going global

Combining electroweak precision, diboson, Higgs, and top data to search for new physics

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Elementary Particle Physics Seminar, University of Warwick
27th January 2022

[J. Ellis, M. Madigan, KM, V. Sanz & T. You; JHEP 04 (2021) 279]

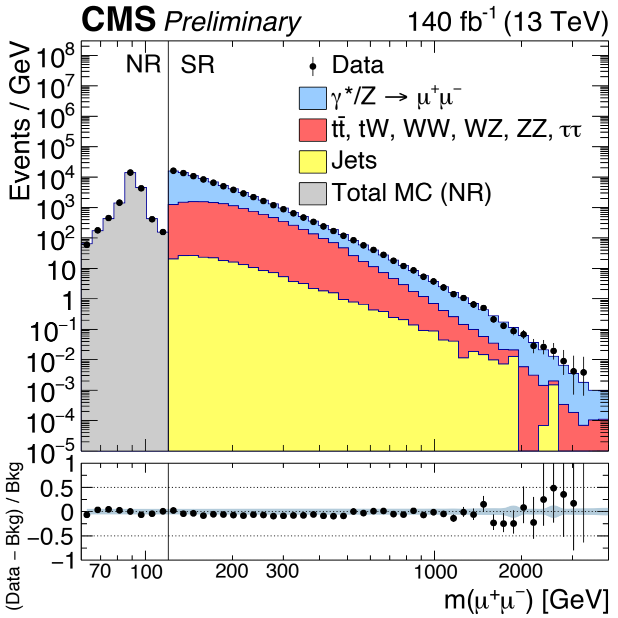
`fitmaker` *https://gitlab.com/kenmimasu/fitrepo*

[G. Durieux, C. Degrande, F. Maltoni, KM, C. Zhang, E. Vryonidou; PRD 103 (2021) 9, 096024]

`SMEFTatNLO` *http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO*

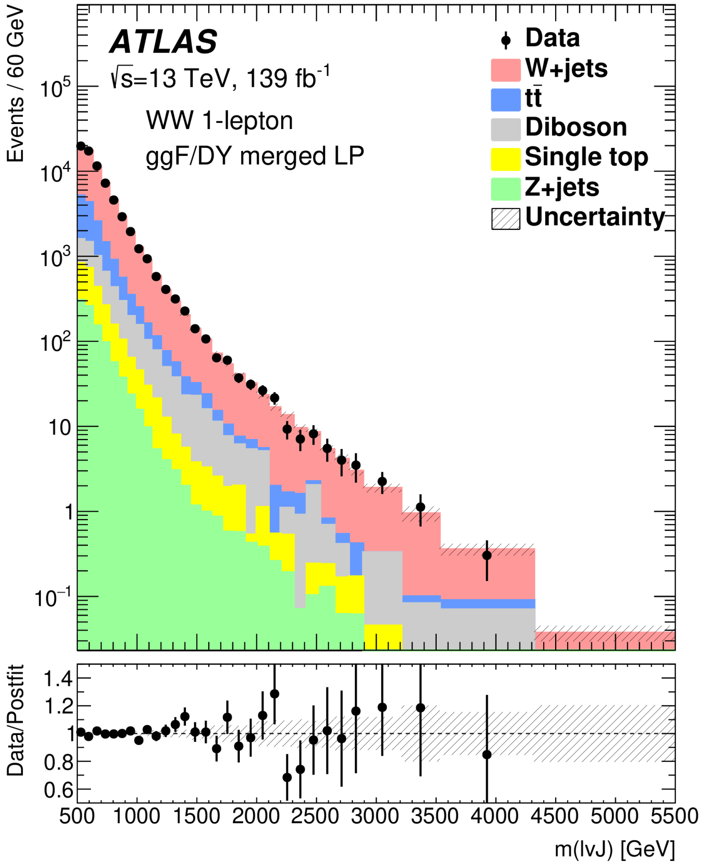
Where are we?

[CMS-PAS-EXO-19-019]

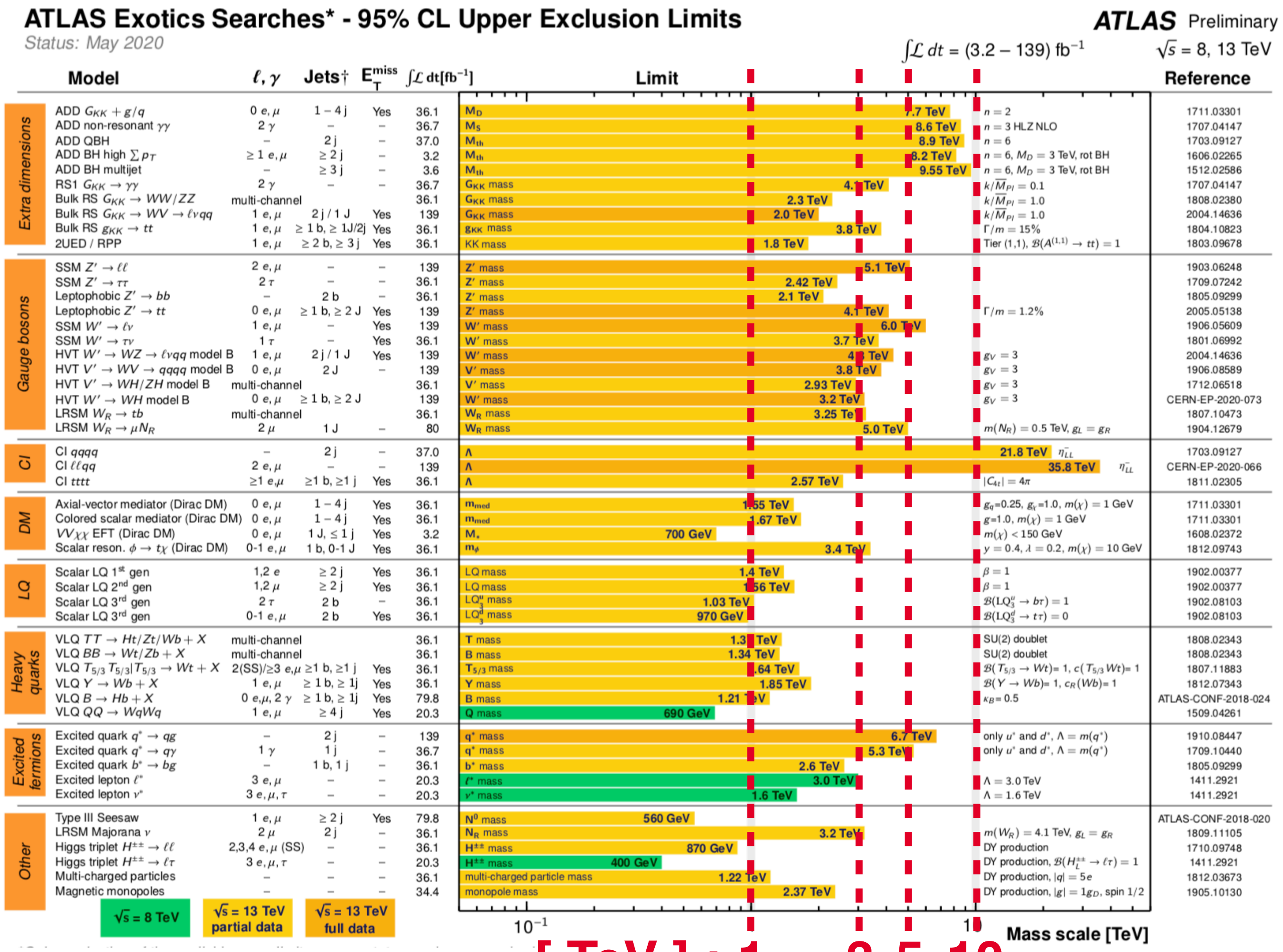


10 years since the start of LHC Run 1

- No clear sign of new physics at the TeV scale
- Direct searches are saturating the energy frontier



[CERN-EP-2020-049]



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 139)$ fb^{-1}

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt$[fb^{-1}]	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 − 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant γγ	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI qqqq	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09127
	CI ℓℓqq	2 e, μ	–	–	139	Λ 35.8 TeV η_{LL}^-		CERN-EP-2020-066
	CI tttt	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV　🟨 $\sqrt{s}$ = 13 TeV partial data　🟧 $\sqrt{s}$ = 13 TeV full data

[TeV] : 1 3 5 10

What have we learnt?

BSM states are too…

Weakly coupled *rate limited*	Room for improvement with increasing luminosity Still 20x more data to come
Exotic *we aren't looking in the right place*	Limited by our creativity Work for theorists & experimentalists to motivate & enable searches for new signatures
Heavy *kinematically out of reach*	Worst-case scenario from direct search point of view Complemented by indirect searches

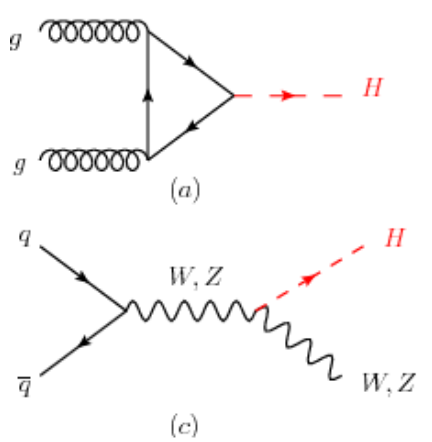
A tremendous amount about the SM!

- Higgs discovery & properties ⇒ precision LHC programme

The LHC explorer

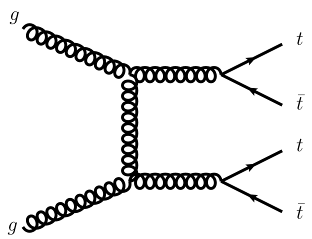
Many new processes observed at the LHC for the first time

Main Higgs production modes

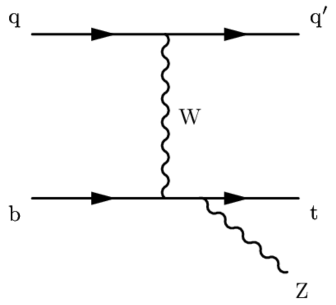


ggF, VH, VBF, ttH

Rare top production

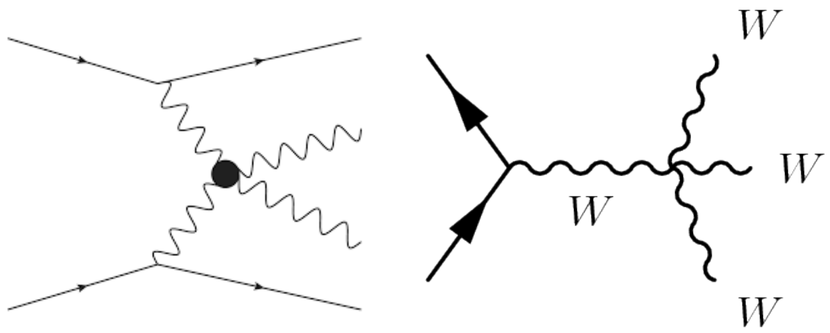


tttt, ttbb



ttV, tW, tZ

Weak boson scattering



VBS, VVV

Each opens a new window, through which we can

- Improve our understanding of the SM
- Search for new physics via new interactions

The SM is broken

Theory & matter content rich with symmetry & structure

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\varphi = \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} : \mathbf{2}_{\frac{1}{2}}$$

Electroweak symmetry breaking

- Offers a **parametrisation**: lacks dynamical origin for the weak scale

Symmetry ↔ Constraints/Relations

$$y_f \, \bar{F}_L f_R \, \varphi \qquad (D^\mu \varphi)^\dagger \, (D_\mu \varphi)$$

Mass ↔ Higgs coupling

$$\frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a \qquad i\bar{F} \not{D} F$$

Self-interactions ↔ Gauge currents

New physics can **indirectly** perturb this delicate balance

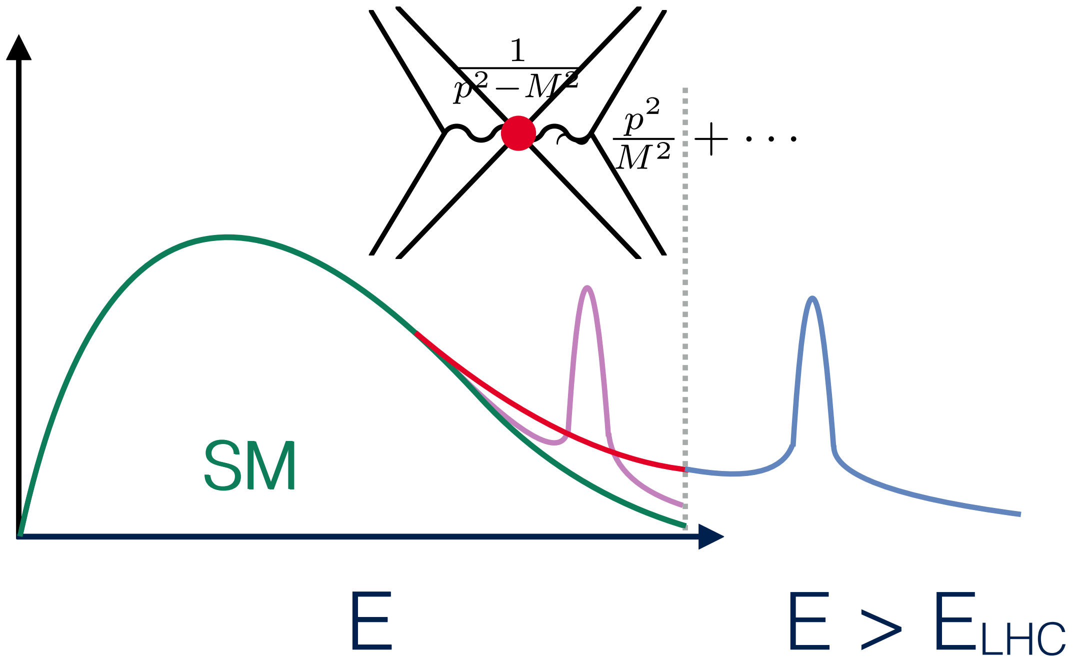
Energy & precision

Paradigm shift at the energy frontier for BSM searches

Direct (bumps)

Indirect (tails)

⇒ New physics is heavy



Heavy new physics
Precision measurements
High energy

Standard Model Effective Field Theory (SMEFT)

A QFT parameter space for BSM interactions between SM particles

SMEFT: SM v2.0

$$\mathcal{L}_{\rm eff} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

SM is low energy effective description

- Supplemented by a tower of irrelevant operators
- Respecting low energy field content & symmetries

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\varphi = \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} : \mathbf{2}_{\frac{1}{2}}$$

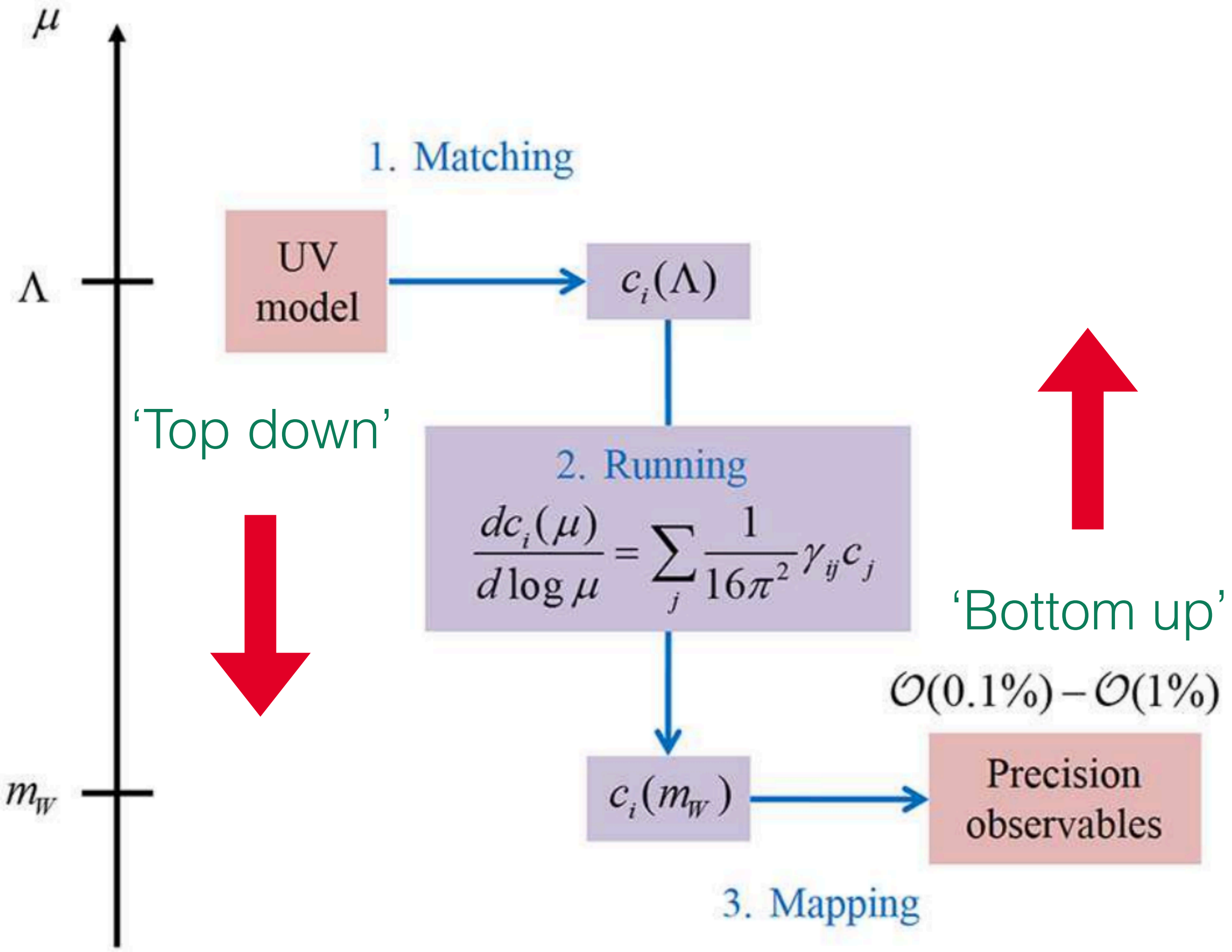
aTGC	$X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$X^2 H^2 : (\varphi^\dagger \varphi)^2 G^a_{\mu\nu} G^{\mu\nu}_a$	ggh(h)
λ_h	$H^6 : (\varphi^\dagger \varphi)^3$	$H^4 D^2 : (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)$	δM_Z
y_f	$\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{q}_i u_j \tilde{\varphi})$	$\psi^2 X H : (\bar{q}_i \sigma^{\mu\nu} u_j \tilde{\varphi}) B_{\mu\nu}$	‘dipole’
ffV	$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j)$	$\psi^4 : (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l)$	4F

More than ‘just’ a parametrisation of ignorance

- Unlike anomalous couplings
- Finite energy range (~Λ)
- Renormalisable QFT (order-by-order)
- Well defined matching procedure

SMEFT strategy

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-4})$$



Map coefficients to the data once and for all

SMEFT is a way to test many BSM scenarios

- Economical
- Well developed

UV matching quasi-automated

- Tree-level dictionary

[de Blas et al.; JHEP 03 (2018) 109]

- Universal one loop effective action

[Henning, Lu & Murayama; JHEP 01 (2016) 023]

[Drozd et al.; JHEP 03 (2016) 180]

RGE are known

[Alonso, Jenkins, Manohar & Trott;*
JHEP 1310 (2013) 087,
JHEP 1401 (2014) 035
JHEP 1404 (2014) 159]*

Mature MC tools

SMEFTsim, SMEFTatNLO, dim6top,…

SMEFT is…

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

Model independent

- Underlying assumptions

Heavy new physics: $M > E_{exp}$

SM field content & gauge symmetries

Linear EWSB: Higgs = doublet

Systematically improvable

- Double expansion *higher dim.* $\frac{E^2}{\Lambda^2}$ & $\{g_S, \, g, \, g'\}$ *more loops*

Global

- Model independence: we don't know what operators NP will generate
- Patterns & correlations among observables are key
- Ultimate goal: complete SMEFT likelihood confronted with HEP data

EWPO, Higgs, multiboson, top, DY, flavor,…

Established part of LHC programme

SMEFT interpretation

Ingredients:

$$\boxed{\Delta o_n} = \boxed{o_n^{\mathrm{EXP}}} - \boxed{o_n^{\mathrm{SM}}} = \sum_i \boxed{\frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2}} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Sensitivity

Experiment:

Best measurements & understanding of uncertainties and correlations

Theory:

Best available predictions for observables (NLO, NNLO, N3LO,…)

Interpretation

Relies on accurate knowledge of the size & correlation among a_i

Determining $c_i^{(6)}$ requires most precise available SMEFT predictions

Status in a nutshell

Global new physics searches via high precision/energy

- Z & W-pole data: handle on the EW gauge sector
- LHC: thriving Higgs & top programmes
- Probing gauge interactions at high energy (VV, VBS, VVV, …)

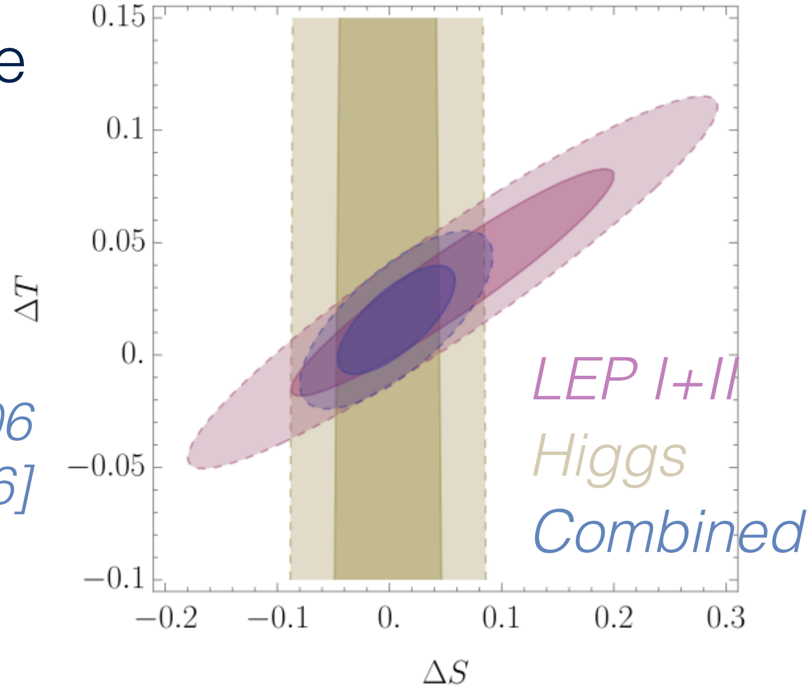
[Han & Skiba; PRD 71 (2005) 075009]
[Falkowski & Riva; JHEP 02 (2015) 039]

How much cross-talk? Where does being global matter?

We know that Higgs data greatly complements LEP

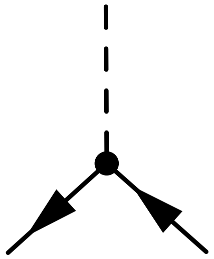
- Access unconstrained directions in parameter space
- Allows for a closed fit to flavor-universal SMEFT
- Crucial to combine EWPO, Diboson & Higgs data

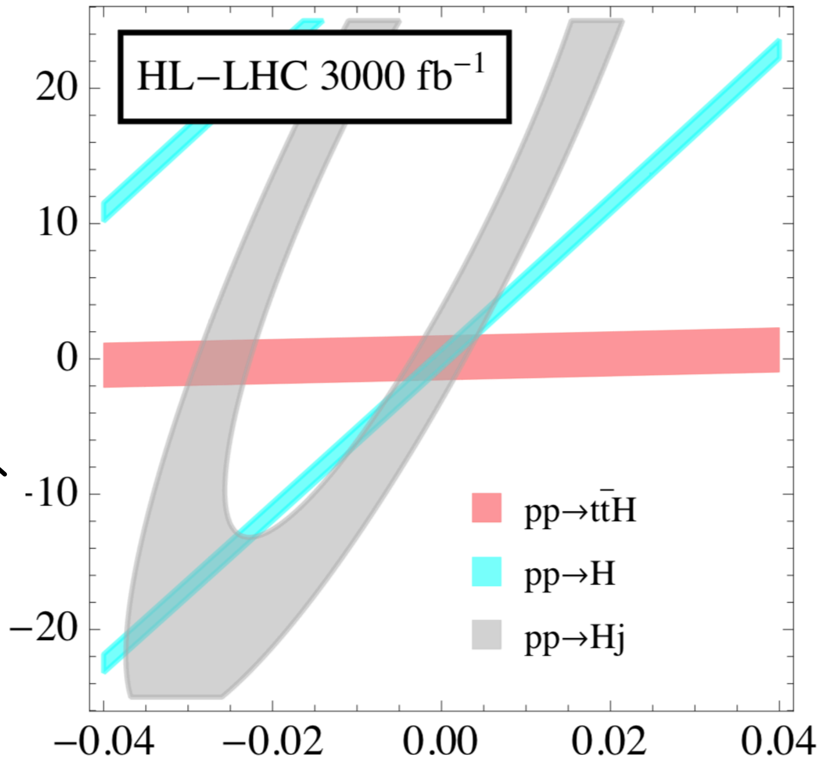
[Corbett et al.; PRD 87 (2013) 015022]
[Pomarol & Riva; JHEP 01 (2014) 151]
[Ellis, Sanz & You; JHEP 03 (2015) 157]
[Biekötter Corbett & Plehn; SciPost Phys 6 (2019) 6, 064]…
[Ellis et al.; JHEP 06 (2018) 146]

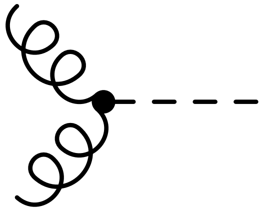


Top & Higgs

[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]







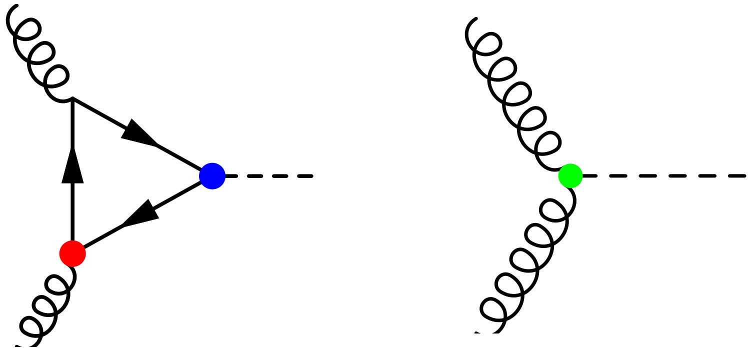
Inextricably linked in the SM

- Yukawa interaction controls ggF
- Strong BSM motivation to study tops

ggF is well measured now

- Does not exclude top partners, anomalous Yukawa!

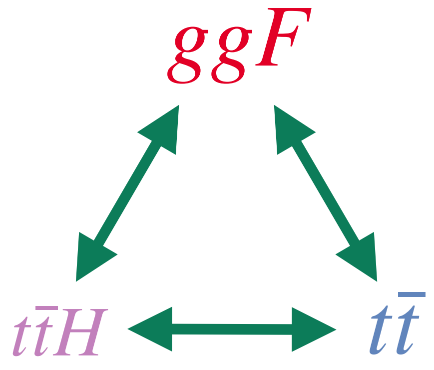
C_{HG} Point-like
C_{tH} Yukawa
C_{tG} Dipole



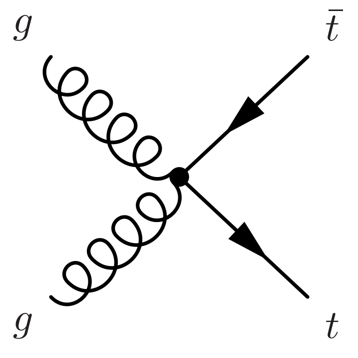
Blind direction in BSM scenarios
=
Effective coupling degeneracy

Need more data to break degeneracy

- $t\bar{t}H$ production for direct Yukawa measurement
- $t\bar{t}$ data to constrain dipole

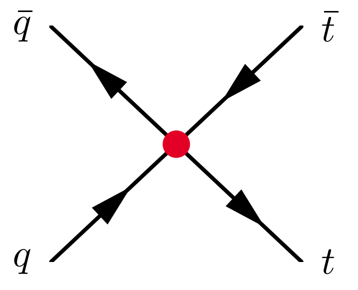


The role of top data



$t\bar{t}$ cross section measurements constrain C_{tG}

- Indirectly improve bounds on C_{HG} and C_{tH}



Several other new interactions can affect $t\bar{t}$

- Notably $q\bar{q}t\bar{t}$ operators, of which there are many (14)
- To what extent do these limit ultimate NP sensitivity in top/Higgs sector?

Can only be addressed in combined fit

- Beyond tree-level (at least for ggF)

[Degrande et al.; PRD 103 (2021) 9, 096024]
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

- Identify other cross-talk (non-trivial correlations)
- Crystallisation of knowledge gained after LHC Run 2
- Broaden range of applicability to UV models

The fit

Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory

John Ellis,[a,b,c] Maeve Madigan,[d] Ken Mimasu,[a] Veronica Sanz[e,f] and Tevong You[b,d,g]

[JHEP 04 (2021) 279]

Global SMEFT interpretation of 4 categories of data

Based on [Ellis et al.; JHEP 06 (2018) 146]

- 14 Electroweak Precision Observables (EWPO): Z-pole & W-mass
- 118 LEP2 & LHC diboson production: differential WW, WZ, Zjj
- 72 Higgs measurements: signal strengths & STXS
- 137 Top data: single-top, ttbar & asymmetries, ttV, tZ, tW

Big thanks to authors of SMEFiT analysis [JHEP 04 (2019) 100] for sharing some of their top predictions

341 measurements across categories

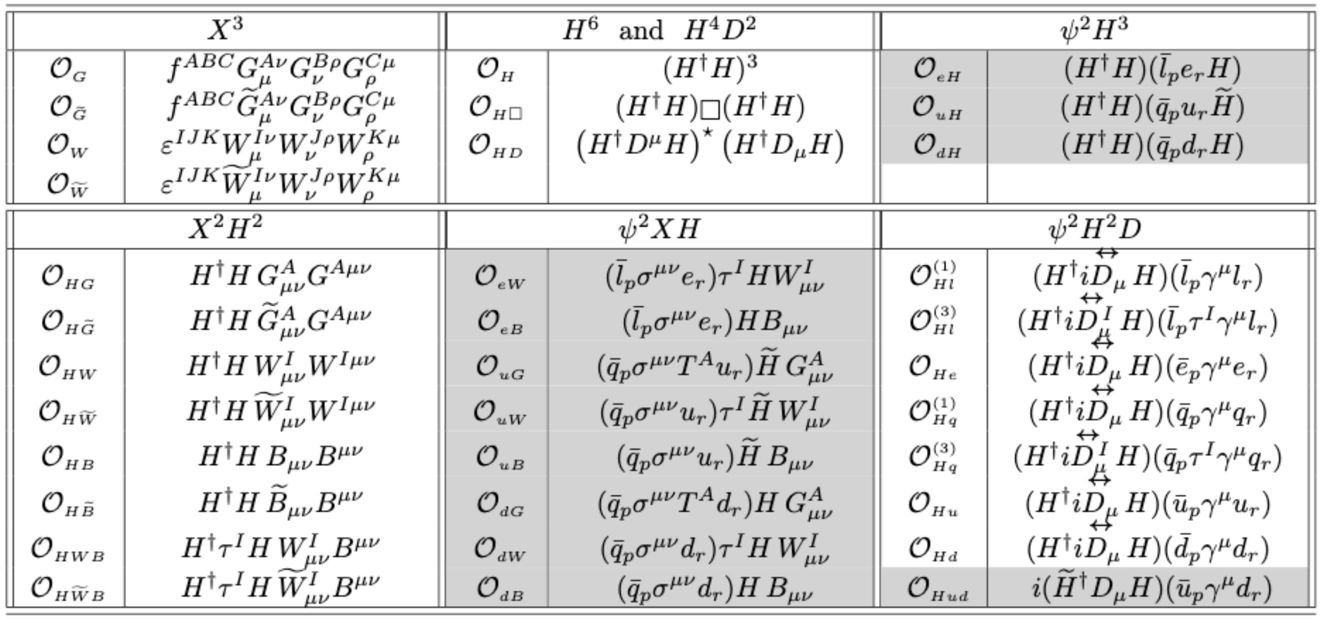
- Chosen to be statistically independent & maximise reach
- Correlations included when publicly available (mostly are)

Linear EFT approximation:

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

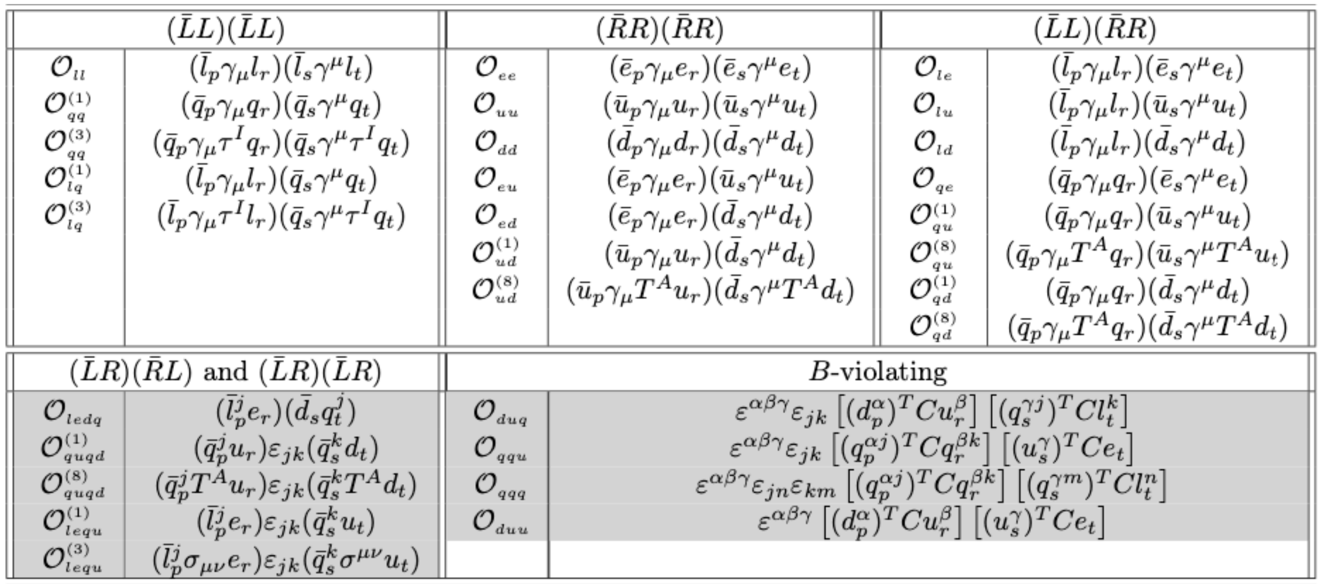
Theory

[Grzadkowski et al.; JHEP 10 (2010) 085]



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



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

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

Warsaw basis with CP & B conservation

- Full ‘bosonic’ sector: Higgs, triple-gauge & gauge-Higgs
- Scenario 1: Flavor-**universal** degrees of freedom

$U(3)_L$ x $U(3)_e$ x $U(3)_Q$ x $U(3)_u$ x $U(3)_d$ + Yukawas: $\mathcal{O}_{tH}, \mathcal{O}_{bH}, \mathcal{O}_{\tau H}, \mathcal{O}_{\mu H}$

- Scenario 2: **top**-centric flavor symmetry

$U(3)_L$ x $U(3)_e$ x $U(2)_Q$ x $U(2)_u$ x $U(3)_d$

cf. Minimal flavor violation

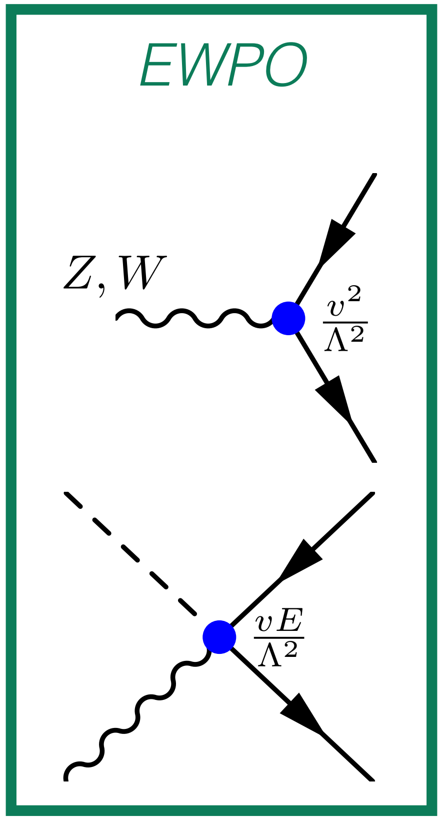
[Buras et al.; PLB 500 (2001) 161]

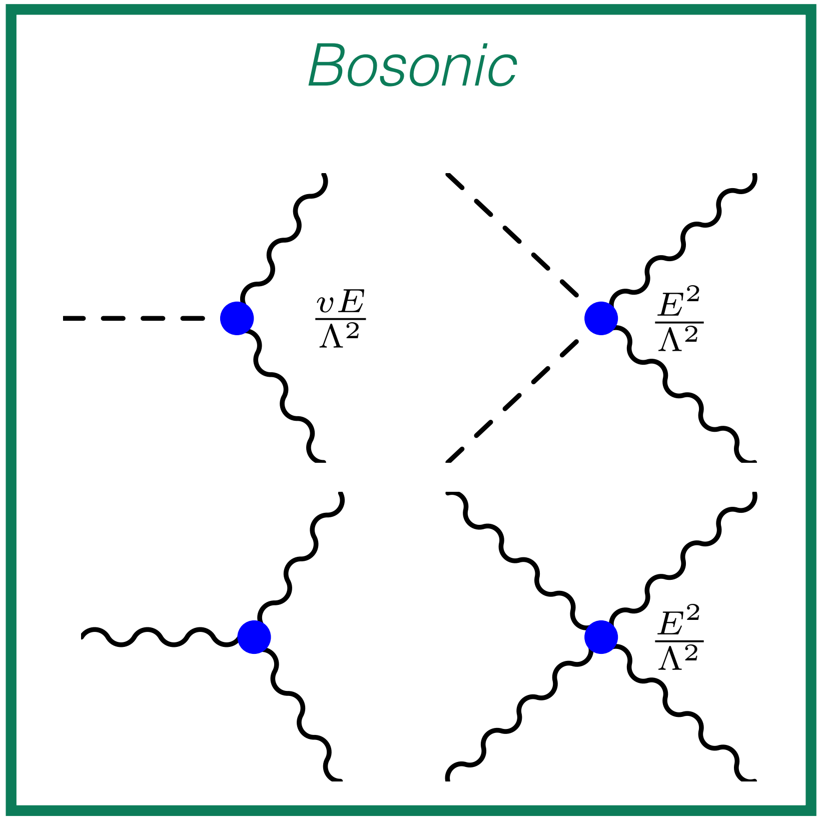
[D’Ambrosio et al.; NPB 645 (2002) 155]

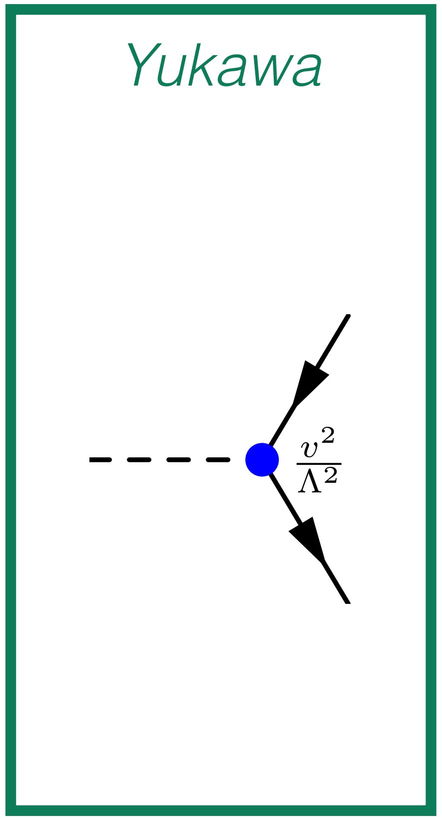
[Aguilar-Saavedra et al.; arXiv:1802.07237]

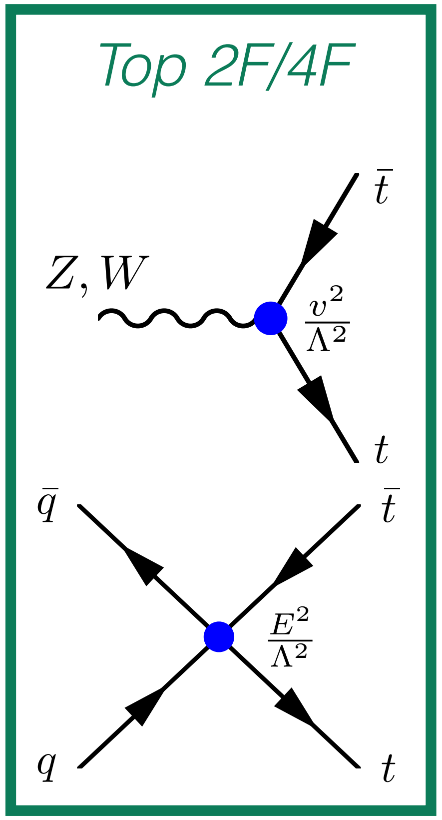
Degrees of freedom

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:	$\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,,$	20
Top 2F:	$\mathcal{O}_{HQ}^{(3)}\,,\ \mathcal{O}_{HQ}^{(1)}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,$	
Top 4F:	$\mathcal{O}_{Qq}^{3,1}\,,\ \mathcal{O}_{Qq}^{3,8}\,,\ \mathcal{O}_{Qq}^{1,8}\,,\ \mathcal{O}_{Qu}^{8}\,,\ \mathcal{O}_{Qd}^{8}\,,\ \mathcal{O}_{tQ}^{8}\,,\ \mathcal{O}_{tu}^{8}\,,\ \mathcal{O}_{td}^{8}\,.$	+14

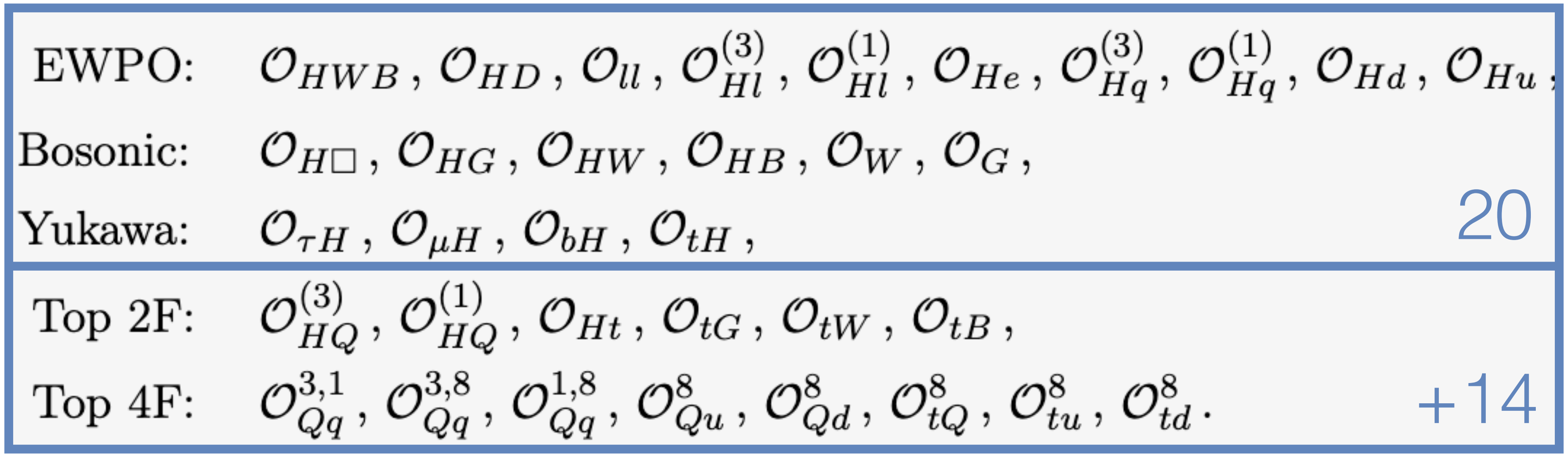








Degrees of freedom



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

20

Top 2F: $\mathcal{O}_{HQ}^{(3)}\,, \mathcal{O}_{HQ}^{(1)}\,, \mathcal{O}_{Ht}\,, \mathcal{O}_{tG}\,, \mathcal{O}_{tW}\,, \mathcal{O}_{tB}\,,$

Top 4F: $\mathcal{O}_{Qq}^{3,1}\,, \mathcal{O}_{Qq}^{3,8}\,, \mathcal{O}_{Qq}^{1,8}\,, \mathcal{O}_{Qu}^{8}\,, \mathcal{O}_{Qd}^{8}\,, \mathcal{O}_{tQ}^{8}\,, \mathcal{O}_{tu}^{8}\,, \mathcal{O}_{td}^{8}\,.$

+14

In total: 20(34) d.o.f. for the two flavor scenarios

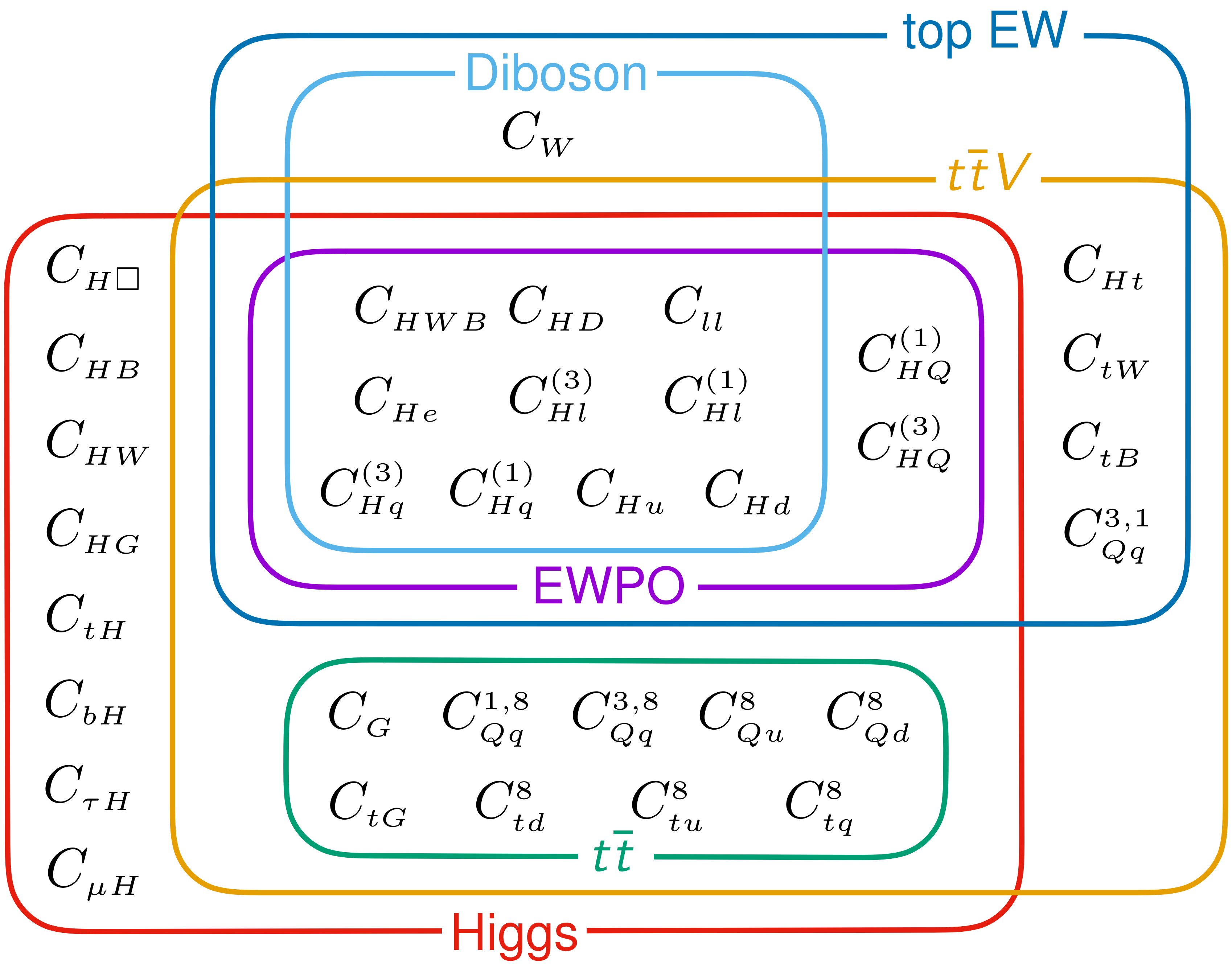
Dim6top conventions: [Aguilar-Saavedra et al.; arXiv:1802.07237]

Dictated by flavor symmetry & sensitivity of dataset

Linear EFT fit: precludes sensitivity to some ops

- Those that cannot interfere due to helicity/symmetries
- e.g. neutral colour-singlet top 4F operators: $(\bar{q}\gamma^{\mu}q)(\bar{t}\gamma^{\mu}t)$ (x 6)
- Four-heavy quark operators in 4top & ttbb (quadratic dominated)

Interplay



top EW

Diboson

C_W

$t\bar{t}V$

$C_{H\Box}$ C_{HB} C_{HW} C_{HG} C_{tH} C_{bH} $C_{\tau H}$ $C_{\mu H}$

C_{HWB} C_{HD} C_{ll}

C_{He} $C_{Hl}^{(3)}$ $C_{Hl}^{(1)}$

$C_{Hq}^{(3)}$ $C_{Hq}^{(1)}$ C_{Hu} C_{Hd}

$C_{HQ}^{(1)}$ $C_{HQ}^{(3)}$

C_{Ht} C_{tW} C_{tB} $C_{Qq}^{3,1}$

EWPO

C_G $C_{Qq}^{1,8}$ $C_{Qq}^{3,8}$ C_{Qu}^{8} C_{Qd}^{8}

C_{tG} C_{td}^{8} C_{tu}^{8} C_{tq}^{8}

$t\bar{t}$

Higgs

Technical details

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

Exp. data: **`HEPdata`**, **`WebPlotDigitizer`**, …

- Construct ‘signal strength’, w.r.t. SM prediction from exp. paper
- Otherwise computed with **`MG5`**, **`fastnlo`**, directly from theory papers
- Combine all sources of uncertainty in quadrature (stat., syst., th.)

Theory predictions: **`MG5`** (**`SMEFTsim`** & **`SMEFTatNLO`**)

- LO, parton-level, linear dependence in (α, G_F, M_Z) scheme
- Tree-level + 1-loop gluon fusion Higgs production
- a_i: Effects from production, decays, total width
- No theory error from EFT, assume SM error dominant

The code

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

public-friendly version w/ example notebooks in progress

Main analysis: linearised least-squares fit

$$\chi^2(C_i) = (\vec{y} - \vec{\mu}(C_i))^T\,\mathbf{V}^{-1}\,(\vec{y} - \vec{\mu}(C_i)) \qquad \mu_\alpha(C_i) = \mu_\alpha^{\rm SM} + \mathbf{H}_{\alpha i}C_i$$

Best fit $$\hat{\vec{C}} = \left(\mathbf{H}^T\mathbf{V}^{-1}\mathbf{H}\right)^{-1}\mathbf{H}^T\mathbf{V}^{-1}(\vec{y} - \vec{\mu}^{\rm SM}) \equiv \mathbf{F}^{-1}\vec{\omega}$$

$$\mathbf{F} \equiv \mathbf{H}^T\mathbf{V}^{-1}\mathbf{H} \quad , \quad \vec{\omega} \equiv \mathbf{H}^T\mathbf{V}^{-1}(\vec{y} - \vec{\mu}^{\rm SM})\,,$$

Fisher information

$\mathbf{F}^{-1} \equiv \mathbf{U}$ Covariance matrix of least-squares estimators

$(\chi^2_{SM}, \hat{\vec{C}}, \mathbf{U})$ fully characterise likelihood

- Individual, profiled/marginalised bounds & correlations
- Principal component analysis (eigensystem of F)

Implemented as part of the `fitmaker` framework

Also nested sampling routine for general likelihoods

The code

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

public-friendly version w/ example notebooks in progress

Database of input measurements encoded in `.json` format

- Values, errors, metadata,…

Python-class based definition of theoretical models

- Predictions for observables can be hard-coded
- …or read-in from a `.json` file

$$\mu^{ggF}_{H\to 4\ell} = 0.98^{+0.12}_{-0.11}$$

```
{
  "observable_name": "mu_ggF_H_ZZ_13", 
  "measurement_name": "mu_ggF_H_ZZ_CMS_Run2", 
  "CDS": "http://cds.cern.ch/record/2706103", 
  "reportnumber": "CMS-PAS-HIG-19-005", 
  "DOI": "", 
  "date": "2020/01/10", 
  "experiment": "CERN LHC Run 2, CMS", 
  "description": "Higgs boson signal strength for 
  "value": 0.98, 
  "uncertainty": {
    "tot": [ 0.12, 0.11 ]
  }, 
  "uncertainty_sigma": 1, 
  "th_flat": true
}
```

$$\mu^{ggF} = 1 + 35.8C_{HG} - 0.122C_{tH}$$
$$-0.959C_{tG} - 0.121C_{H\Box} + \ldots$$

```
{
  "observable": "ggF0j",
  "params": [ "CHG", "CuH", "CuG", "CHbox" ],
  "constant": 1.0,
  "linear": [ 35.8, -0.122, 0.959, -0.121 ],
  "quadratic": [
  [ 321.0, -1.095, 8.45, -1.085 ],
 [ -1.095, 0.00371, -0.02925, 0.003695 ],
 [ 8.45, -0.02925, 0.23, -0.0291 ],
 [ -1.085, 0.003695, -0.0291, 0.00367 ]
  ],
  "lambda_gen": 1000.0
}
```

[G. Durieux, C. Degrande, F. Maltoni, KM, C. Zhang, E. Vryonidou; PRD 103 (2021) 9, 096024]

SMEFT@NLO

Loops & SMEFT: active field in recent years

- Non-universal K-factors in EFT space ⇔ new information at NLO
- Loop-induced sensitivity (e.g. $gg \to H$)
- Control theoretical uncertainties
- Experimental interest in higher precision for SMEFT analyses/interpretations

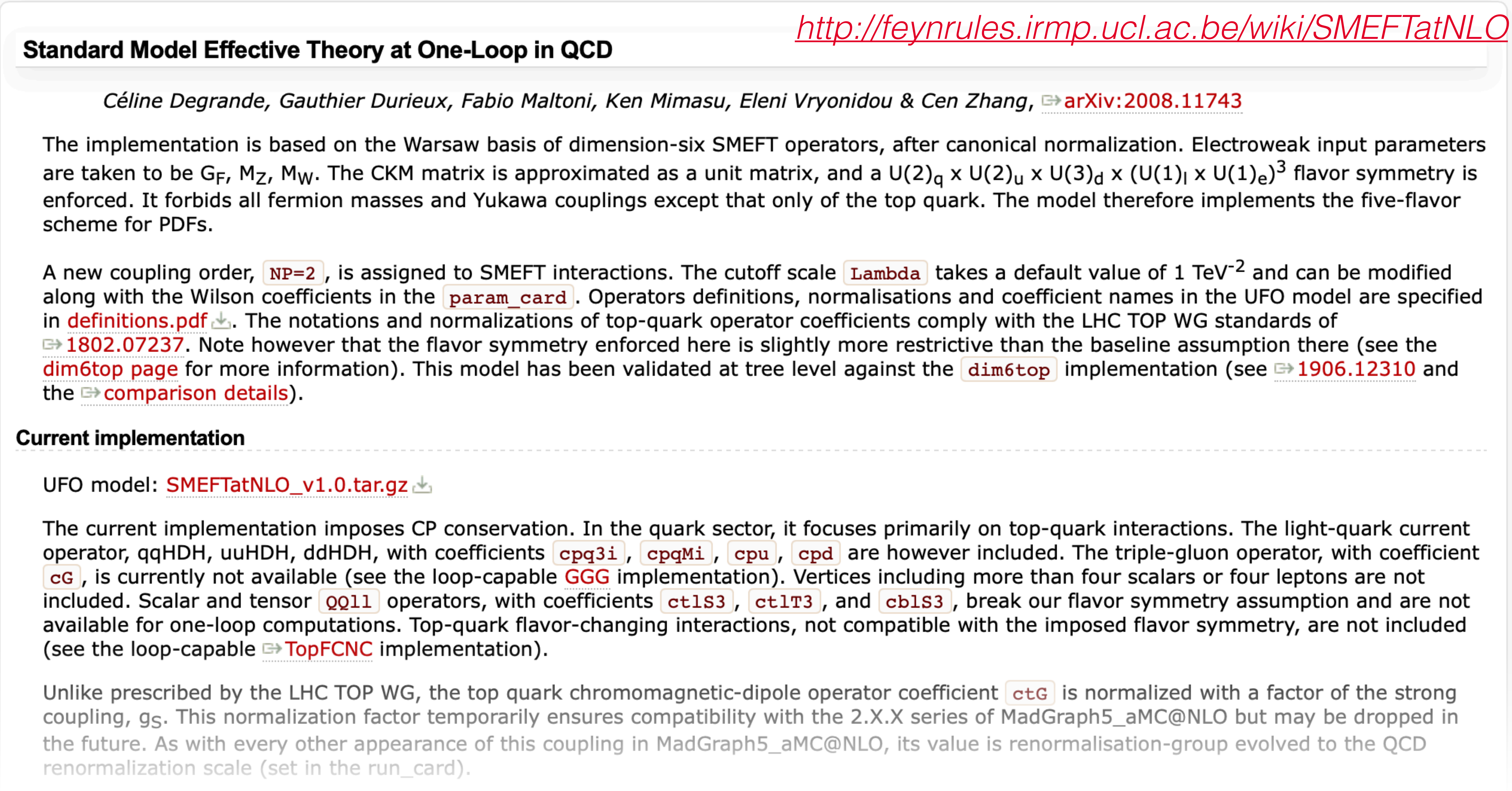
Challenge: many processes x many operators

- LO ⇒ NLO = more cross-talk/operators/complexity
- Automated tools for fixed-order/NLO+PS are essential to the LHC programme

Solution: SMEFT@NLO

- UFO model for `MadGraph5_aMC@NLO`
- Process-independent implementation: SMEFT in top-specific flavor limit

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO



Standard Model Effective Theory at One-Loop in QCD

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang, arXiv:2008.11743

The implementation is based on the Warsaw basis of dimension-six SMEFT operators, after canonical normalization. Electroweak input parameters are taken to be G_F, M_Z, M_W. The CKM matrix is approximated as a unit matrix, and a $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_l \times U(1)_e)^3$ flavor symmetry is enforced. It forbids all fermion masses and Yukawa couplings except that only of the top quark. The model therefore implements the five-flavor scheme for PDFs.

A new coupling order, `NP=2`, is assigned to SMEFT interactions. The cutoff scale `Lambda` takes a default value of 1 TeV^{-2} and can be modified along with the Wilson coefficients in the `param_card`. Operators definitions, normalisations and coefficient names in the UFO model are specified in definitions.pdf. The notations and normalizations of top-quark operator coefficients comply with the LHC TOP WG standards of 1802.07237. Note however that the flavor symmetry enforced here is slightly more restrictive than the baseline assumption there (see the dim6top page for more information). This model has been validated at tree level against the `dim6top` implementation (see 1906.12310 and the comparison details).

Current implementation

UFO model: SMEFTatNLO_v1.0.tar.gz

The current implementation imposes CP conservation. In the quark sector, it focuses primarily on top-quark interactions. The light-quark current operator, qqHDH, uuHDH, ddHDH, with coefficients `cpq3i`, `cpqMi`, `cpu`, `cpd` are however included. The triple-gluon operator, with coefficient `cG`, is currently not available (see the loop-capable GGG implementation). Vertices including more than four scalars or four leptons are not included. Scalar and tensor `QQll` operators, with coefficients `ctlS3`, `ctlT3`, and `cblS3`, break our flavor symmetry assumption and are not available for one-loop computations. Top-quark flavor-changing interactions, not compatible with the imposed flavor symmetry, are not included (see the loop-capable TopFCNC implementation).

Unlike prescribed by the LHC TOP WG, the top quark chromomagnetic-dipole operator coefficient `ctG` is normalized with a factor of the strong coupling, g_S. This normalization factor temporarily ensures compatibility with the 2.X.X series of MadGraph5_aMC@NLO but may be dropped in the future. As with every other appearance of this coupling in MadGraph5_aMC@NLO, its value is renormalisation-group evolved to the QCD renormalization scale (set in the run_card).

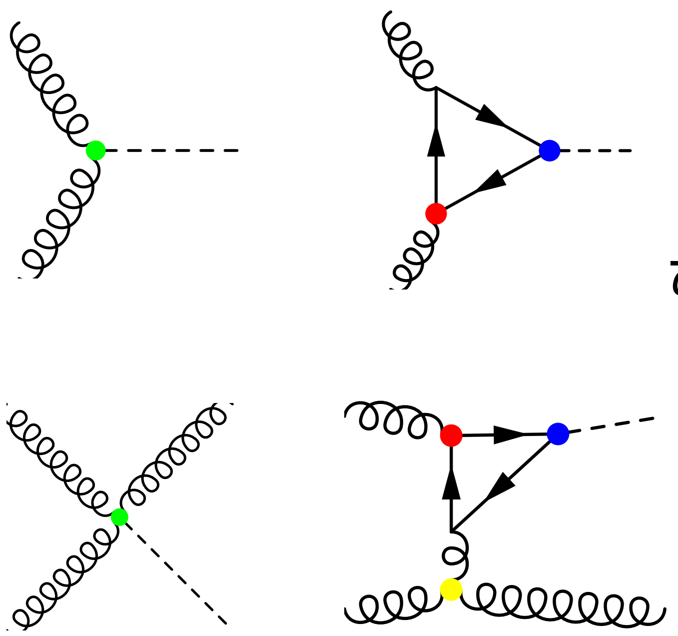
```
MG5_aMC>import model SMEFTatNLO

MG5_aMC>generate p p > t t~ NP=2 [QCD]

MG5_aMC>output

MG5_aMC>launch
```

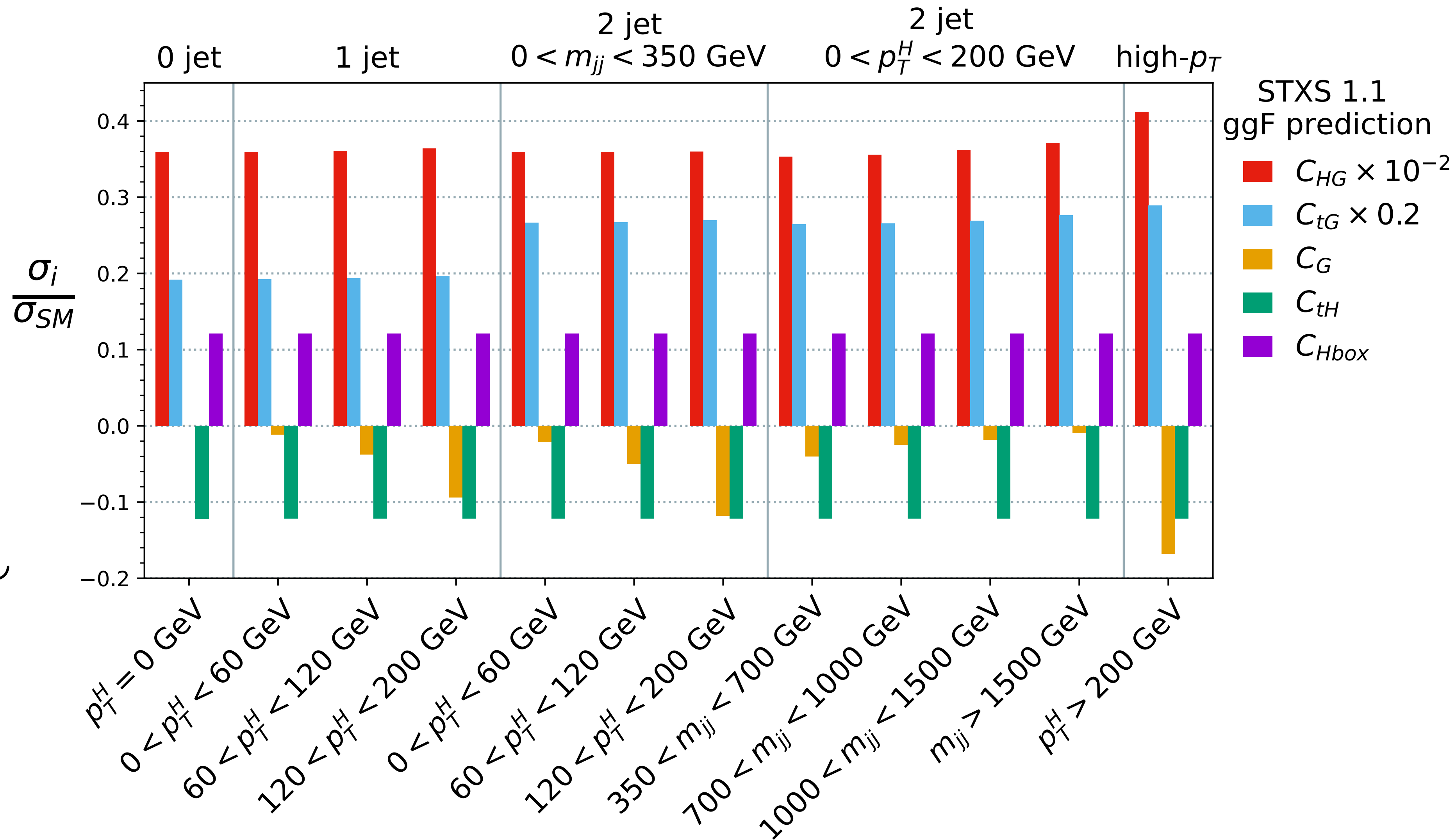
See also: [ATLAS-CONF-2020-053]

SMEFT@NLO in STXS

Gluon fusion Simplified Template Cross Section bins

- LO in the SM is one-loop
- Tree-EFT x loop-SM + loop-EFT x loop-SM interference terms
- Heavy top limit is OK for 0-jet, breaks down at high-p_T





Results roadmap

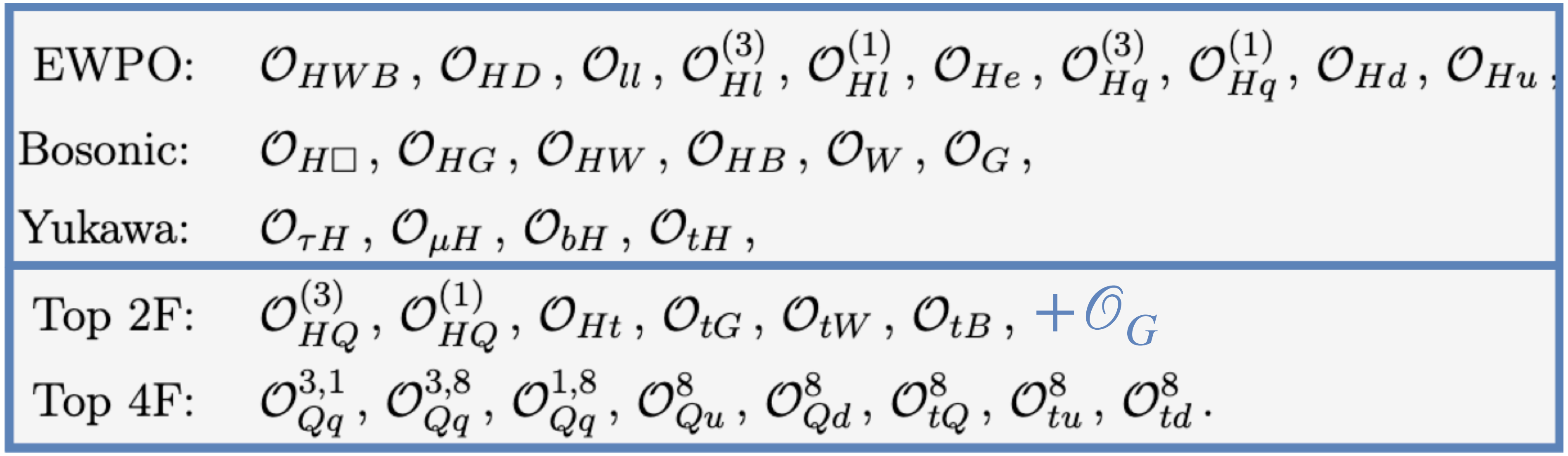
1. Flavor universal: EWPO + diboson + Higgs

2. Top only: EWPO + top

Interlude: Top-Higgs interplay

3. Top-specific : EWPO + diboson + Higgs + top

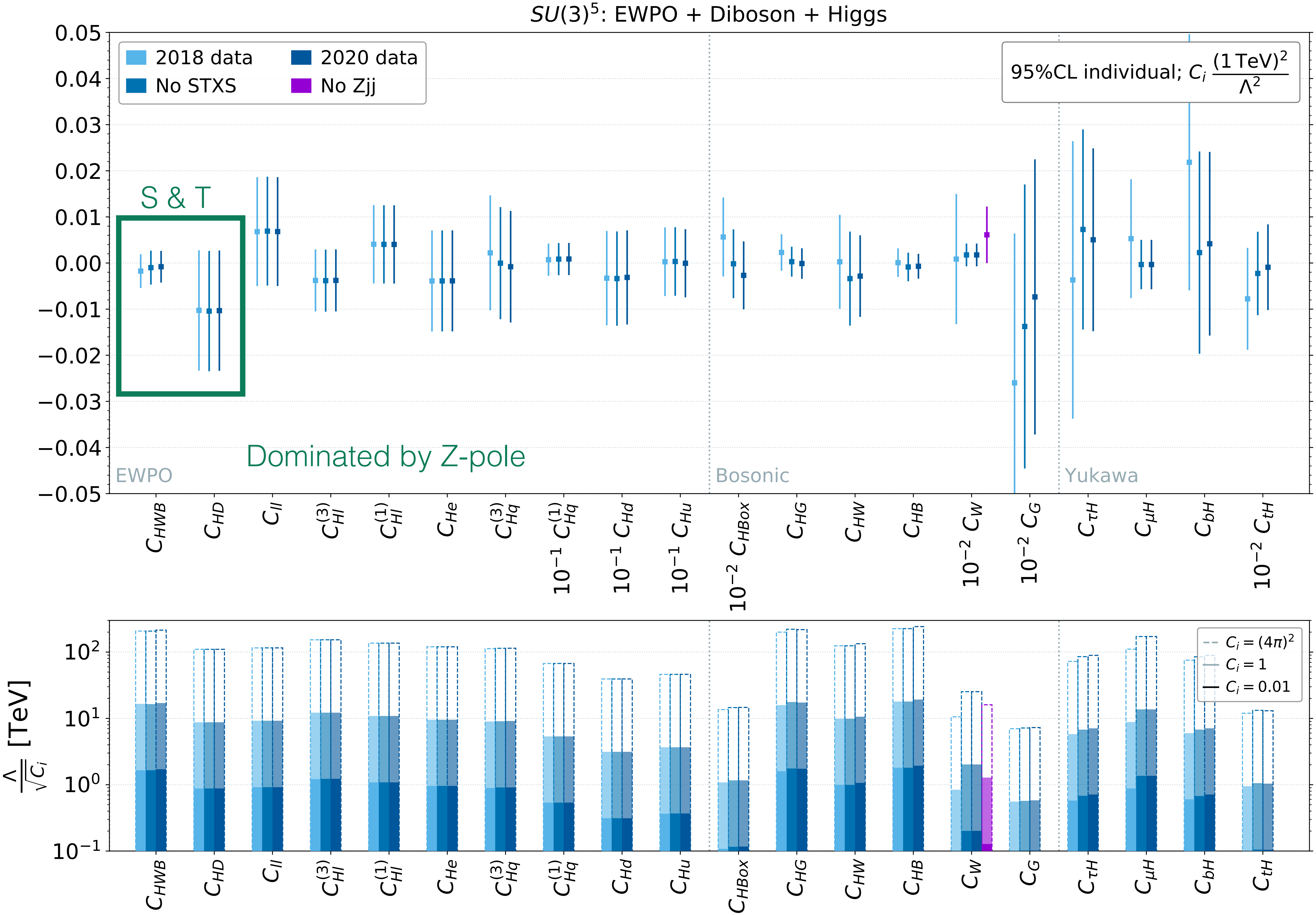
$U(3)^5$
↓
$U(2)^2 \times U(3)^3$



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:	$\mathcal{O}_{HQ}^{(3)}\,,\ \mathcal{O}_{HQ}^{(1)}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,$ $+\mathcal{O}_G$
Top 4F:	$\mathcal{O}_{Qq}^{3,1}\,,\ \mathcal{O}_{Qq}^{3,8}\,,\ \mathcal{O}_{Qq}^{1,8}\,,\ \mathcal{O}_{Qu}^{8}\,,\ \mathcal{O}_{Qd}^{8}\,,\ \mathcal{O}_{tQ}^{8}\,,\ \mathcal{O}_{tu}^{8}\,,\ \mathcal{O}_{td}^{8}\,.$

Individual limits: U(3)^5

2018 data: *[Ellis et al.; JHEP 06 (2018) 146]*

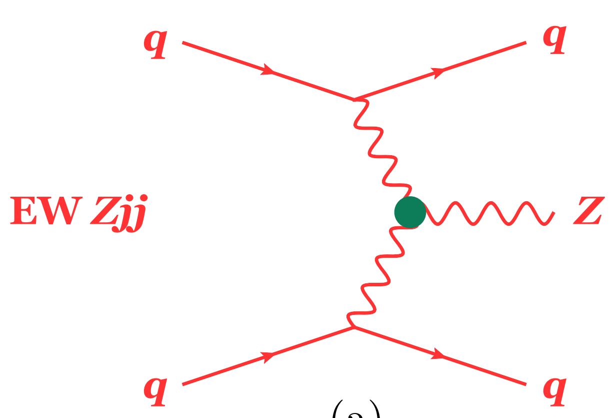


S & T

Dominated by Z-pole

Zjj for triple gauge coupling

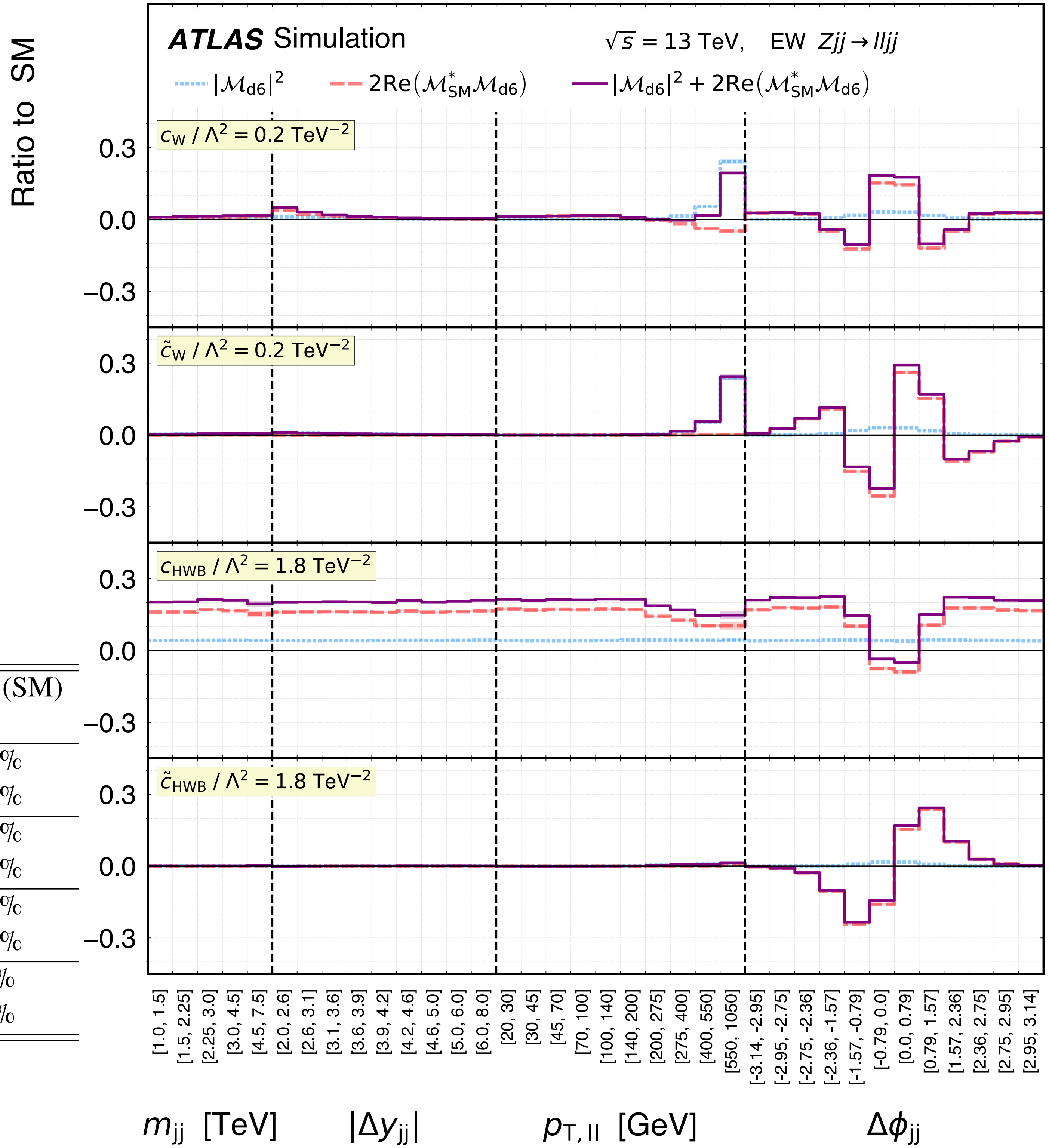
[ATLAS; CERN-EP-2020-045]



(a)

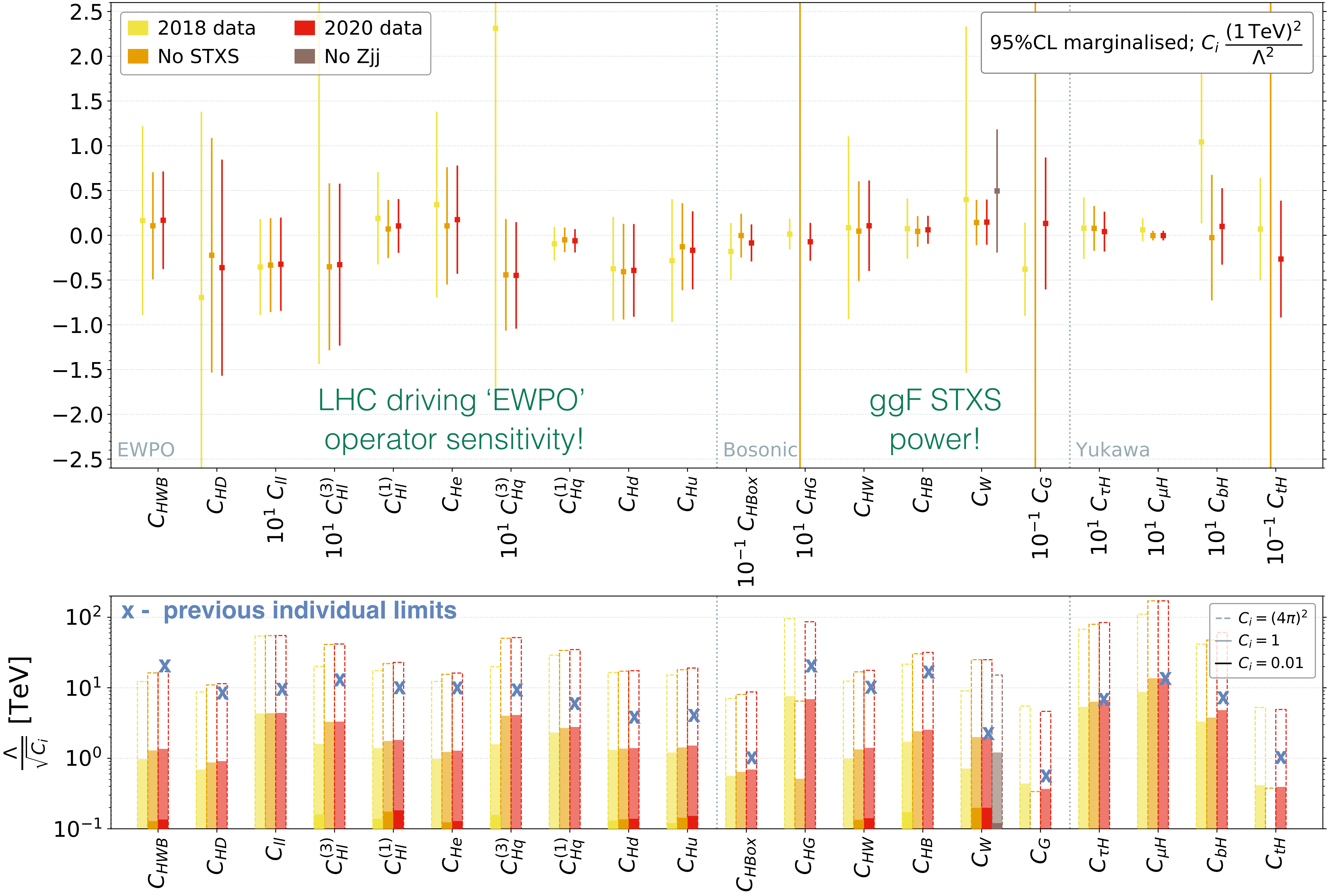
$\Delta\phi_{jj}$ distribution sensitive to linear C_W contributions

Wilson coefficient	Includes $\lvert\mathcal{M}_{\mathrm{d6}}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	$[-0.30,\ 0.30]$	$[-0.19,\ 0.41]$	45.9%
	yes	$[-0.31,\ 0.29]$	$[-0.19,\ 0.41]$	43.2%
$\tilde{c}_W/\Lambda^2$	no	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	82.0%
	yes	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	81.8%
c_{HWB}/Λ^2	no	$[-2.45,\ 2.45]$	$[-3.78,\ 1.13]$	29.0%
	yes	$[-3.11,\ 2.10]$	$[-6.31,\ 1.01]$	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	$[-1.06,\ 1.06]$	$[0.23,\ 2.34]$	1.7%
	yes	$[-1.06,\ 1.06]$	$[0.23,\ 2.35]$	1.6%



Marginalised limits: U(3)^5

2018 ⇒ 2020: only LHC data changed

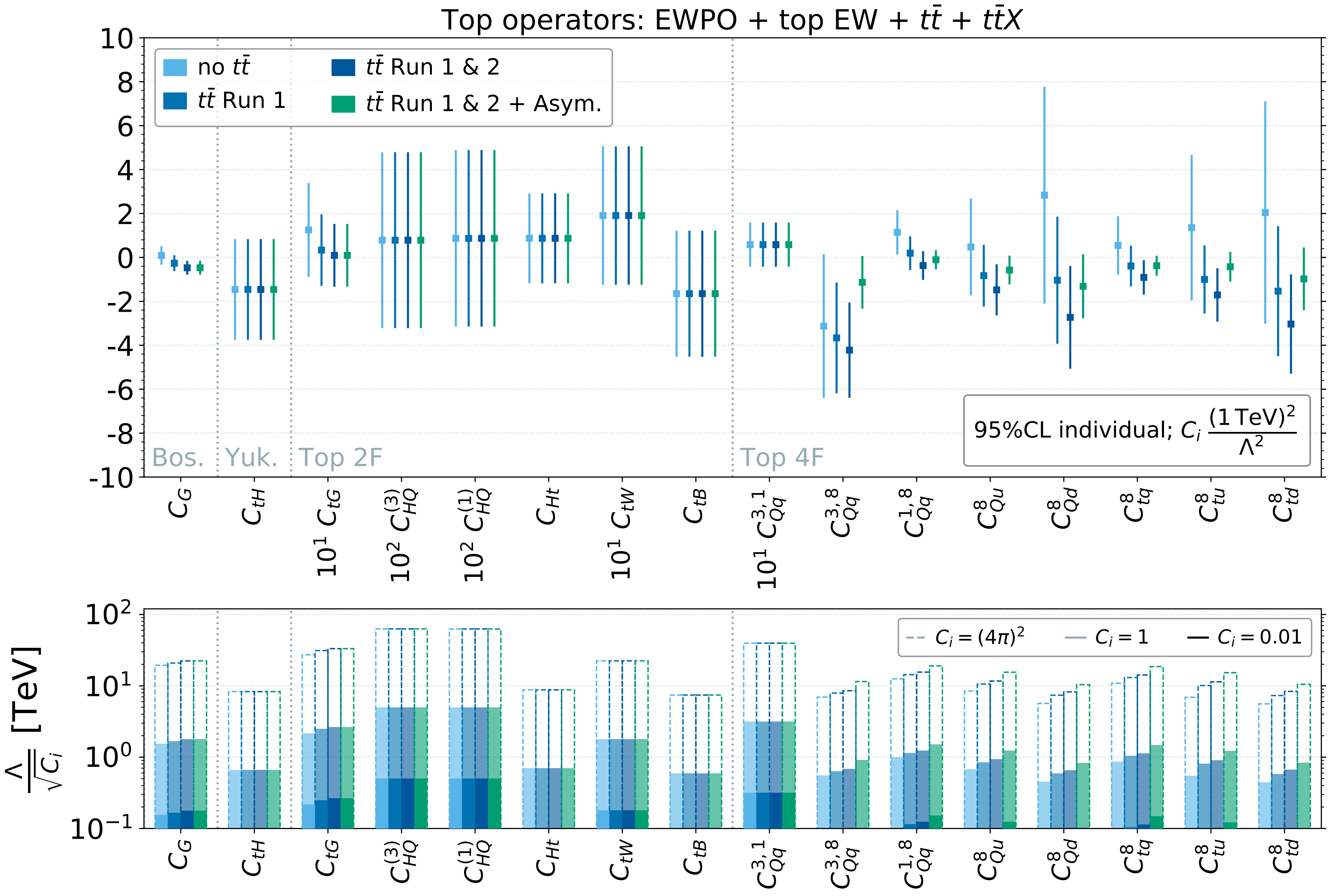


LHC driving 'EWPO' operator sensitivity!

ggF STXS power!

x - previous individual limits

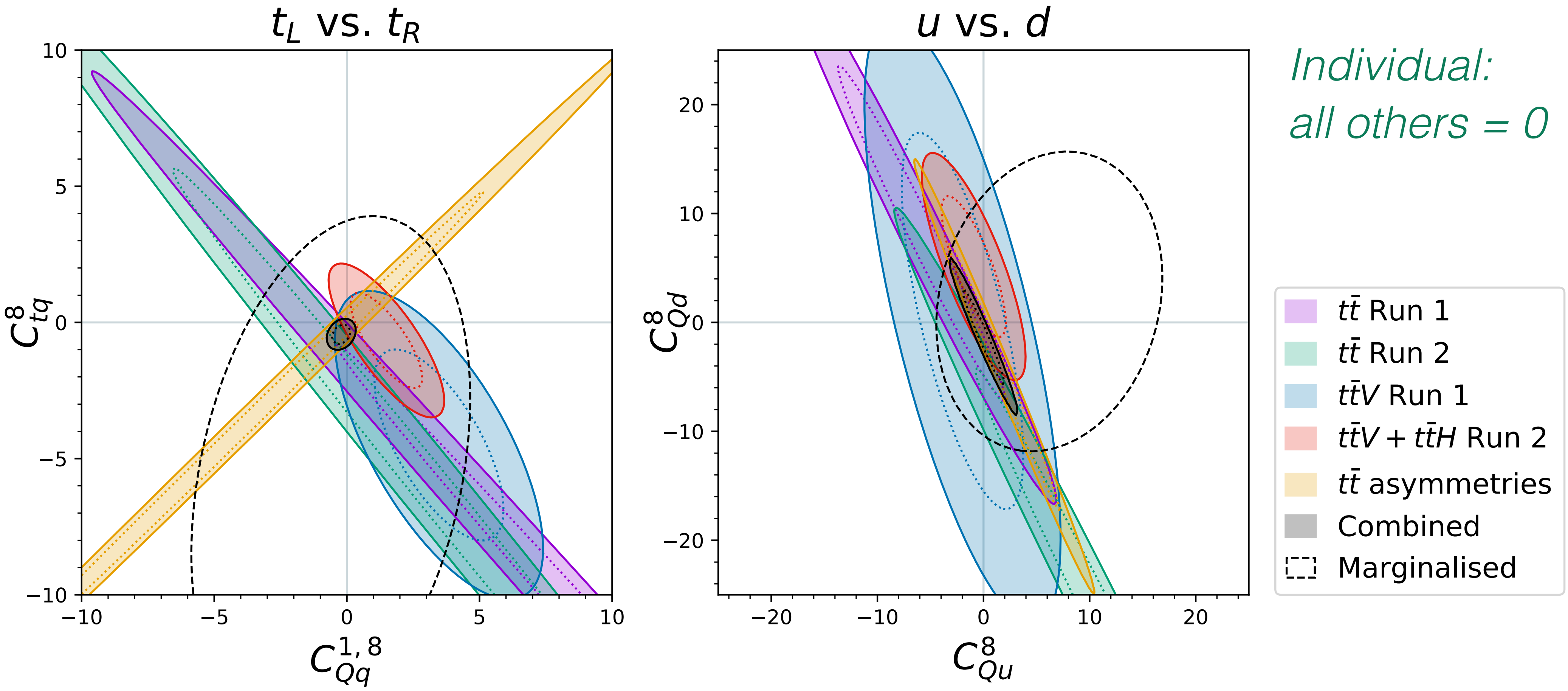
Top-only: top + EWPO individual



- Some tension in $t\bar{t}$ data
- Asymmetries help to improve agreement

See also dedicated top fits: *SMEFiT [Hartland et al.; JHEP 04 (2019) 100]*
SFitter [Brivio et al.; JHEP 02 (2020) 131]

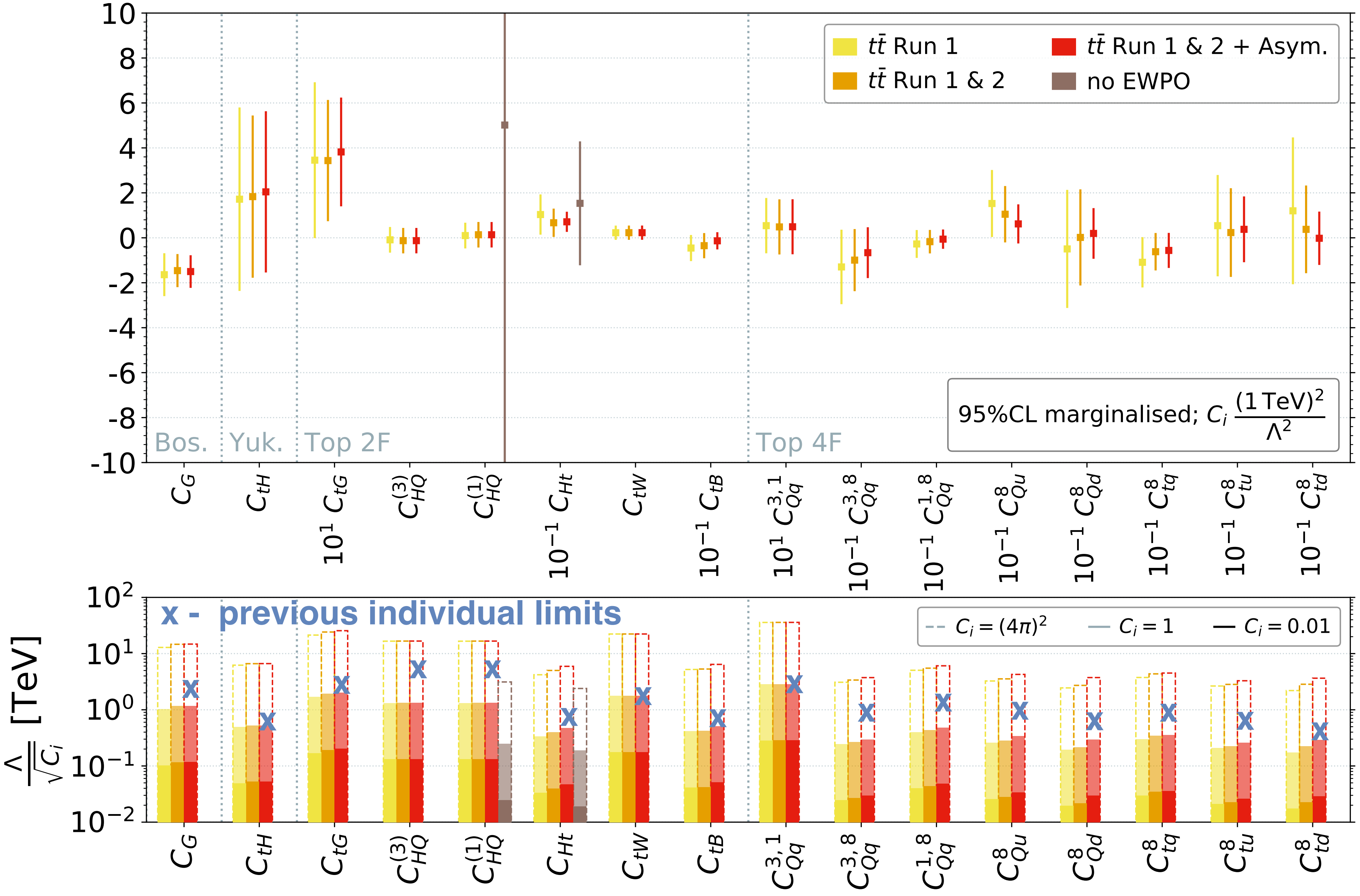
Top-only: breakdown



Individual:
all others = 0

- $t\bar{t}$ asymmetries constrain orthogonal direction to cross section
- Large marginalisation effects: many similar operators
- $t\bar{t}V$ & $t\bar{t}H$ help to close the space
- Marginalised linear sensitivity: $C_{4F}\left[\dfrac{1\,\mathrm{TeV}^2}{\Lambda^2}\right] \sim (5-15)$ *significant* $\dfrac{1}{\Lambda^4}$ *effects*

Top-only: top + EWPO marginalised

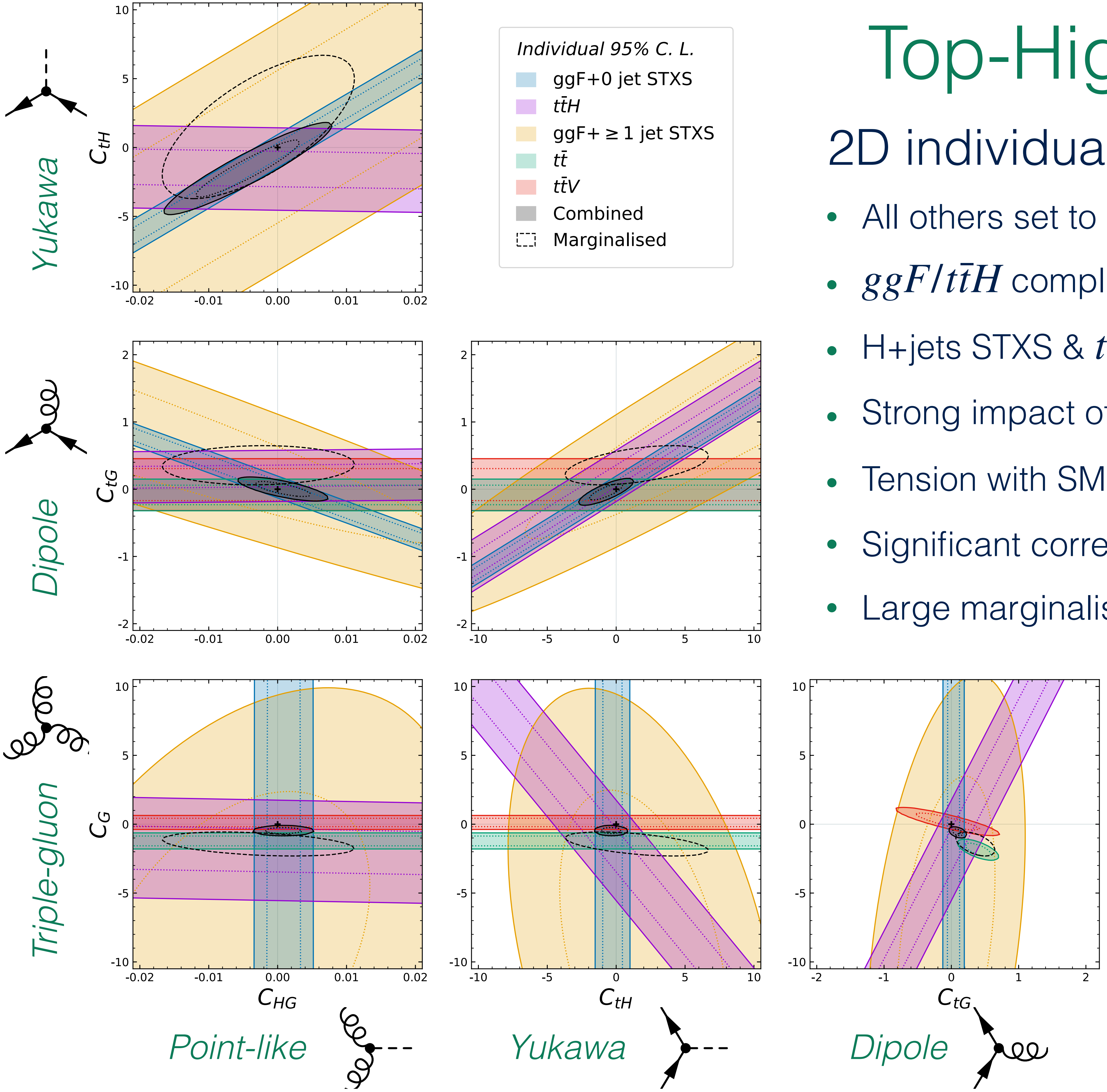


- C_{tH}: $t\bar{t}H$ bound alone is quite weak
- C_{tG}: Strong constraint but tension with SM
- Neutral top couplings poorly constrained
- EWPO closes $Zb\bar{b}$ coupling direction
- Impact of asymmetries in 4F
- Somewhat low scales (validity?)

Top-Higgs interplay

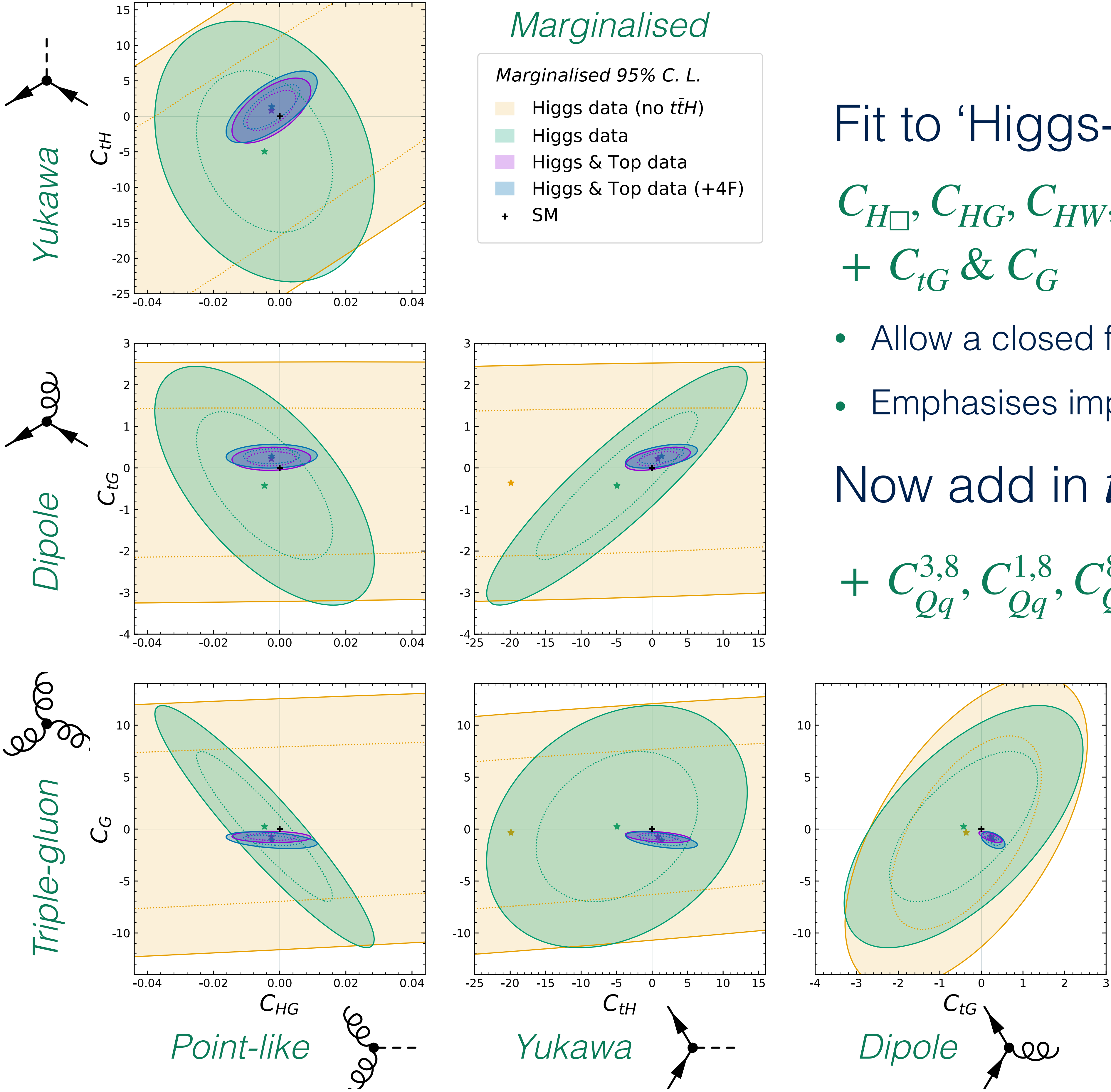
2D individual constraints

- All others set to 0
- $ggF/t\bar{t}H$ complementarity for (C_{HG}, C_{tH})
- H+jets STXS & $t\bar{t}V$ not yet competitive
- Strong impact of $t\bar{t}$ evident for (C_{tG}, C_G)
- Tension with SM $\sim 2\sigma$
- Significant correlations remain
- Large marginalisation effects



What is the concrete impact of 4F?

4F impact



Fit to ‘Higgs-only’ subspace

$C_{H\Box}, C_{HG}, C_{HW}, C_{HB}, C_{tH}, C_{bH}, C_{\tau H}, C_{\mu H}$
$+\ C_{tG}\ \&\ C_G$

- Allow a closed fit to Higgs data only
- Emphasises impact of $t\bar{t}H\ \&\ t\bar{t}$

Now add in $t\bar{t}$ 4F operators

$+\ C^{3,8}_{Qq}, C^{1,8}_{Qq}, C^{8}_{Qu}, C^{8}_{Qd}, C^{8}_{tq}, C^{8}_{tu}, C^{8}_{td}$

- Relatively mild impact
- Preferred $t\bar{t}$ phase space is different

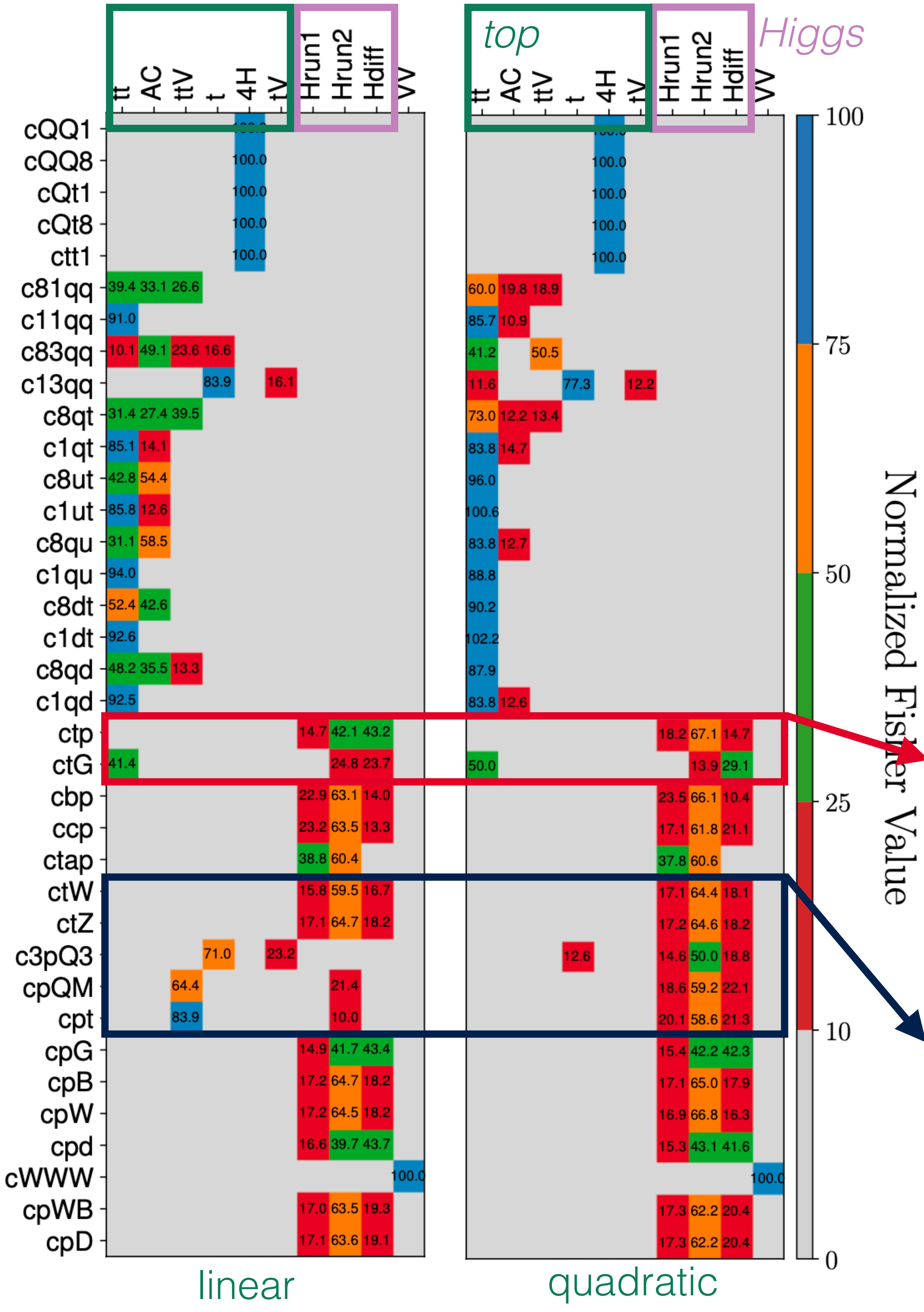
  C_{tG} : low $m_{t\bar{t}}$

  $4F$: high $m_{t\bar{t}}$
- Able to constrain them independently

[ATLAS-CONF-2021-031]

More top/Higgs interplay

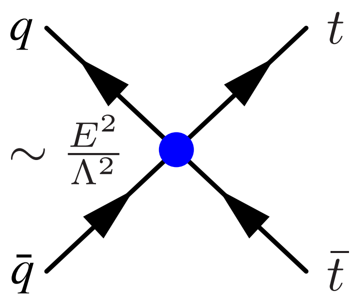
[Ethier et al.; JHEP 11 (2021) 089]



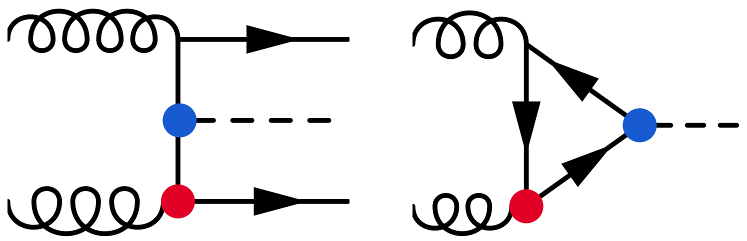
Fisher Information:

Hessian of Log-likelihood
at the best-fit point

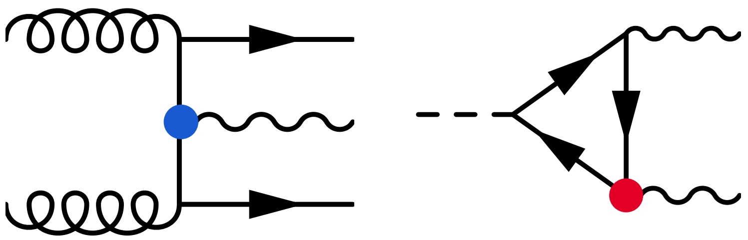
4F operators:
mostly top data



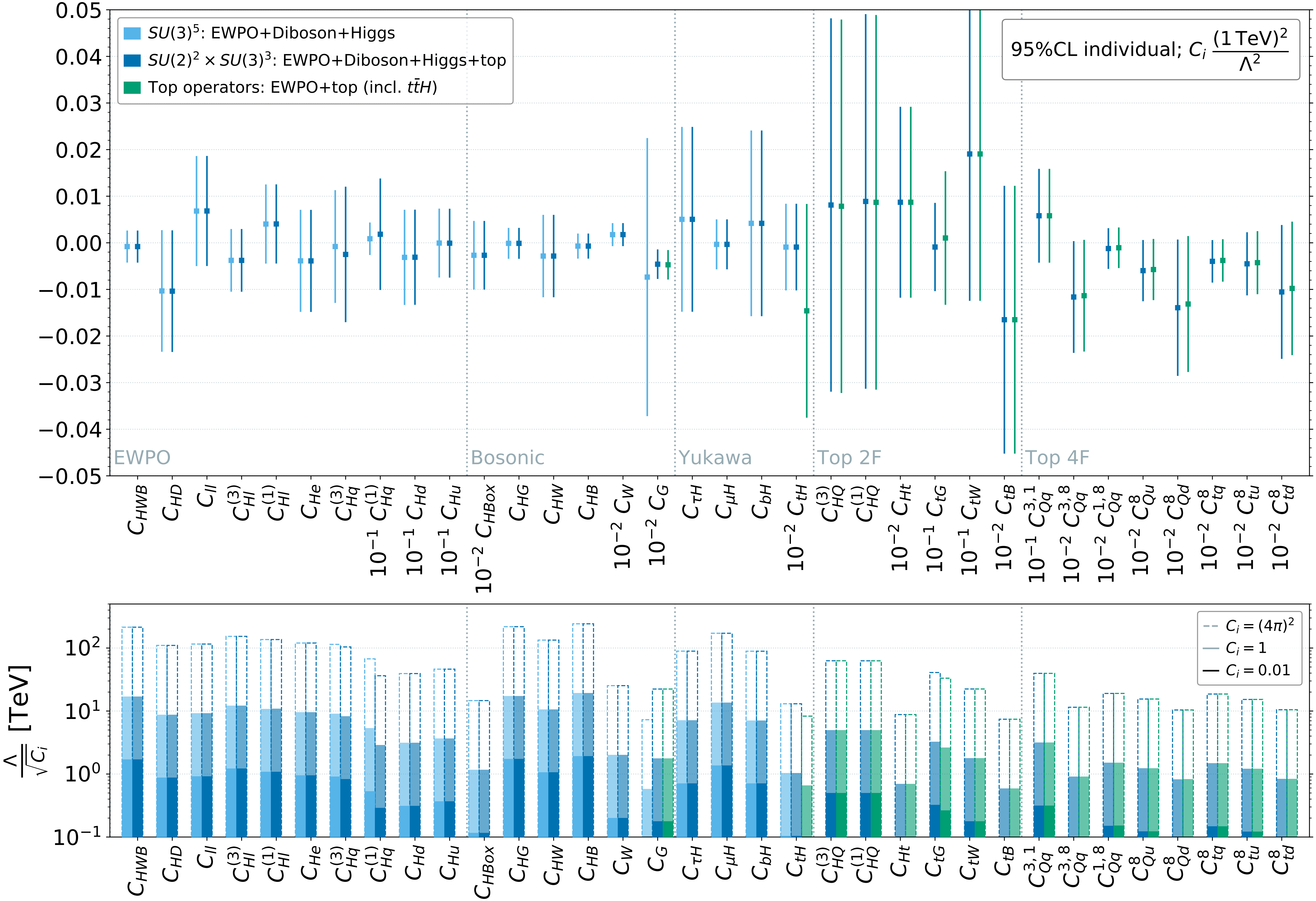
Yukawa &
Chromo-dipole



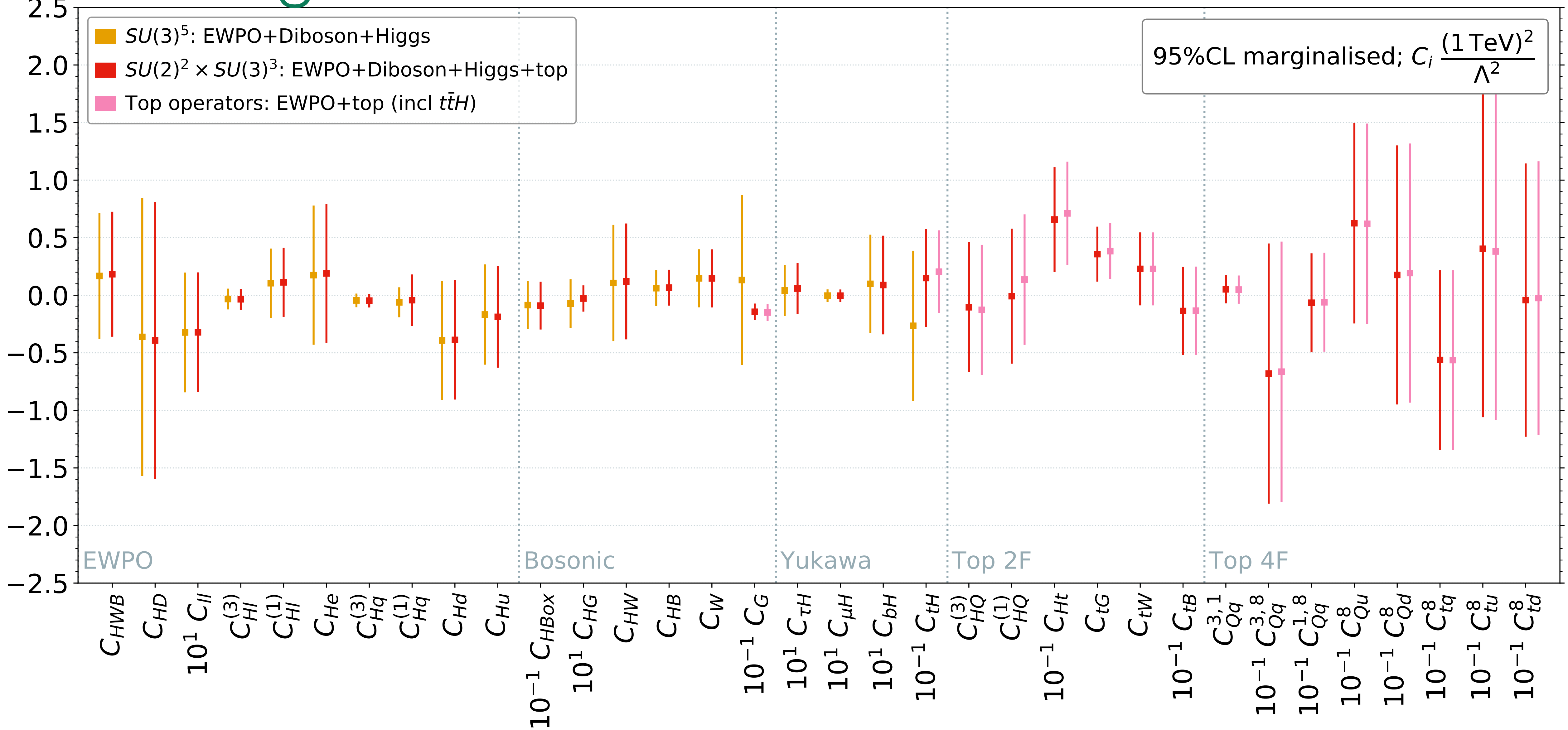
$t\bar{t}V$ couplings

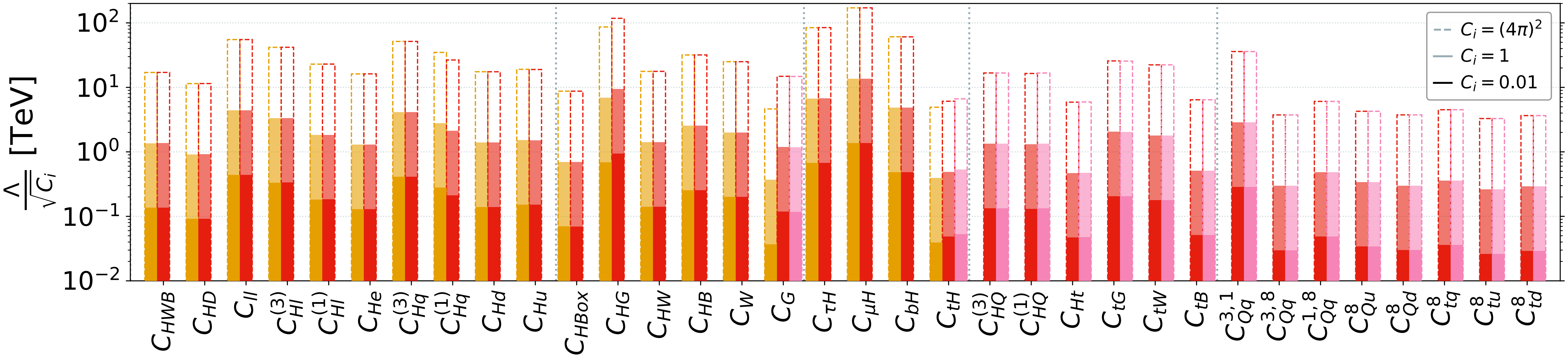


Full fit: individual



Full fit: marginalised





Correlations

Block diagonal: correlations *within* ‘sector’

Block off-diagonal: correlations *among* ‘sectors’

EWPO & top ~uncorrelated

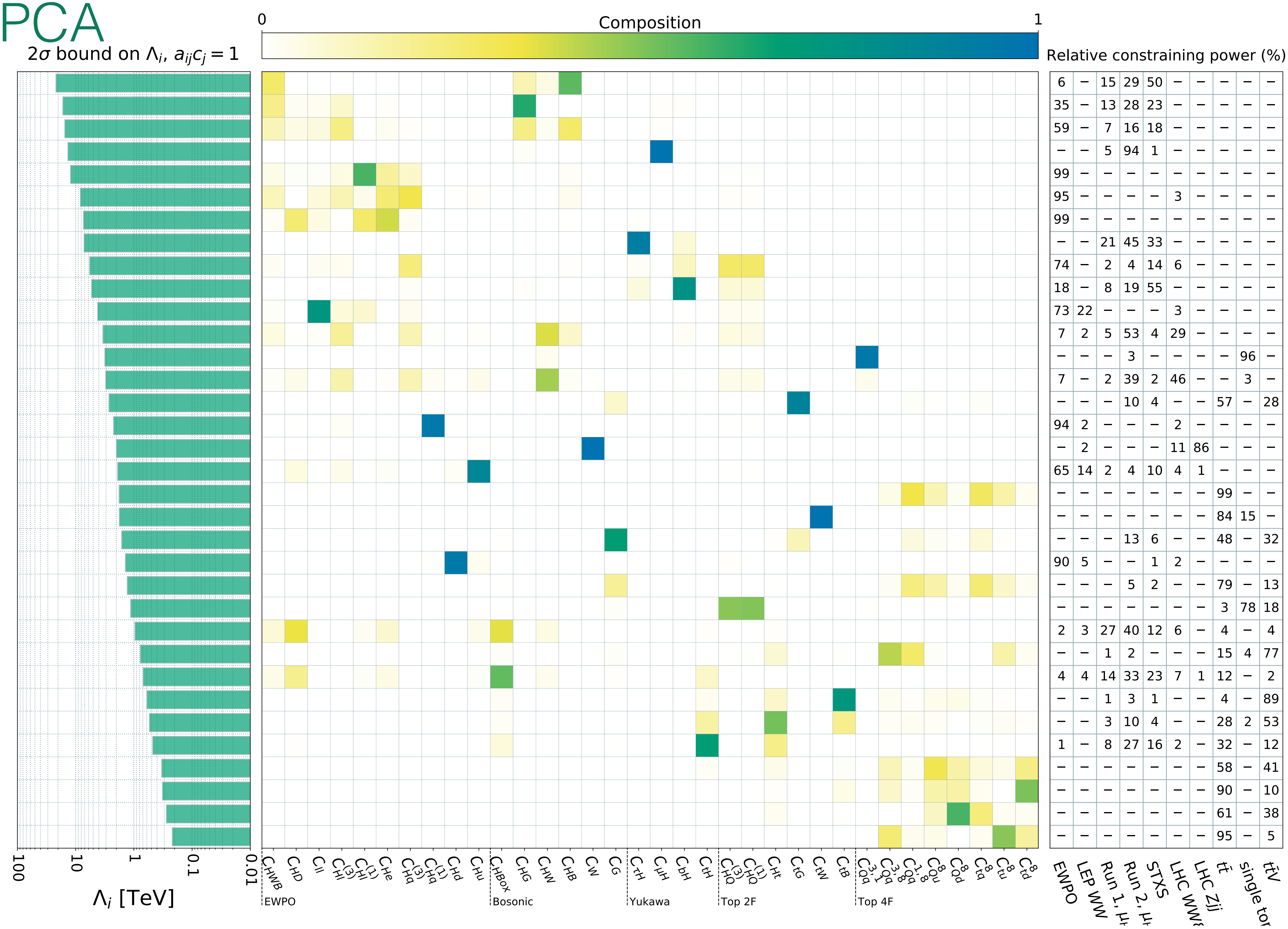
EWPO-Higgs $C_{HB}, C_{HW}, C_{H\Box}$ & Yukawa with EWPO

Higgs precision rivalling LEP

Top-Higgs C_{HG}, C_{G}, C_{tH} with 4F

	C_{HWB}	C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{Hq}^{(3)}$	$C_{Hq}^{(1)}$	C_{Hd}	C_{Hu}	C_{HBox}	C_{HG}	C_{HW}	C_{HB}	C_{W}	C_{G}	$C_{\tau H}$	$C_{\mu H}$	C_{bH}	C_{tH}	$C_{HQ}^{(3)}$	$C_{HQ}^{(1)}$	C_{Ht}	C_{tG}	C_{tW}	C_{tB}	$C_{Qq}^{3,1}$	$C_{Qq}^{3,8}$	$C_{Qq}^{1,8}$	C_{Qu}^{8}	C_{Qd}^{8}	C_{tq}^{8}	C_{tu}^{8}	C_{td}^{8}
C_{td}^{8}	+0.6	-0.6	+0.2	-0.2	+0.6	+0.6	-0.3	-0.3	+0.4	-0.6	0.5	+32	+0.6	+0.6	0	-32	+0.4	-0	0	+24	3.0	+2.8	-0.3	-2.4	+0.2	-5.0	-1.8	+42	+34	-22	-0.9	+18	-68	+100
C_{tu}^{8}	-0.4	+0.4	-0	0	-0.4	-0.4	+0.2	+0.2	-0.2	+0.3	0.4	-24	-0.4	-0.4	-0	+28	-0.4	0	-0.1	-20	-2.3	-2.1	+3.7	-1.9	-0.2	-13	+1.3	-93	-91	+35	+1.7	-30	+100	-68
C_{tq}^{8}	+2.6	-2.5	+0.6	-1.1	+2.5	+2.5	-1.4	-1.2	+1.7	-2.2	1.5	+21	+2.6	+2.6	+0.2	-19	0	+0.1	+0.3	+12	-12	+11	-57	-7.8	+0.8	+0.2	-7.4	+35	+30	-88	-60	+100	-30	+18
C_{Qd}^{8}	-1.2	+1.1	-0.3	+0.7	-1.1	-1.1	+0.7	+0.6	-0.9	+1.1	0.5	+9.6	-1.2	-1.2	-0.1	-8.5	+0.4	-0.1	-0.1	+13	-4.2	-3.8	+25	+11	-0.1	+48	+3.0	-6.3	-4.3	+16	+100	-60	+1.7	-0.9
C_{Qu}^{8}	-2.5	+2.4	-0.6	+1.0	-2.4	-2.4	+1.3	+1.2	-1.6	+2.1	1.5	-29	-2.5	-2.5	-0.2	+25	-0.2	-0	-0.3	-21	+12	-11	+58	+2.9	-0.9	-28	+7.4	-37	-32	+100	+16	-88	+35	-22
$C_{Qq}^{1,8}$	+0.5	-0.5	-0.1	+0.1	+0.5	+0.5	-0.2	-0.2	+0.1	-0.3	0.4	+16	+0.5	+0.5	0	-22	+0.3	-0	+0.1	+14	2.3	+2.2	-9.5	+2.6	+0.2	+16	-1.3	+93	+100	-32	-4.3	+30	-91	+34
$C_{Qq}^{3,8}$	+0.2	-0.2	+0.1	-0	+0.2	+0.2	-0.1	-0.1	+0.1	-0.2	0.3	+18	+0.2	+0.2	0	-25	+0.4	-0	0	+16	1.6	+1.5	-0.8	+2.7	+0.2	+17	-0.8	+100	+93	-37	-6.3	+35	-93	+42
$C_{Qq}^{3,1}$	+1.2	-1.2	-0.2	+0.2	+1.2	+1.2	+0.3	-0.5	+0.5	-1.0	0.6	-2.8	+1.3	+1.2	+0.3	+5.5	+1.5	+0.4	+2.3	-4.2	+57	-55	-2.8	-3.8	+1.1	-0.3	+100	-0.8	-1.3	+7.4	+3.0	-7.4	+1.3	-1.8
C_{tB}	+0.1	-0.1	-0.1	+0.4	+0.1	+0.1	+0.1	0	-0.1	+0.1	0.2	+11	+0.1	+0.1	0	-15	+0.1	-0	+0.1	+7.7	1.4	+1.4	-0.1	-2.3	-4.3	+100	-0.3	+17	+16	-28	+48	+0.2	-13	-5.0
C_{tW}	+0.1	-0	+0.4	-1.0	-0	0	-1.0	-0.1	+0.3	-0.2	0.1	+0.6	+0.1	+0.1	-0.2	-1.8	-0.1	-0.1	-0.6	+1.5	6.6	+6.3	+0.8	+2.5	+100	-4.3	+1.1	+0.2	+0.2	-0.9	-0.1	+0.8	-0.2	+0.2
C_{tG}	+0.2	-0.2	-0.1	+0.2	+0.2	+0.2	+0.1	-0.1	+0.1	-0.1	0.8	+5.3	+0.2	+0.3	+0.1	-51	+2.6	-0.2	-0.2	+49	7.2	+7.0	+18	+100	+2.5	-2.3	-3.8	+2.7	+2.6	+2.9	+11	-7.8	-1.9	-2.4
C_{Ht}	-17	+17	-2.0	-1.2	-17	-17	+5.6	+8.1	-2.0	+14	9.7	-3.2	-17	-17	-1.5	-35	-1.3	-1.3	-7.2	+9.4	7.4	+11	+100	+18	+0.8	-0.1	-2.8	-0.8	-9.5	+58	+25	-57	+3.7	-0.3
$C_{HQ}^{(1)}$	-21	+20	-3.6	+4.4	-20	-21	+13	+13	+4.6	+21	11	+3.9	-21	-21	-0.4	-10	-4.5	-1.9	-8.6	+11	-96	+100	+11	+7.0	+6.3	+1.4	-55	+1.5	+2.2	-11	-3.8	+11	-2.1	+2.8
$C_{HQ}^{(3)}$	+1.9	-2.2	-0.9	+2.6	+2.2	+2.2	+1.0	-0.5	-0.6	-0.8	1.2	-5.2	+2.0	+1.9	+0.3	+11	+2.8	+0.8	+4.8	-7.8	100	-96	-7.4	-7.2	-6.6	-1.4	+57	-1.6	-2.3	+12	+4.2	-12	+2.3	-3.0
C_{tH}	-20	+21	-2.3	-5.0	-21	-21	+2.0	+11	-4.6	+14	+44	+67	-22	-19	-2.7	-52	+9.3	-1.2	-7.8	+100	-7.8	+11	+9.4	+49	+1.5	+7.7	-4.2	+16	+14	-21	+13	+12	-20	+24
C_{bH}	+40	-43	+0.5	+39	+43	+43	+20	-24	+1.2	-21	-41	-21	+41	+38	+10	-0.1	+24	+4.9	+100	-7.8	+4.8	-8.6	-7.2	-0.2	-0.6	+0.1	+2.3	0	+0.1	-0.3	-0.1	+0.3	-0.1	0
$C_{\mu H}$	+6.6	-6.7	+0.6	+1.7	+6.7	+6.7	-0.9	-2.7	+1.3	-4.8	2.0	+1.1	+6.6	+6.3	+0.8	+0.2	+4.0	+100	+4.9	-1.2	+0.8	-1.9	-1.3	-0.2	-0.1	-0	+0.4	-0	-0	-0	-0.1	+0.1	0	-0
$C_{\tau H}$	+11	-11	+0.7	+3.0	+11	+11	-1.9	-3.5	+1.7	-8.0	+17	-11	+9.8	+11	+1.2	-2.2	+100	+4.0	+24	+9.3	+2.8	-4.5	-1.3	+2.6	-0.1	+0.1	+1.5	+0.4	+0.3	-0.2	+0.4	0	-0.4	+0.4
C_{G}	-1.4	+1.4	-0.2	-0.1	-1.4	-1.4	+0.4	+0.6	-0.6	+1.0	-1.5	-37	-1.4	-1.5	-0.1	+100	-2.2	+0.2	-0.1	-52	+11	-10	-35	-51	-1.8	-15	+5.5	-25	-22	+25	-8.5	-19	+28	-32
C_{W}	+8.5	-9.6	+3.9	+13	+9.4	+9.6	+14	-5.4	+2.0	-7.4	8.0	-1.1	+8.4	+8.5	+100	-0.1	+1.2	+0.8	+10	-2.7	+0.3	-0.4	-1.5	+0.1	-0.2	0	+0.3	0	0	-0.2	-0.1	+0.2	-0	0
C_{HB}	+98	-98	+14	+3.1	+98	+98	-31	-43	+26	-77	-54	+2.3	+93	+100	+8.5	-1.5	+11	+6.3	+38	-19	+1.9	-21	-17	+0.3	+0.1	+0.1	+1.2	+0.2	+0.5	-2.5	-1.2	+2.6	-0.4	+0.6
C_{HW}	+98	-98	+14	+3.0	+97	+98	-31	-43	+26	-77	-61	+2.0	+100	+93	+8.4	-1.4	+9.8	+6.6	+41	-22	+2.0	-21	-17	+0.2	+0.1	+0.1	+1.3	+0.2	+0.5	-2.5	-1.2	+2.6	-0.4	+0.6
C_{HG}	+2.2	-1.5	+1.3	-7.0	+1.4	+1.5	-7.1	+0.8	+2.3	-3.7	1.4	+100	+2.0	+2.3	-1.1	-37	-11	+1.1	-21	+67	-5.2	+3.9	-3.2	+5.3	+0.6	+11	-2.8	+18	+16	-29	+9.6	+21	-24	+32
C_{HBox}	-58	+59	-6.8	-16	-59	-59	+3.7	+32	-13	+40	100	-1.4	-61	-54	-8.0	+1.5	+17	-2.0	-41	+44	-1.2	+11	+9.7	-0.8	+0.1	-0.2	-0.6	-0.3	-0.4	+1.5	+0.5	-1.5	+0.4	-0.5
C_{Hu}	-78	+76	-22	+20	-75	-76	+19	+32	-6.1	+100	+40	-3.7	-77	-77	-7.4	+1.0	-8.0	-4.8	-21	+14	-0.8	+21	+14	-0.1	-0.2	+0.1	-1.0	-0.2	-0.3	+2.1	+1.1	-2.2	+0.3	-0.6
C_{Hd}	+27	-24	+9.8	-34	+22	+23	-5.5	+6.5	+100	-6.1	-13	+2.3	+26	+26	+2.0	-0.6	+1.7	+1.3	+1.2	-4.6	-0.6	+4.6	-2.0	+0.1	+0.3	-0.1	+0.5	+0.1	+0.1	-1.6	-0.9	+1.7	-0.2	+0.4
$C_{Hq}^{(1)}$	-43	+42	-11	+6.7	-42	-42	+14	+100	+6.5	+32	+32	+0.8	-43	-43	-5.4	+0.6	-3.5	-2.7	-24	+11	-0.5	+13	+8.1	-0.1	-0.1	0	-0.5	-0.1	-0.2	+1.2	+0.6	-1.2	+0.2	-0.3
$C_{Hq}^{(3)}$	-32	+26	-5.1	+57	-26	-26	+100	+14	-5.5	+19	+3.7	-7.1	-31	-31	+14	+0.4	-1.9	-0.9	+20	+2.0	+1.0	+13	+5.6	+0.1	-1.0	+0.1	+0.3	-0.1	-0.2	+1.3	+0.7	-1.4	+0.2	-0.3
C_{He}	+100	-100	+13	+12	+100	+100	-26	-42	+23	-76	-59	+1.5	+98	+98	+9.6	-1.4	+11	+6.7	+43	-21	+2.2	-21	-17	+0.2	0	+0.1	+1.2	+0.2	+0.5	-2.4	-1.1	+2.5	-0.4	+0.6
$C_{Hl}^{(1)}$	+99	-100	+7.4	+11	+100	+100	-26	-42	+22	-75	-59	+1.4	+97	+98	+9.4	-1.4	+11	+6.7	+43	-21	+2.2	-20	-17	+0.2	-0	+0.1	+1.2	+0.2	+0.5	-2.4	-1.1	+2.5	-0.4	+0.6
$C_{Hl}^{(3)}$	+2.7	-12	+12	+100	+11	+12	+57	+6.7	-34	+20	-16	-7.0	+3.0	+3.1	+13	-0.1	+3.0	+1.7	+39	-5.0	+2.6	+4.4	-1.2	+0.2	-1.0	+0.4	+0.2	-0	+0.1	+1.0	+0.7	-1.1	0	-0.2
C_{ll}	+15	-13	+100	+12	+7.4	+13	-5.1	-11	+9.8	-22	-6.8	+1.3	+14	+14	+3.9	-0.2	+0.7	+0.6	+0.5	-2.3	-0.9	-3.6	-2.0	-0.1	+0.4	-0.1	-0.2	+0.1	-0.1	-0.6	-0.3	+0.6	-0	+0.2
C_{HD}	-100	+100	-13	-12	-100	-100	+26	+42	-24	+76	+59	-1.5	-98	-98	-9.6	+1.4	-11	-6.7	-43	+21	-2.2	+20	+17	-0.2	-0	-0.1	-1.2	-0.2	-0.5	+2.4	+1.1	-2.5	+0.4	-0.6
C_{HWB}	+100	-100	+15	+2.7	+99	+100	-32	-43	+27	-78	-58	+2.2	+98	+98	+8.5	-1.4	+11	+6.6	+40	-20	+1.9	-21	-17	+0.2	+0.1	+0.1	+1.2	+0.2	+0.5	-2.5	-1.2	+2.6	-0.4	+0.6

PCA



Relative constraining power (%)

EWPO	LEP WW	Run 1, μ_F	Run 2, μ_F	STXS	LHC WW	LHC Zjj	$t\bar{t}$	single to	$t\bar{t}V$
6	–	15	29	50	–	–	–	–	–
35	–	13	28	23	–	–	–	–	–
59	–	7	16	18	–	–	–	–	–
–	–	5	94	1	–	–	–	–	–
99	–	–	–	–	–	–	–	–	–
95	–	–	–	–	3	–	–	–	–
99	–	–	–	–	–	–	–	–	–
–	–	21	45	33	–	–	–	–	–
74	–	2	4	14	6	–	–	–	–
18	–	8	19	55	–	–	–	–	–
73	22	–	–	–	3	–	–	–	–
7	2	5	53	4	29	–	–	–	–
–	–	–	3	–	–	–	–	96	–
7	–	2	39	2	46	–	–	3	–
–	–	–	10	4	–	–	57	–	28
94	2	–	–	–	2	–	–	–	–
–	2	–	–	–	11	86	–	–	–
65	14	2	4	10	4	1	–	–	–
–	–	–	–	–	–	–	99	–	–
–	–	–	–	–	–	–	84	15	–
–	–	–	13	6	–	–	48	–	32
90	5	–	–	1	2	–	–	–	–
–	–	–	5	2	–	–	79	–	13
–	–	–	–	–	–	–	3	78	18
2	3	27	40	12	6	–	4	–	4
–	–	1	2	–	–	–	15	4	77
4	4	14	33	23	7	1	12	–	2
–	–	1	3	1	–	–	4	–	89
–	–	3	10	4	–	–	28	2	53
1	–	8	27	16	2	–	32	–	12
–	–	–	–	–	–	–	58	–	41
–	–	–	–	–	–	–	90	–	10
–	–	–	–	–	–	–	61	–	38
–	–	–	–	–	–	–	95	–	5

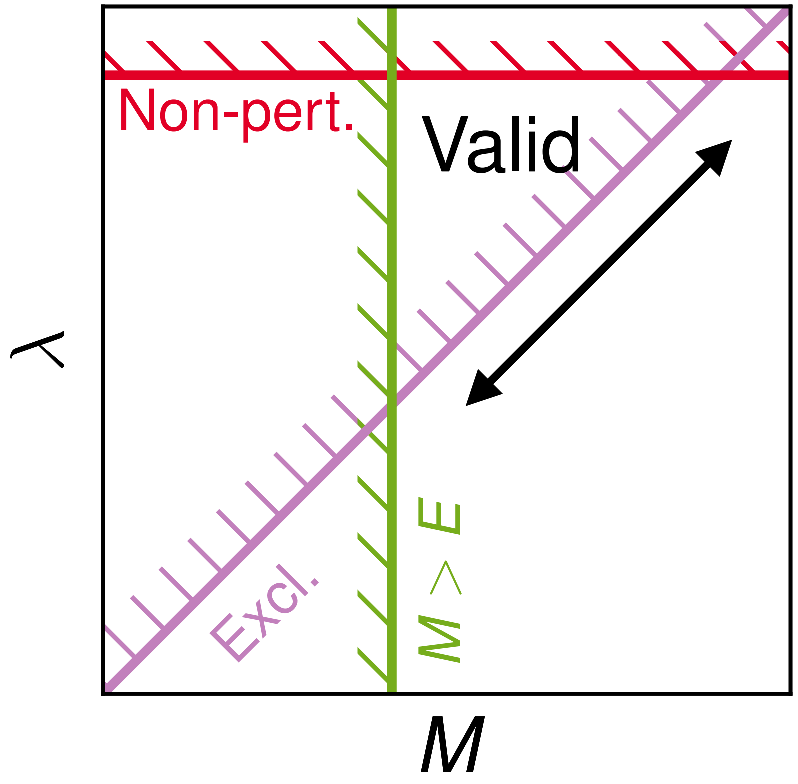
BSM implications

SMEFT-UV connection is model dependent by construction

- Implications on heavy new physics & validity of EFT is ***a posteriori***
- Depends on sensitivity & energy scale probed by data
- Bottom-up philosophy: new physics scale unknown

arbitrary dimensionful parameter $\frac{c_S}{\Lambda^2} = \frac{\lambda^2}{M^2}$ *coupling/mass scale of new physics*

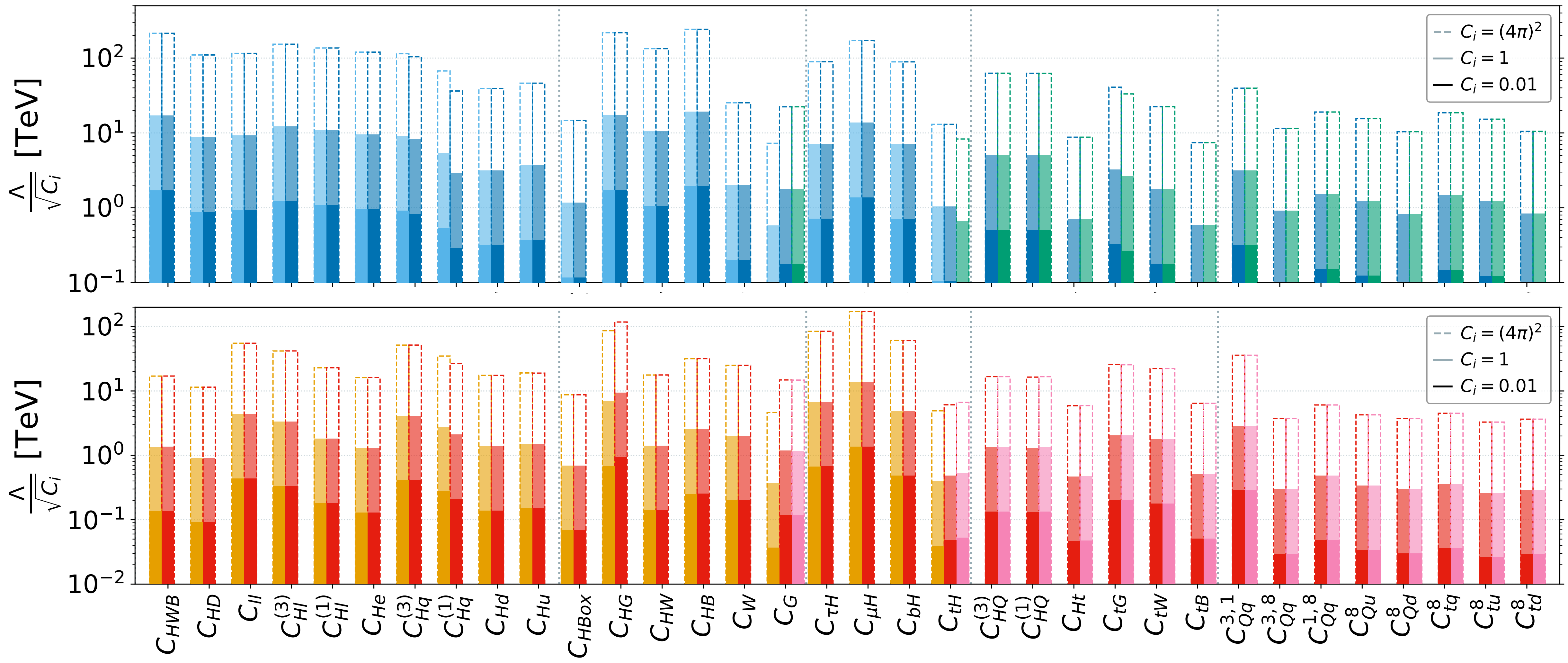
constraint: $c/\Lambda^2 < X$



Difficult to address in a general way

- Today we are probing TeV scale new physics
- Hierarchies in sensitivity EWPO $\gtrsim$ Higgs $>$ top (EW)
- Moderate-to-strong coupling scenarios most safe
- Generic NP in loops looks challenging for the LHC

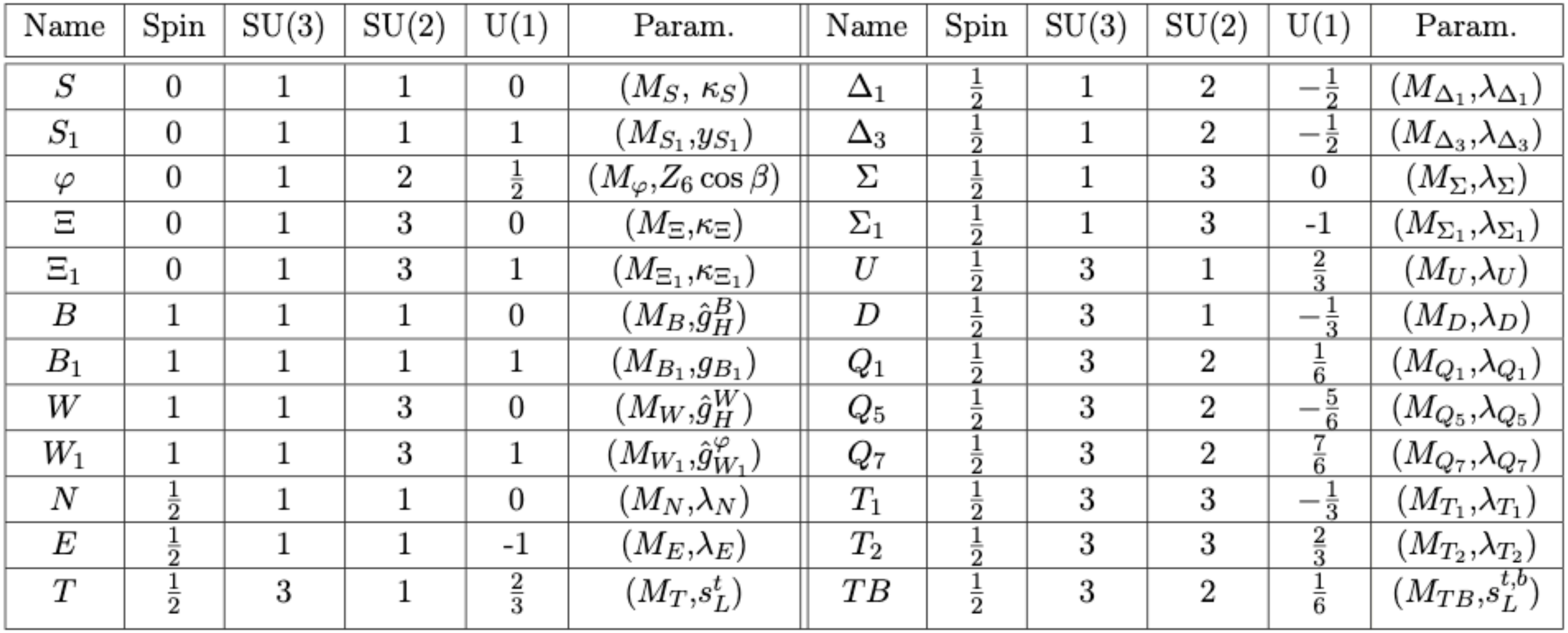
BSM implications



Individual/marginalised = optimistic/pessimistic

- Real models should lie somewhere in between
- Less underlying parameters - more correlations
- Need to ‘re-run’ the fits to infer on underlying model parameters

Single field extensions



Scalars

Z’

W’

VLL

VLQ

VLL

VLQ

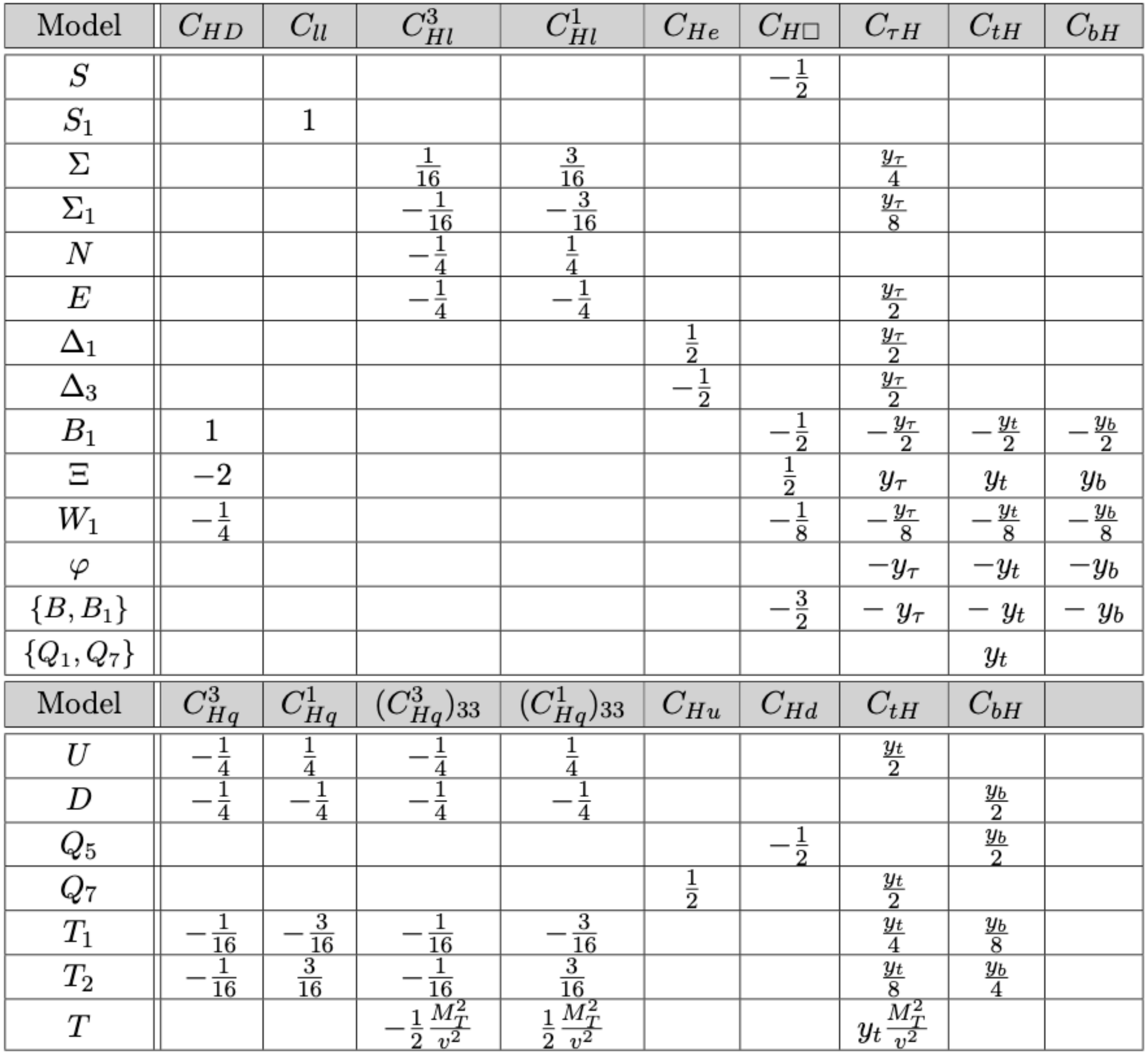
Name	Spin	SU(3)	SU(2)	U(1)	Param.	Name	Spin	SU(3)	SU(2)	U(1)	Param.
S	0	1	1	0	$(M_S,\, \kappa_S)$	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_1},\lambda_{\Delta_1})$
S_1	0	1	1	1	(M_{S_1},y_{S_1})	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$	$(M_{\Delta_3},\lambda_{\Delta_3})$
φ	0	1	2	$\frac{1}{2}$	$(M_\varphi,Z_6\cos\beta)$	Σ	$\frac{1}{2}$	1	3	0	$(M_\Sigma,\lambda_\Sigma)$
Ξ	0	1	3	0	(M_Ξ,κ_Ξ)	Σ_1	$\frac{1}{2}$	1	3	-1	$(M_{\Sigma_1},\lambda_{\Sigma_1})$
Ξ_1	0	1	3	1	$(M_{\Xi_1},\kappa_{\Xi_1})$	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_U,λ_U)
B	1	1	1	0	$(M_B,\hat{g}_H^B)$	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	(M_D,λ_D)
B_1	1	1	1	1	(M_{B_1},g_{B_1})	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$	(M_{Q_1},λ_{Q_1})
W	1	1	3	0	$(M_W,\hat{g}_H^W)$	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$	(M_{Q_5},λ_{Q_5})
W_1	1	1	3	1	$(M_{W_1},\hat{g}_{W_1}^\varphi)$	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$	(M_{Q_7},λ_{Q_7})
N	$\frac{1}{2}$	1	1	0	(M_N,λ_N)	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$	(M_{T_1},λ_{T_1})
E	$\frac{1}{2}$	1	1	-1	(M_E,λ_E)	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$	(M_{T_2},λ_{T_2})
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	(M_T,s_L^t)	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$	$(M_{TB},s_L^{t,b})$

Considered single field extensions of the SM

- Complete tree-level matching dictionary is known *[de Blas et al.; JHEP 03 (2018) 109]*
- Interpret in terms of simplified 1 & 2 parameter versions of the models

See also: *[Dawson et al.; PRD 102 (2020) 5, 055012]*

One parameter models

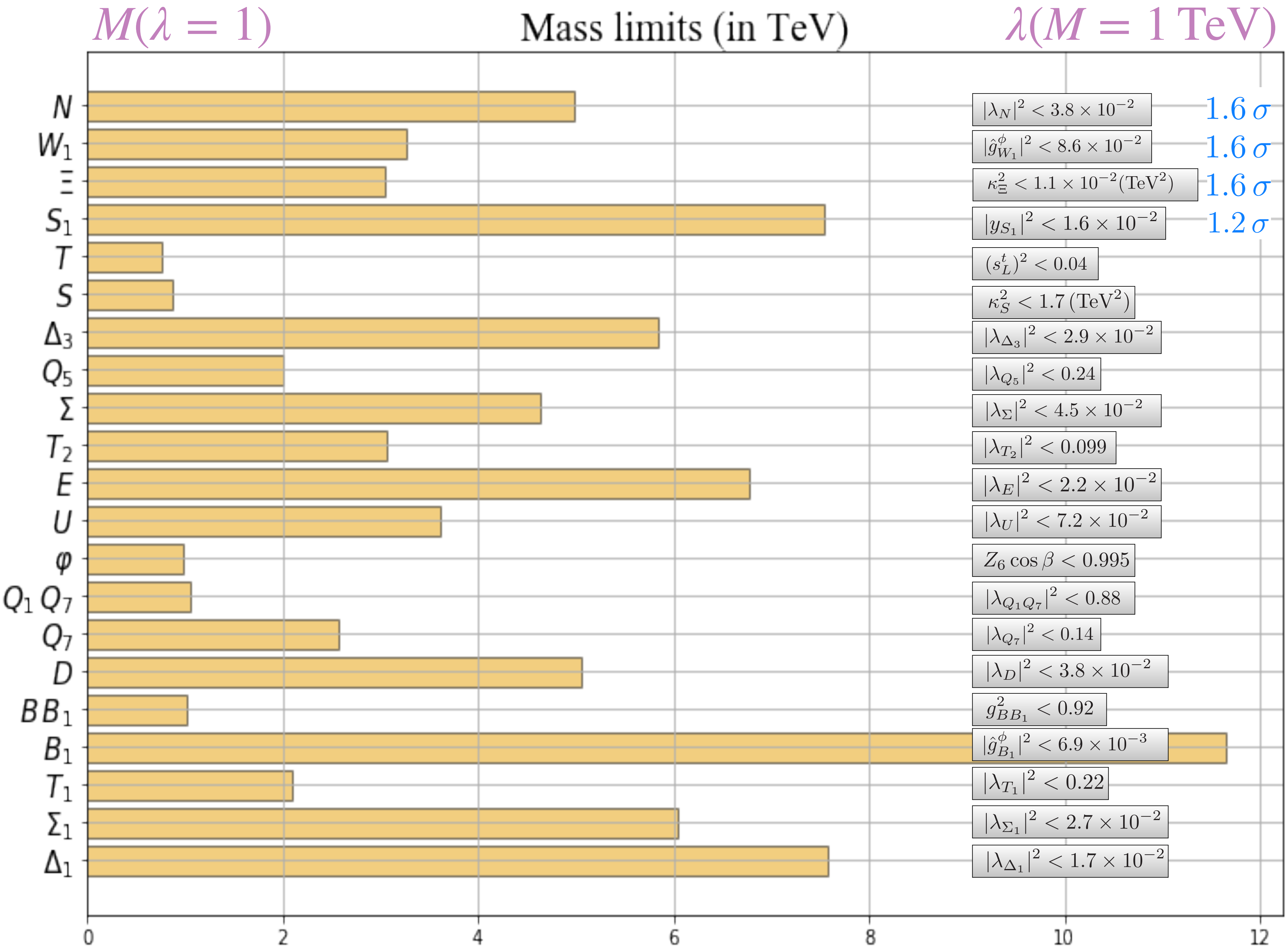


Model	C_{HD}	C_{ll}	C^3_{Hl}	C^1_{Hl}	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						$-\frac{1}{2}$			
S_1		1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$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

Model	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	$-\frac{1}{16}$	$-\frac{3}{16}$	$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$	
T_2	$-\frac{1}{16}$	$\frac{3}{16}$	$-\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$	
T			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$		

$$\times \frac{\lambda^2}{M^2}$$

One parameter models

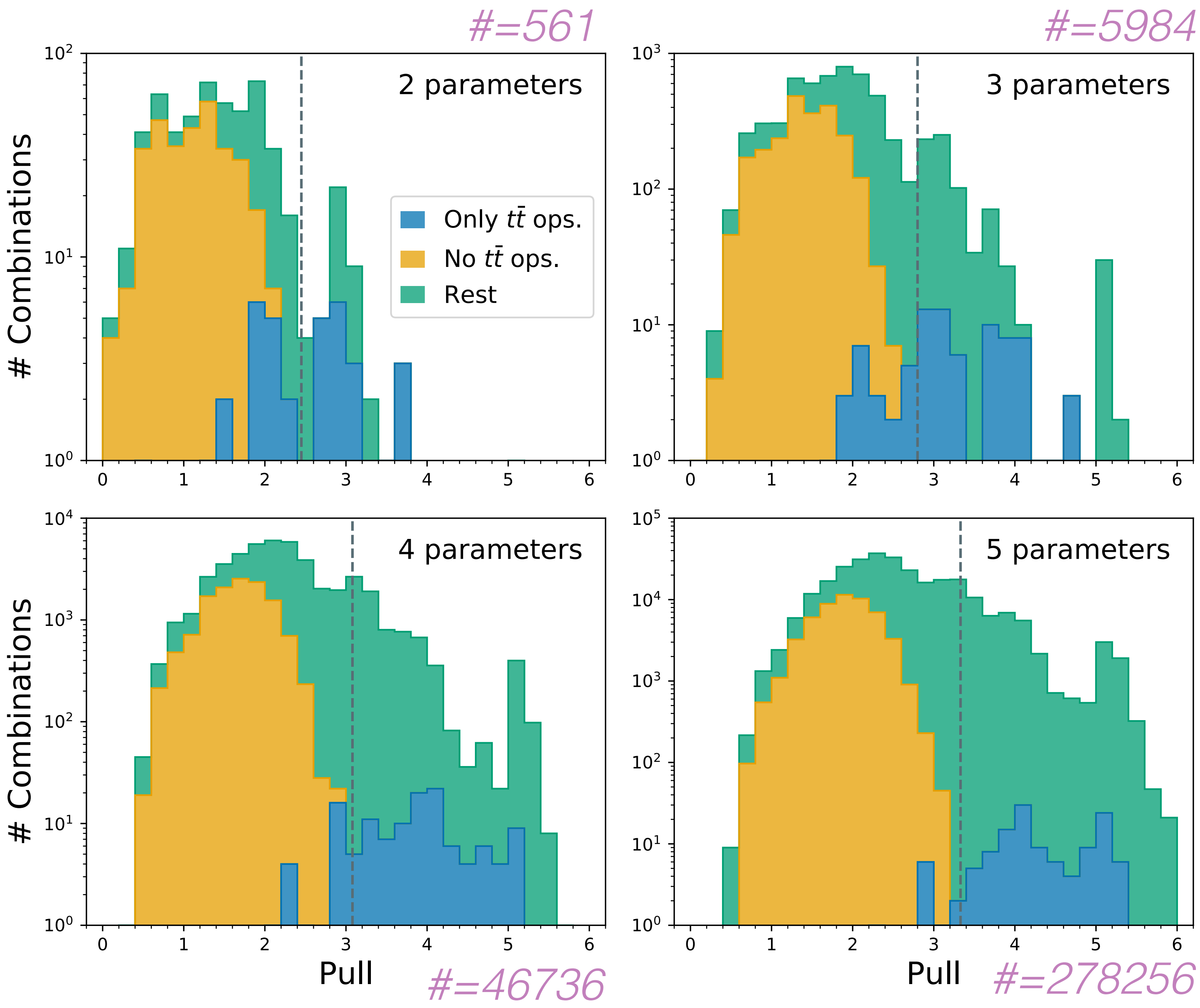


Pull-ology

Brute force: fit to all combinations of n-coefficients

$$P \equiv \sqrt{\chi^2_{SM} - \chi^2_{\rm fit}}$$

- Agnostic search for improved fit w.r.t SM
- NP hints could show up in this way
- Advantage of fast, linear fit method
- Highlights tension in $t\bar{t}$ data
- No conclusive NP hints so far…



#=561

#=5984

#=46736

#=278256

Conclusions

Presented first EWPO, Higgs, Diboson & Top fit in SMEFT

- Include leading contributions from top operators in ggF
- Top & Higgs sector are starting to talk to each other
- $t\bar{t}$ 4 fermion operators don't appear to spoil naive picture of interplay

Analytic, linear analysis has many benefits

- Simple likelihood described by best fit+correlations, PCA exact
- Easy to interpret/combine with other likelihoods
- Fast: repeat for subsets, BSM interpretations

& Drawbacks

- Potentially important quadratic effects, especially in top data
- Gaussian priors only, not really appropriate for th. errors

Outlook

Much more to be done

- Explore the likelihood further - how? opportunity for exp/th exchange
- Compare results to a quadratic fit to test validity
- SMEFT theory errors?
- Explore impact of new observables: VBS, VVV, rare top modes

Impact of loops

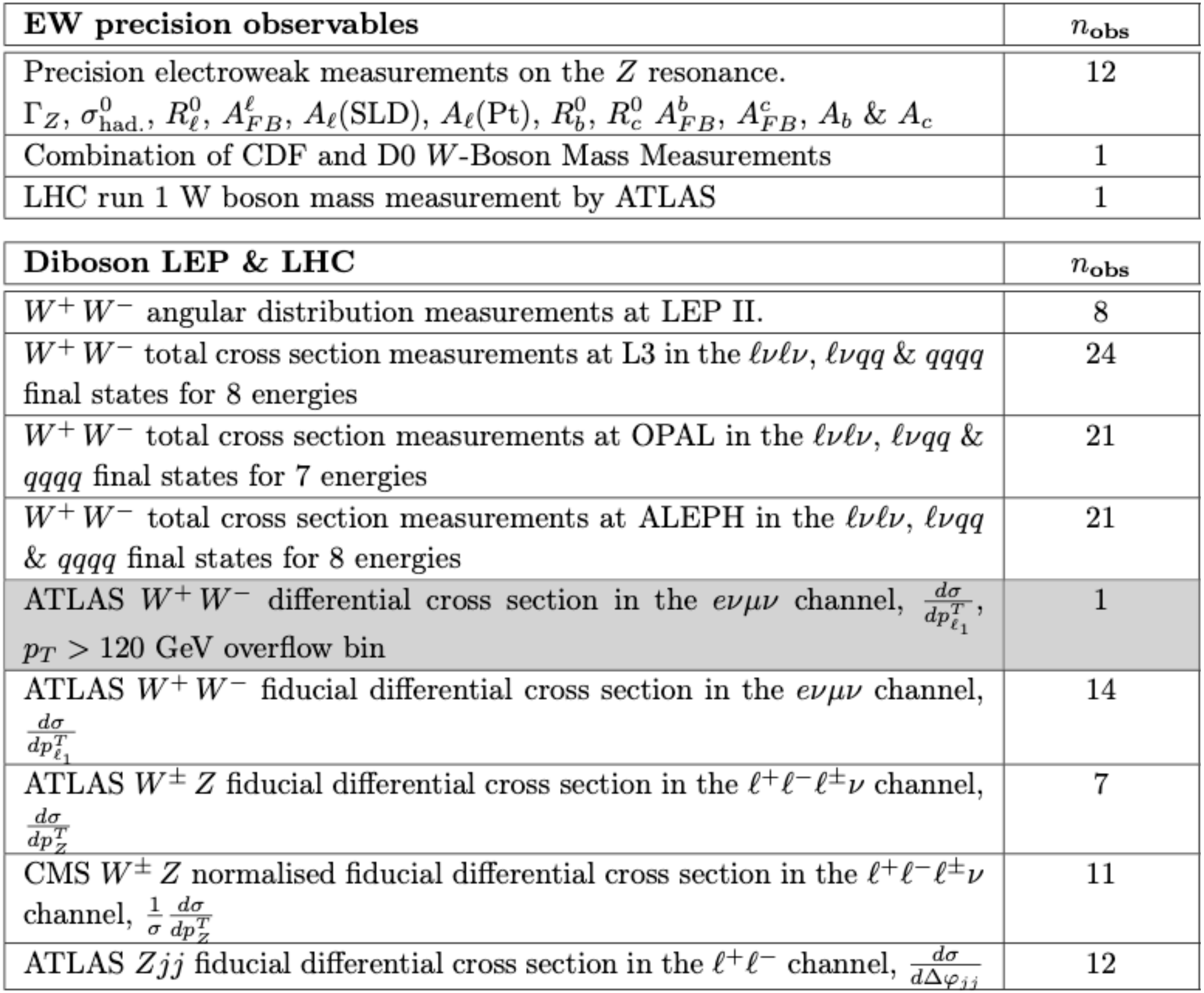
- Top operators in loops: Higgs decays + EWPO
- NLO corrections

BSM implications

- Go beyond 1 particle benchmarks towards realistic models
- Are there compelling top/Higgs scenarios that admit a valid EFT interpretation with LHC data?

Backup

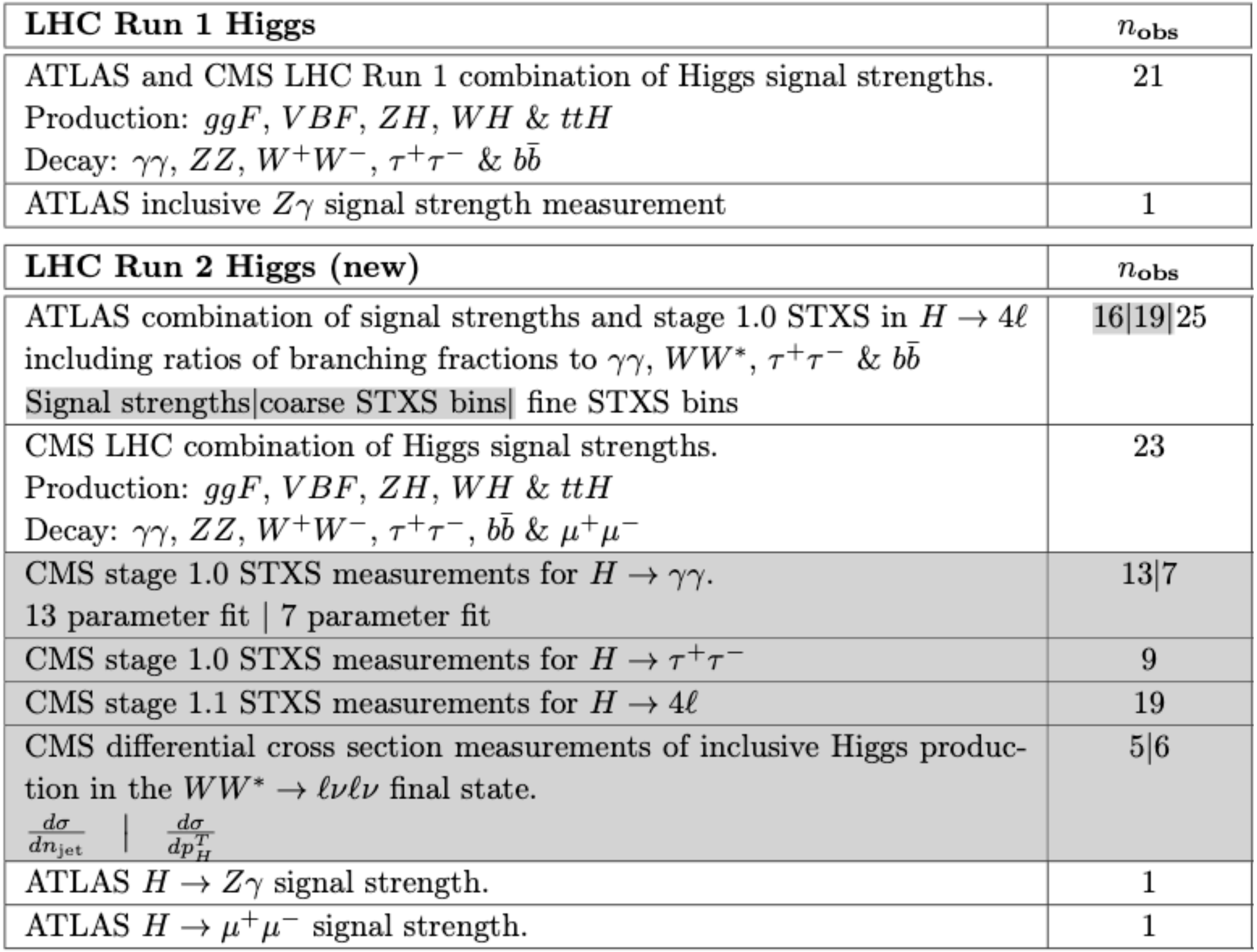
Data: EWPO & Diboson



EW precision observables	n_{obs}
Precision electroweak measurements on the Z resonance. Γ_Z, $\sigma^0_{\mathrm{had.}}$, R^0_ℓ, A^ℓ_{FB}, A_ℓ(SLD), A_ℓ(Pt), R^0_b, R^0_c A^b_{FB}, A^c_{FB}, A_b & A_c	12
Combination of CDF and D0 W-Boson Mass Measurements	1
LHC run 1 W boson mass measurement by ATLAS	1

Diboson LEP & LHC	n_{obs}
W^+W^- angular distribution measurements at LEP II.	8
W^+W^- total cross section measurements at L3 in the $\ell\nu\ell\nu$, $\ell\nu qq$ & $qqqq$ final states for 8 energies	24
W^+W^- total cross section measurements at OPAL in the $\ell\nu\ell\nu$, $\ell\nu qq$ & $qqqq$ final states for 7 energies	21
W^+W^- total cross section measurements at ALEPH in the $\ell\nu\ell\nu$, $\ell\nu qq$ & $qqqq$ final states for 8 energies	21
ATLAS W^+W^- differential cross section in the $e\nu\mu\nu$ channel, $\frac{d\sigma}{dp^T_{\ell_1}}$, $p_T > 120$ GeV overflow bin	1
ATLAS W^+W^- fiducial differential cross section in the $e\nu\mu\nu$ channel, $\frac{d\sigma}{dp^T_{\ell_1}}$	14
ATLAS $W^\pm Z$ fiducial differential cross section in the $\ell^+\ell^-\ell^\pm\nu$ channel, $\frac{d\sigma}{dp^T_Z}$	7
CMS $W^\pm Z$ normalised fiducial differential cross section in the $\ell^+\ell^-\ell^\pm\nu$ channel, $\frac{1}{\sigma}\frac{d\sigma}{dp^T_Z}$	11
ATLAS Zjj fiducial differential cross section in the $\ell^+\ell^-$ channel, $\frac{d\sigma}{d\Delta\varphi_{jj}}$	12

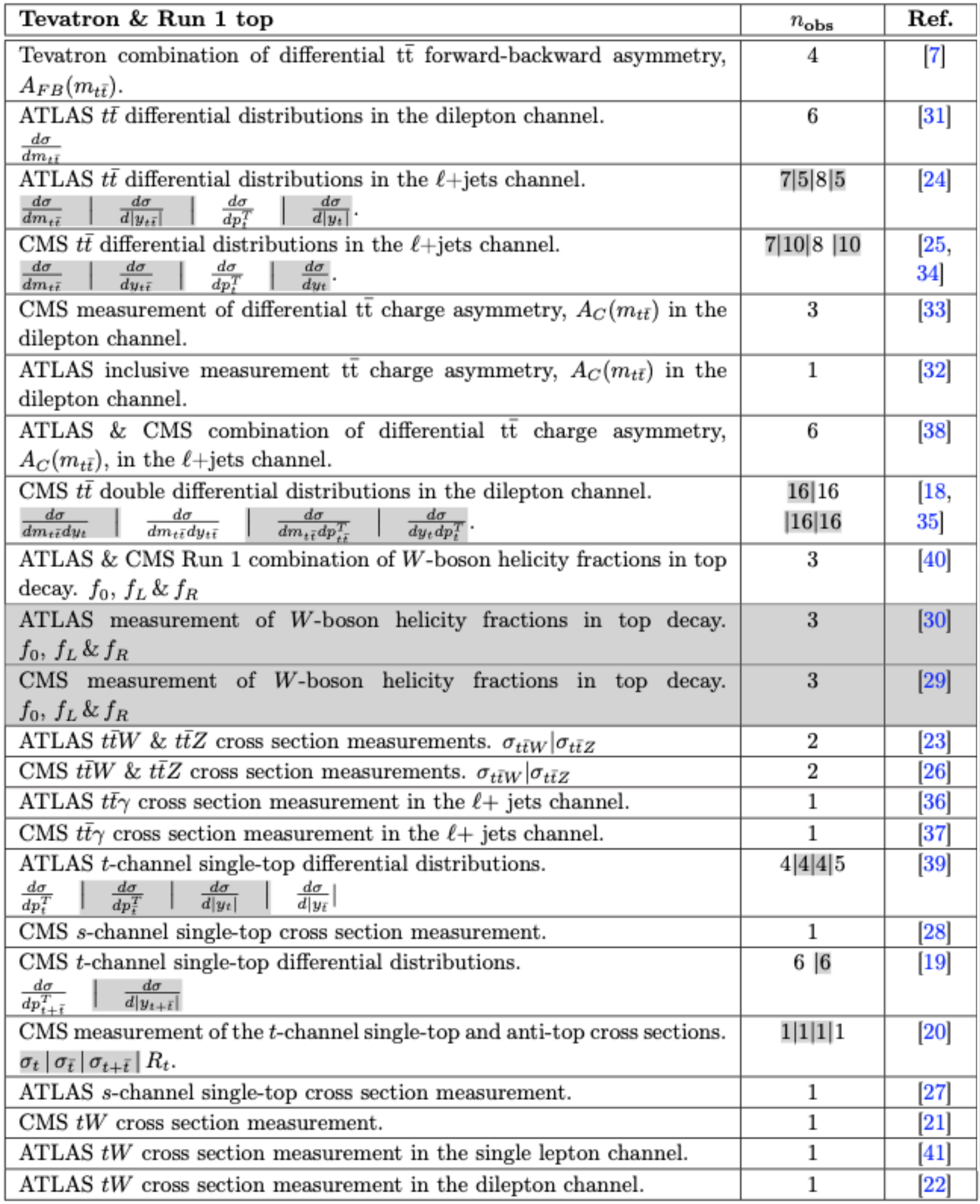
Data: Higgs



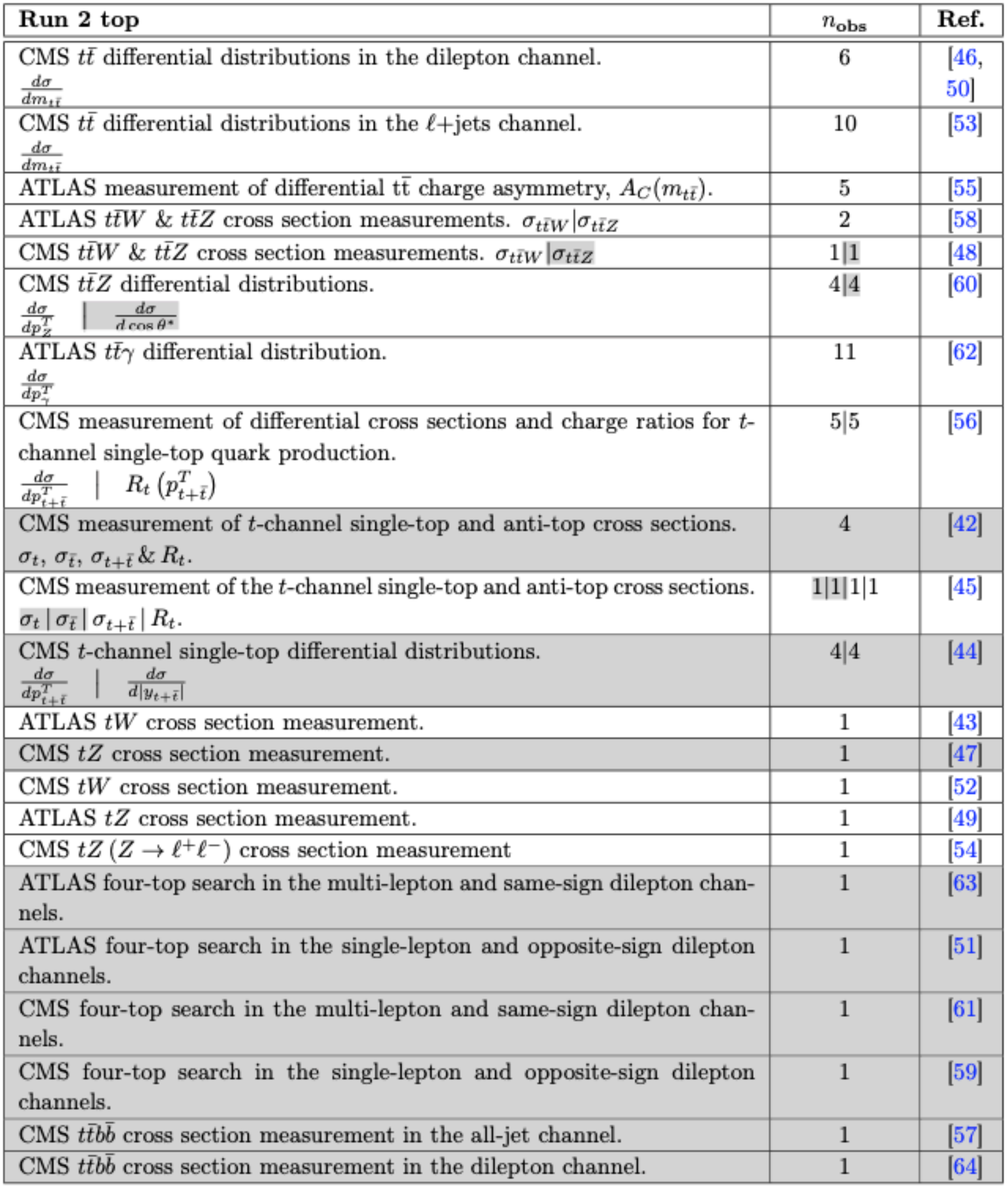
LHC Run 1 Higgs	n_{obs}
ATLAS and CMS LHC Run 1 combination of Higgs signal strengths. Production: ggF, VBF, ZH, WH & ttH Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ & $b\bar{b}$	21
ATLAS inclusive $Z\gamma$ signal strength measurement	1

LHC Run 2 Higgs (new)	n_{obs}
ATLAS combination of signal strengths and stage 1.0 STXS in $H \to 4\ell$ including ratios of branching fractions to $\gamma\gamma$, WW^*, $\tau^+\tau^-$ & $b\bar{b}$ Signal strengths|coarse STXS bins| fine STXS bins	16|19|25
CMS LHC combination of Higgs signal strengths. Production: ggF, VBF, ZH, WH & ttH Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, $b\bar{b}$ & $\mu^+\mu^-$	23
CMS stage 1.0 STXS measurements for $H \to \gamma\gamma$. 13 parameter fit | 7 parameter fit	13|7
CMS stage 1.0 STXS measurements for $H \to \tau^+\tau^-$	9
CMS stage 1.1 STXS measurements for $H \to 4\ell$	19
CMS differential cross section measurements of inclusive Higgs production in the $WW^* \to \ell\nu\ell\nu$ final state. $\frac{d\sigma}{dn_{\text{jet}}} \;\vert\; \frac{d\sigma}{dp_H^T}$	5|6
ATLAS $H \to Z\gamma$ signal strength.	1
ATLAS $H \to \mu^+\mu^-$ signal strength.	1

Data: Tevatron, LHC Run 1 & 2 top

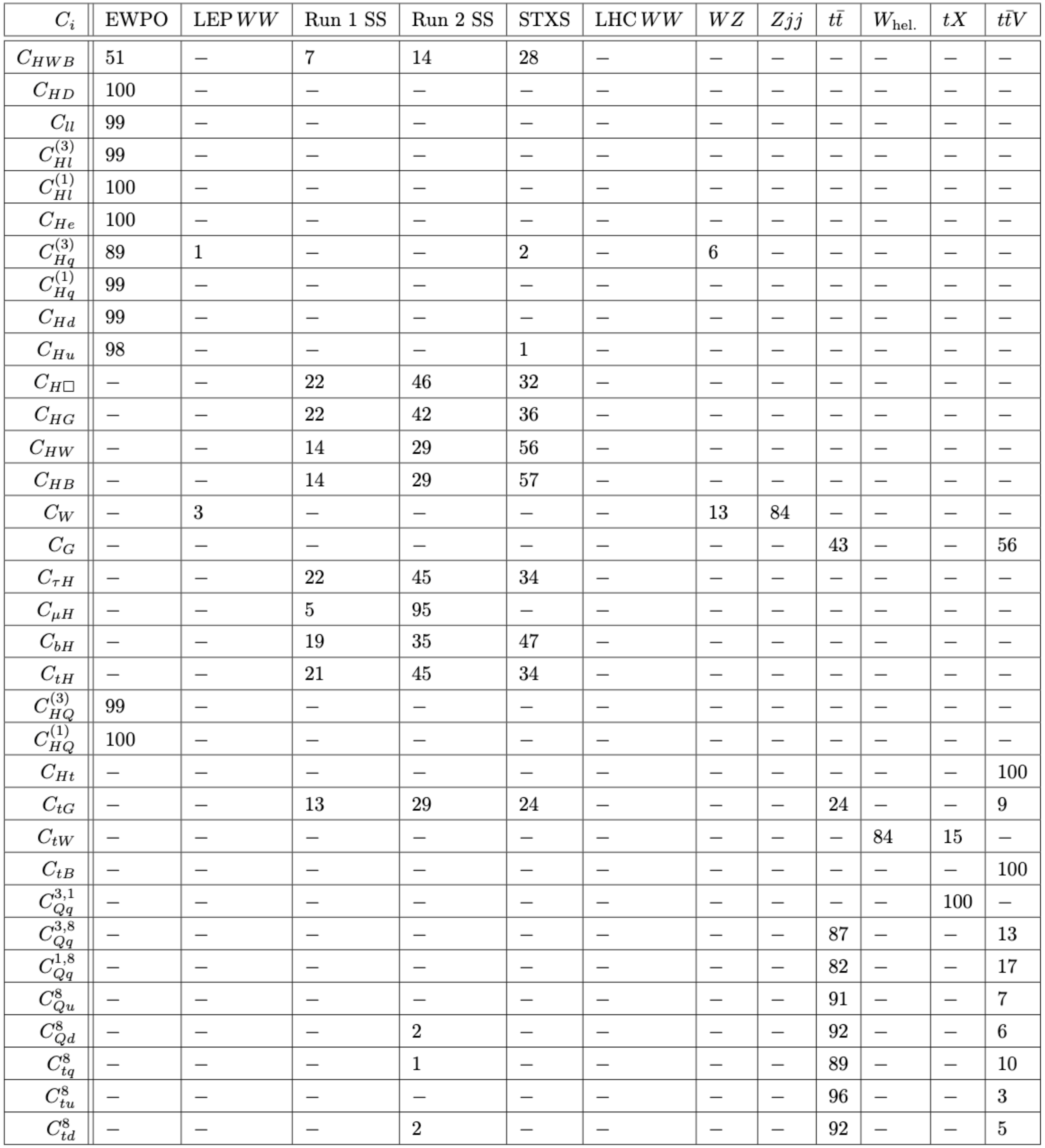


Tevatron & Run 1 top	n_{obs}	**Ref.**
Tevatron combination of differential $\mathrm{t\bar t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar t})$.	4	[7]
ATLAS $t\bar t$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar t}}$	6	[31]
ATLAS $t\bar t$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar t}} \vert \frac{d\sigma}{d\vert y_{t\bar t}\vert} \vert \frac{d\sigma}{dp_t^T} \vert \frac{d\sigma}{d\vert y_t\vert}$.	7|5|8|5	[24]
CMS $t\bar t$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar t}} \vert \frac{d\sigma}{dy_{t\bar t}} \vert \frac{d\sigma}{dp_t^T} \vert \frac{d\sigma}{dy_t}$.	7|10|8 |10	[25, 34]
CMS measurement of differential $\mathrm{t\bar t}$ charge asymmetry, $A_C(m_{t\bar t})$ in the dilepton channel.	3	[33]
ATLAS inclusive measurement $\mathrm{t\bar t}$ charge asymmetry, $A_C(m_{t\bar t})$ in the dilepton channel.	1	[32]
ATLAS & CMS combination of differential $\mathrm{t\bar t}$ charge asymmetry, $A_C(m_{t\bar t})$, in the ℓ+jets channel.	6	[38]
CMS $t\bar t$ double differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar t}dy_t} \vert \frac{d\sigma}{dm_{t\bar t}dy_{t\bar t}} \vert \frac{d\sigma}{dm_{t\bar t}dp_{t\bar t}^T} \vert \frac{d\sigma}{dy_t dp_t^T}$.	16|16 |16|16	[18, 35]
ATLAS & CMS Run 1 combination of W-boson helicity fractions in top decay. f_0, f_L & f_R	3	[40]
ATLAS measurement of W-boson helicity fractions in top decay. f_0, f_L & f_R	3	[30]
CMS measurement of W-boson helicity fractions in top decay. f_0, f_L & f_R	3	[29]
ATLAS $t\bar tW$ & $t\bar tZ$ cross section measurements. $\sigma_{t\bar tW} \vert \sigma_{t\bar tZ}$	2	[23]
CMS $t\bar tW$ & $t\bar tZ$ cross section measurements. $\sigma_{t\bar tW} \vert \sigma_{t\bar tZ}$	2	[26]
ATLAS $t\bar t\gamma$ cross section measurement in the ℓ+ jets channel.	1	[36]
CMS $t\bar t\gamma$ cross section measurement in the ℓ+ jets channel.	1	[37]
ATLAS t-channel single-top differential distributions. $\frac{d\sigma}{dp_t^T} \vert \frac{d\sigma}{dp_{\bar t}^T} \vert \frac{d\sigma}{d\vert y_t\vert} \vert \frac{d\sigma}{d\vert y_{\bar t}\vert}$	4|4|4|5	[39]
CMS s-channel single-top cross section measurement.	1	[28]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp_{t+\bar t}^T} \vert \frac{d\sigma}{d\vert y_{t+\bar t}\vert}$	6 |6	[19]
CMS measurement of the t-channel single-top and anti-top cross sections. $\sigma_t \vert \sigma_{\bar t} \vert \sigma_{t+\bar t} \vert R_t$.	1|1|1|1	[20]
ATLAS s-channel single-top cross section measurement.	1	[27]
CMS tW cross section measurement.	1	[21]
ATLAS tW cross section measurement in the single lepton channel.	1	[41]
ATLAS tW cross section measurement in the dilepton channel.	1	[22]



Run 2 top	n_{obs}	**Ref.**
CMS $t\bar t$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar t}}$	6	[46, 50]
CMS $t\bar t$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar t}}$	10	[53]
ATLAS measurement of differential $\mathrm{t\bar t}$ charge asymmetry, $A_C(m_{t\bar t})$.	5	[55]
ATLAS $t\bar tW$ & $t\bar tZ$ cross section measurements. $\sigma_{t\bar tW} \vert \sigma_{t\bar tZ}$	2	[58]
CMS $t\bar tW$ & $t\bar tZ$ cross section measurements. $\sigma_{t\bar tW} \vert \sigma_{t\bar tZ}$	1|1	[48]
CMS $t\bar tZ$ differential distributions. $\frac{d\sigma}{dp_Z^T} \vert \frac{d\sigma}{d\cos\theta^*}$	4|4	[60]
ATLAS $t\bar t\gamma$ differential distribution. $\frac{d\sigma}{dp_\gamma^T}$	11	[62]
CMS measurement of differential cross sections and charge ratios for t-channel single-top quark production. $\frac{d\sigma}{dp_{t+\bar t}^T} \vert R_t\left(p_{t+\bar t}^T\right)$	5|5	[56]
CMS measurement of t-channel single-top and anti-top cross sections. σ_t, $\sigma_{\bar t}$, $\sigma_{t+\bar t}$ & R_t.	4	[42]
CMS measurement of the t-channel single-top and anti-top cross sections. $\sigma_t \vert \sigma_{\bar t} \vert \sigma_{t+\bar t} \vert R_t$.	1|1|1|1	[45]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp_{t+\bar t}^T} \vert \frac{d\sigma}{d\vert y_{t+\bar t}\vert}$	4|4	[44]
ATLAS tW cross section measurement.	1	[43]
CMS tZ cross section measurement.	1	[47]
CMS tW cross section measurement.	1	[52]
ATLAS tZ cross section measurement.	1	[49]
CMS tZ ($Z \to \ell^+\ell^-$) cross section measurement	1	[54]
ATLAS four-top search in the multi-lepton and same-sign dilepton channels.	1	[63]
ATLAS four-top search in the single-lepton and opposite-sign dilepton channels.	1	[51]
CMS four-top search in the multi-lepton and same-sign dilepton channels.	1	[61]
CMS four-top search in the single-lepton and opposite-sign dilepton channels.	1	[59]
CMS $t\bar tb\bar b$ cross section measurement in the all-jet channel.	1	[57]
CMS $t\bar tb\bar b$ cross section measurement in the dilepton channel.	1	[64]

Fisher information breakdown

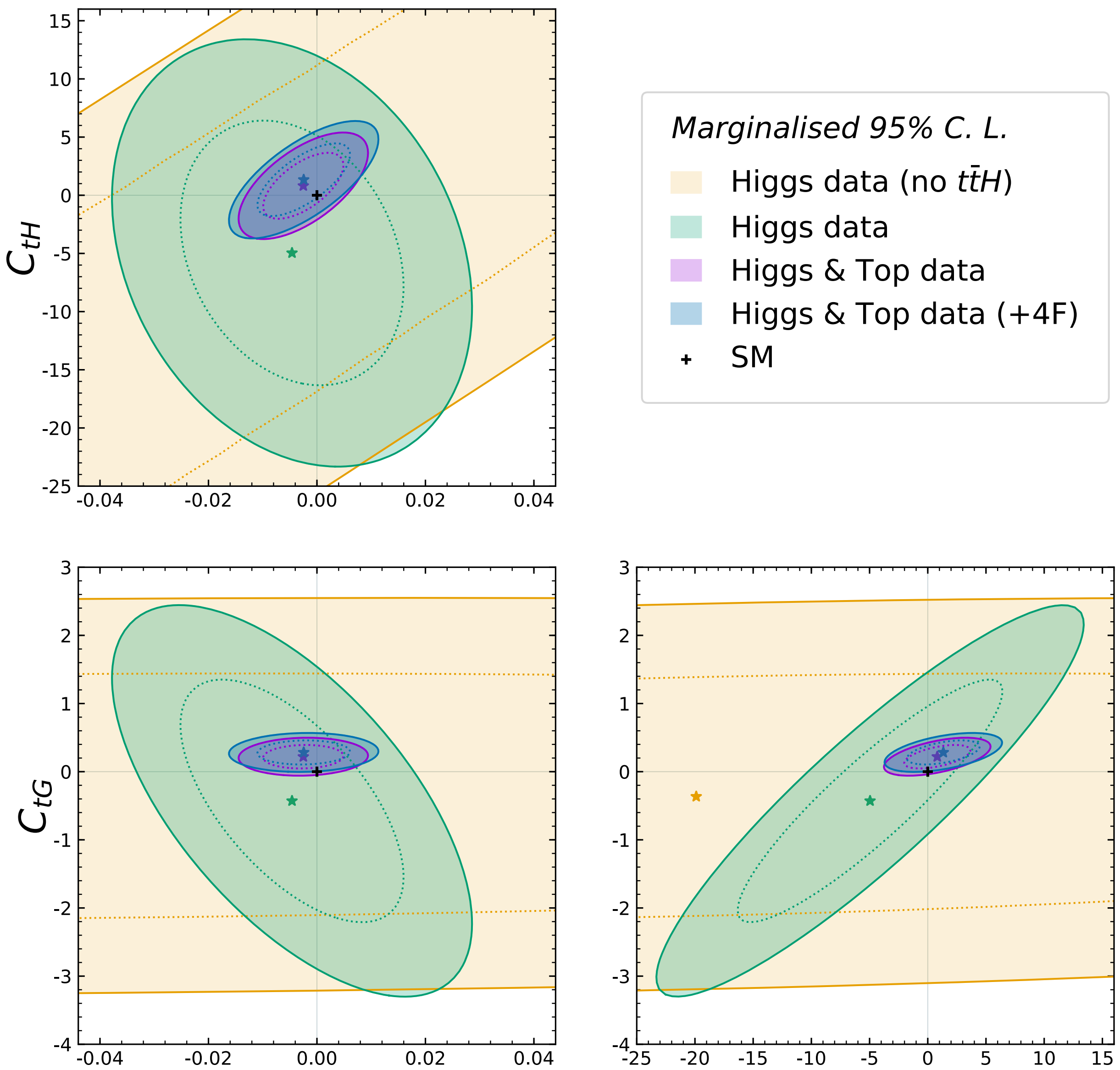


C_i	EWPO	LEP WW	Run 1 SS	Run 2 SS	STXS	LHC WW	WZ	Zjj	$t\bar{t}$	$W_{\text{hel.}}$	tX	$t\bar{t}V$
C_{HWB}	51	–	7	14	28	–	–	–	–	–	–	–
C_{HD}	100	–	–	–	–	–	–	–	–	–	–	–
C_{ll}	99	–	–	–	–	–	–	–	–	–	–	–
$C_{Hl}^{(3)}$	99	–	–	–	–	–	–	–	–	–	–	–
$C_{Hl}^{(1)}$	100	–	–	–	–	–	–	–	–	–	–	–
C_{He}	100	–	–	–	–	–	–	–	–	–	–	–
$C_{Hq}^{(3)}$	89	1	–	–	2	–	6	–	–	–	–	–
$C_{Hq}^{(1)}$	99	–	–	–	–	–	–	–	–	–	–	–
C_{Hd}	99	–	–	–	–	–	–	–	–	–	–	–
C_{Hu}	98	–	–	–	1	–	–	–	–	–	–	–
$C_{H\Box}$	–	–	22	46	32	–	–	–	–	–	–	–
C_{HG}	–	–	22	42	36	–	–	–	–	–	–	–
C_{HW}	–	–	14	29	56	–	–	–	–	–	–	–
C_{HB}	–	–	14	29	57	–	–	–	–	–	–	–
C_W	–	3	–	–	–	–	13	84	–	–	–	–
C_G	–	–	–	–	–	–	–	–	43	–	–	56
$C_{\tau H}$	–	–	22	45	34	–	–	–	–	–	–	–
$C_{\mu H}$	–	–	5	95	–	–	–	–	–	–	–	–
C_{bH}	–	–	19	35	47	–	–	–	–	–	–	–
C_{tH}	–	–	21	45	34	–	–	–	–	–	–	–
$C_{HQ}^{(3)}$	99	–	–	–	–	–	–	–	–	–	–	–
$C_{HQ}^{(1)}$	100	–	–	–	–	–	–	–	–	–	–	–
C_{Ht}	–	–	–	–	–	–	–	–	–	–	–	100
C_{tG}	–	–	13	29	24	–	–	–	24	–	–	9
C_{tW}	–	–	–	–	–	–	–	–	–	84	15	–
C_{tB}	–	–	–	–	–	–	–	–	–	–	–	100
$C_{Qq}^{3,1}$	–	–	–	–	–	–	–	–	–	–	100	–
$C_{Qq}^{3,8}$	–	–	–	–	–	–	–	–	87	–	–	13
$C_{Qq}^{1,8}$	–	–	–	–	–	–	–	–	82	–	–	17
C_{Qu}^{8}	–	–	–	–	–	–	–	–	91	–	–	7
C_{Qd}^{8}	–	–	–	2	–	–	–	–	92	–	–	6
C_{tq}^{8}	–	–	–	1	–	–	–	–	89	–	–	10
C_{tu}^{8}	–	–	–	–	–	–	–	–	96	–	–	3
C_{td}^{8}	–	–	–	2	–	–	–	–	92	–	–	5

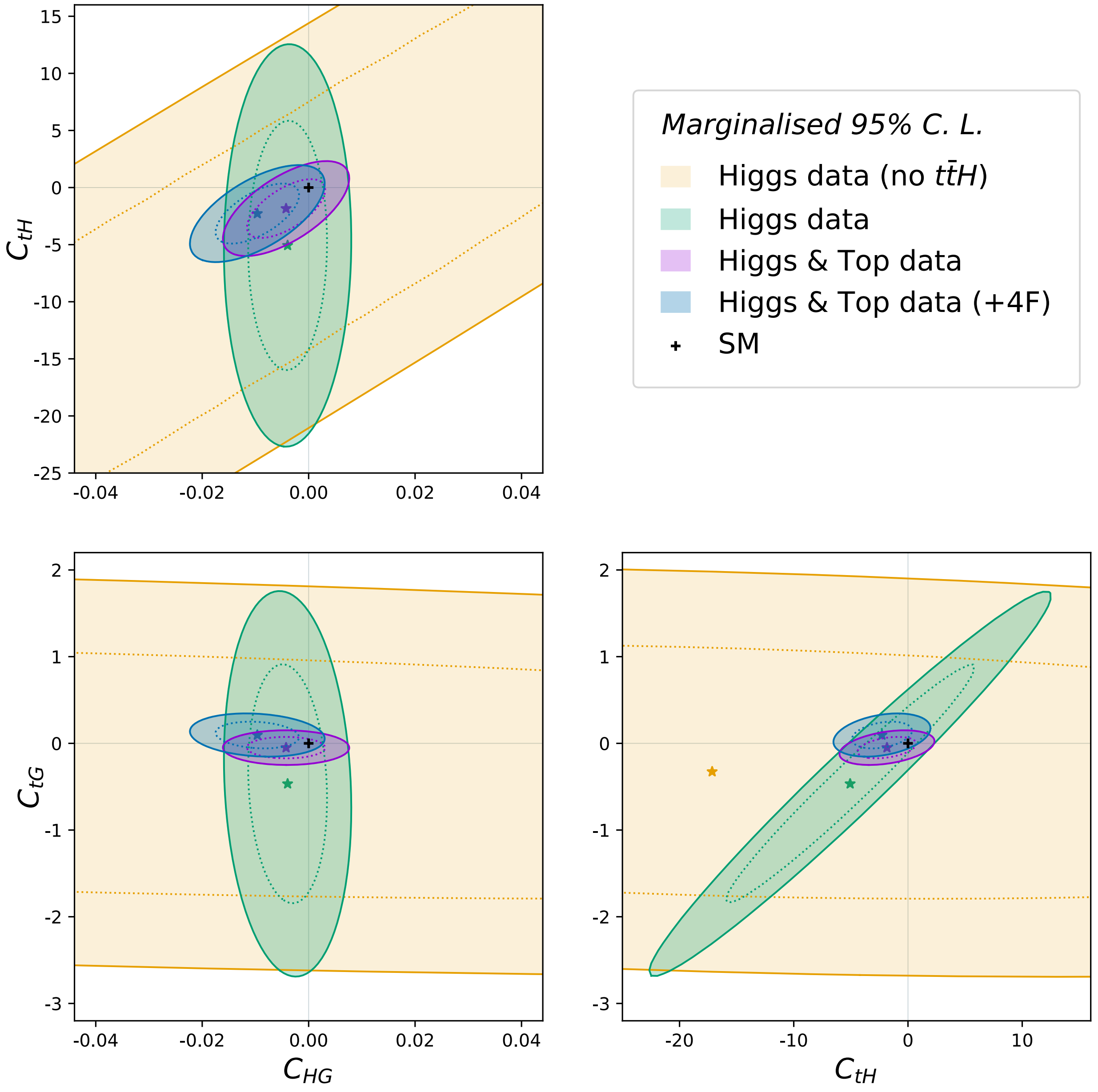
see also [ATLAS-CONF-2020-053]

Removing C_G

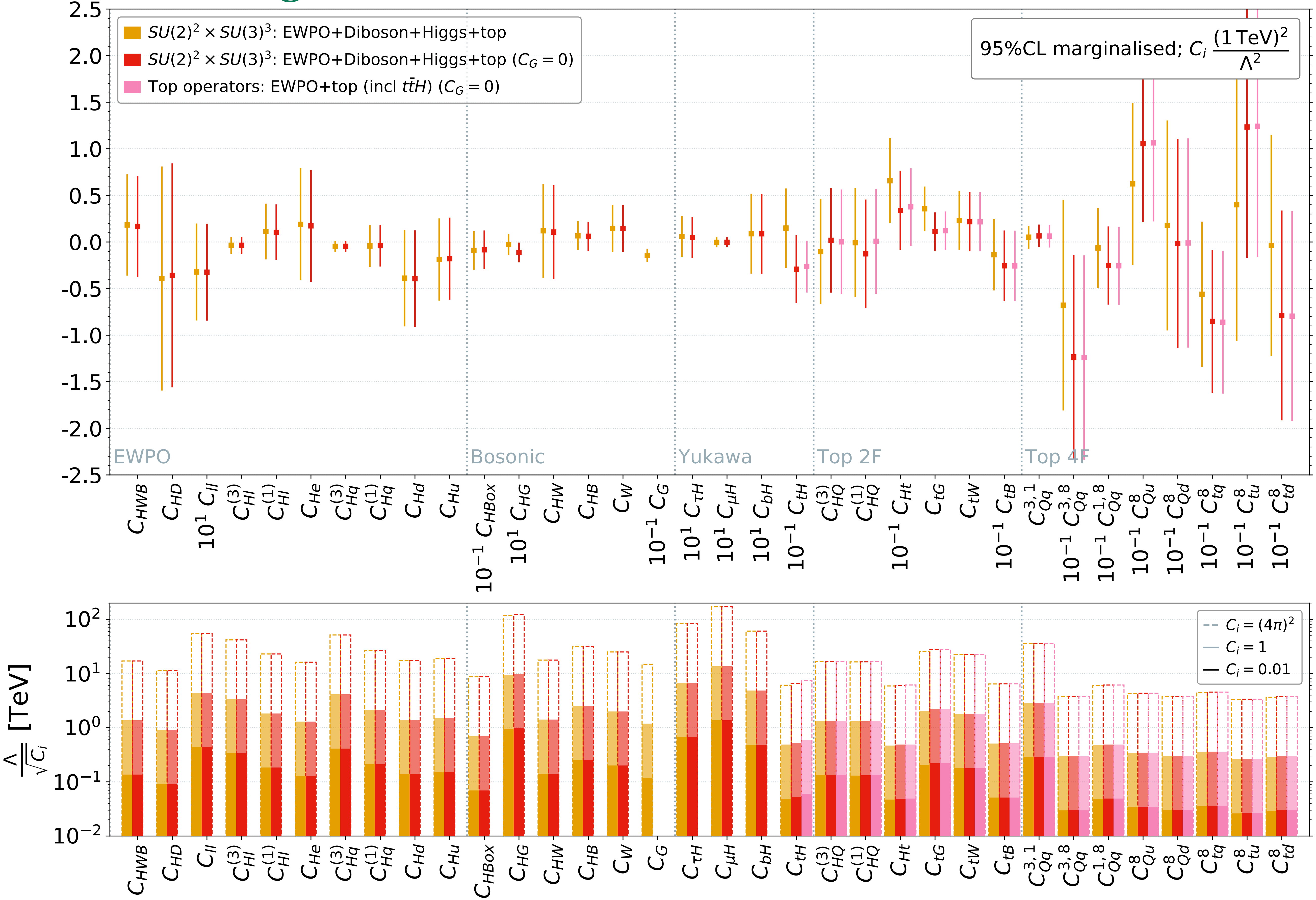
With



Without



Removing C_G


$SU(2)^2 \times SU(3)^3$: EWPO+Diboson+Higgs+top
$SU(2)^2 \times SU(3)^3$: EWPO+Diboson+Higgs+top ($C_G = 0$)
Top operators: EWPO+top (incl $t\bar{t}H$) ($C_G = 0$)
95%CL marginalised; $C_i \frac{(1\,\text{TeV})^2}{\Lambda^2}$
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
EWPO
Bosonic
Yukawa
Top 2F
Top 4F
C_{HWB}
C_{HD}
$10^1\ C_{ll}$
$C_{Hl}^{(3)}$
$C_{Hl}^{(1)}$
C_{He}
$C_{Hq}^{(3)}$
$C_{Hq}^{(1)}$
C_{Hd}
C_{Hu}
$10^{-1}\ C_{HBox}$
$10^1\ C_{HG}$
C_{HW}
C_{HB}
C_W
$10^{-1}\ C_G$
$10^1\ C_{\tau H}$
$10^1\ C_{\mu H}$
$10^1\ C_{bH}$
$10^{-1}\ C_{tH}$
$C_{HQ}^{(3)}$
$C_{HQ}^{(1)}$
$10^{-1}\ C_{Ht}$
C_{tG}
C_{tW}
$10^{-1}\ C_{tB}$
$C_{Qq}^{3,1}$
$10^{-1}\ C_{Qq}^{3,8}$
$10^{-1}\ C_{Qq}^{1,8}$
$10^{-1}\ C_{Qu}^8$
$10^{-1}\ C_{Qd}^8$
$10^{-1}\ C_{tq}^8$
$10^{-1}\ C_{tu}^8$
$10^{-1}\ C_{td}^8$
$\frac{\Lambda}{\sqrt{C_i}}$ [TeV]
10^2
10^1
10^0
10^{-1}
10^{-2}
$C_i = (4\pi)^2$
$C_i = 1$
$C_i = 0.01$
C_{HWB}
C_{HD}
C_{ll}
$C_{Hl}^{(3)}$
$C_{Hl}^{(1)}$
C_{He}
$C_{Hq}^{(3)}$
$C_{Hq}^{(1)}$
C_{Hd}
C_{Hu}
C_{HBox}
C_{HG}
C_{HW}
C_{HB}
C_W
C_G
$C_{\tau H}$
$C_{\mu H}$
C_{bH}
C_{tH}
$C_{HQ}^{(3)}$
$C_{HQ}^{(1)}$
C_{Ht}
C_{tG}
C_{tW}
C_{tB}
$C_{Qq}^{3,1}$
$C_{Qq}^{3,8}$
$C_{Qq}^{1,8}$
C_{Qu}^8
C_{Qd}^8
C_{tq}^8
C_{tu}^8
C_{td}^8