Top, Higgs, Diboson and Electroweak Fit to the SMEFT

[J. Ellis, M. Madigan, KM, V. Sanz & T. You; arXiv:2012.02779]

fitmaker

https://gitlab.com/kenmimasu/fitrepo

Ken Mimasu
King's College London

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The story

New physics searches via high precision/energy

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

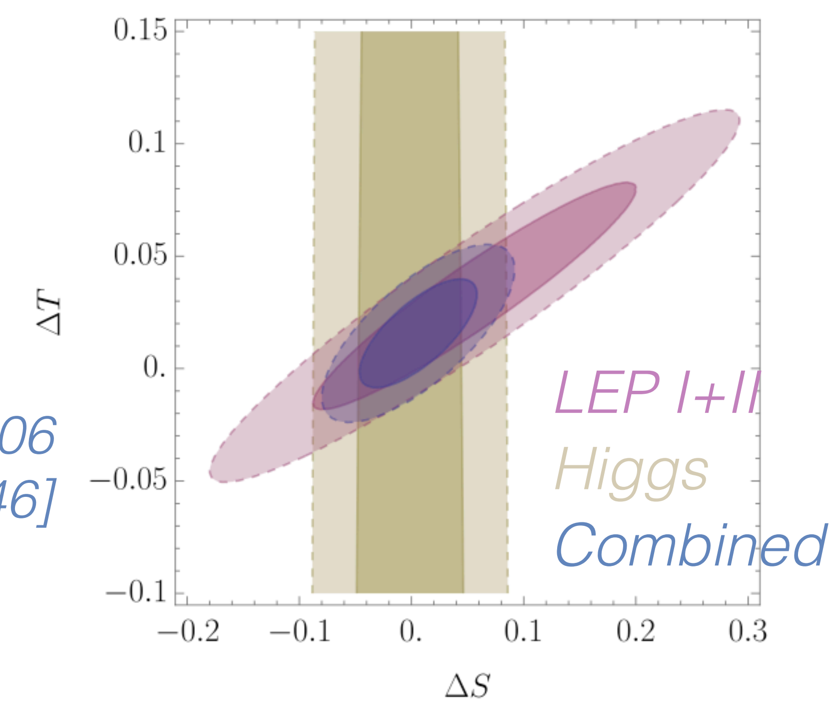
How much cross-talk? Where does being global matter?

We know that Higgs physics greatly complements LEP data

- Access to parameter directions not probed at LEP
- 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]
…

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

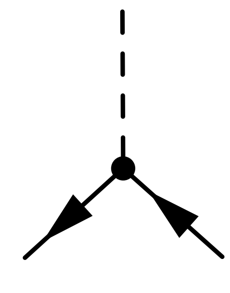


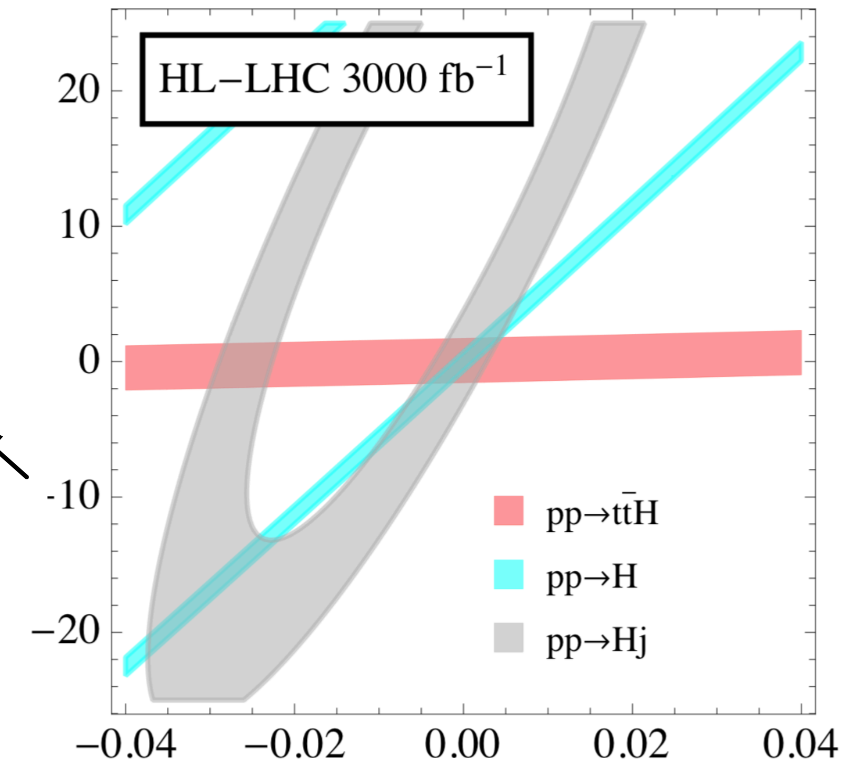
Top & Higgs

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

Inextricably linked in the SM

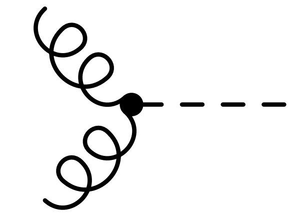
- Crucial interaction that controls ggF
- Strong BSM motivation to looks for hints





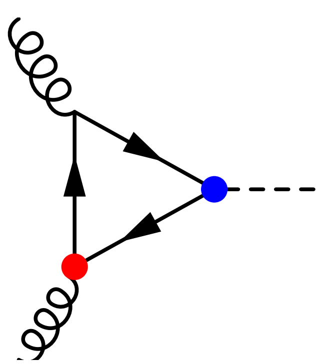
ggF is well measured now

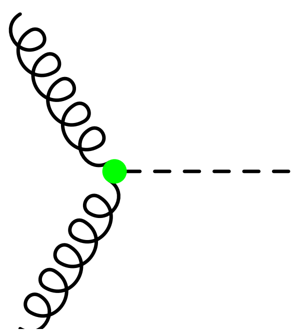
- Exclude top partners, anomalous Yukawa,…? No!



Blind direction in BSM scenarios = Effective coupling degeneracy

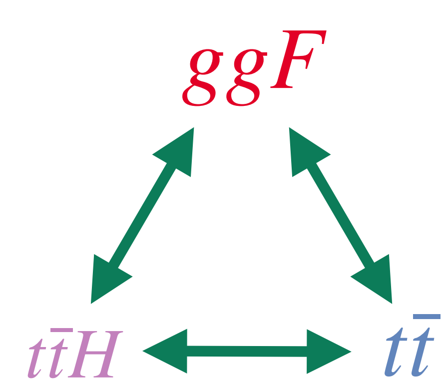
C_{HG} *Point-like*
C_{tH} *Yukawa*
C_{tG} *Dipole*





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)
- Identify other cross-talk (non-trivial correlations)
- Broaden range of applicability to UV models

[Degrande et al.; arXiv:2008.11743]
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

arXiv:2012.02779 **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]

The fit

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

public-friendly version w/ example notebooks in progress

Global SMEFT interpretation of 4 categories of data

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

- Electroweak Precision Observables (EWPO): Z-pole & W-mass
- Diboson production: differential WW, Zjj (WZ to be added)
- Higgs measurements: signal strengths & STXS
- 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

310 measurements across categories

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

Linearised, least-squares fit at LO (tree + 1-loop ggF)

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

Convert data to 'signal strengths', folding in best known SM prediction & uncertainty

Theory

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

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

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

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

$(\bar{L}R)(\bar{R}L)$ 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
- Flavor-**universal** degrees of freedom

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

- 2nd, **top**-centric flavor scenario

$U(3)_L \times U(3)_e \times U(2)_Q \times U(2)_u \times U(3)_d$

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

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

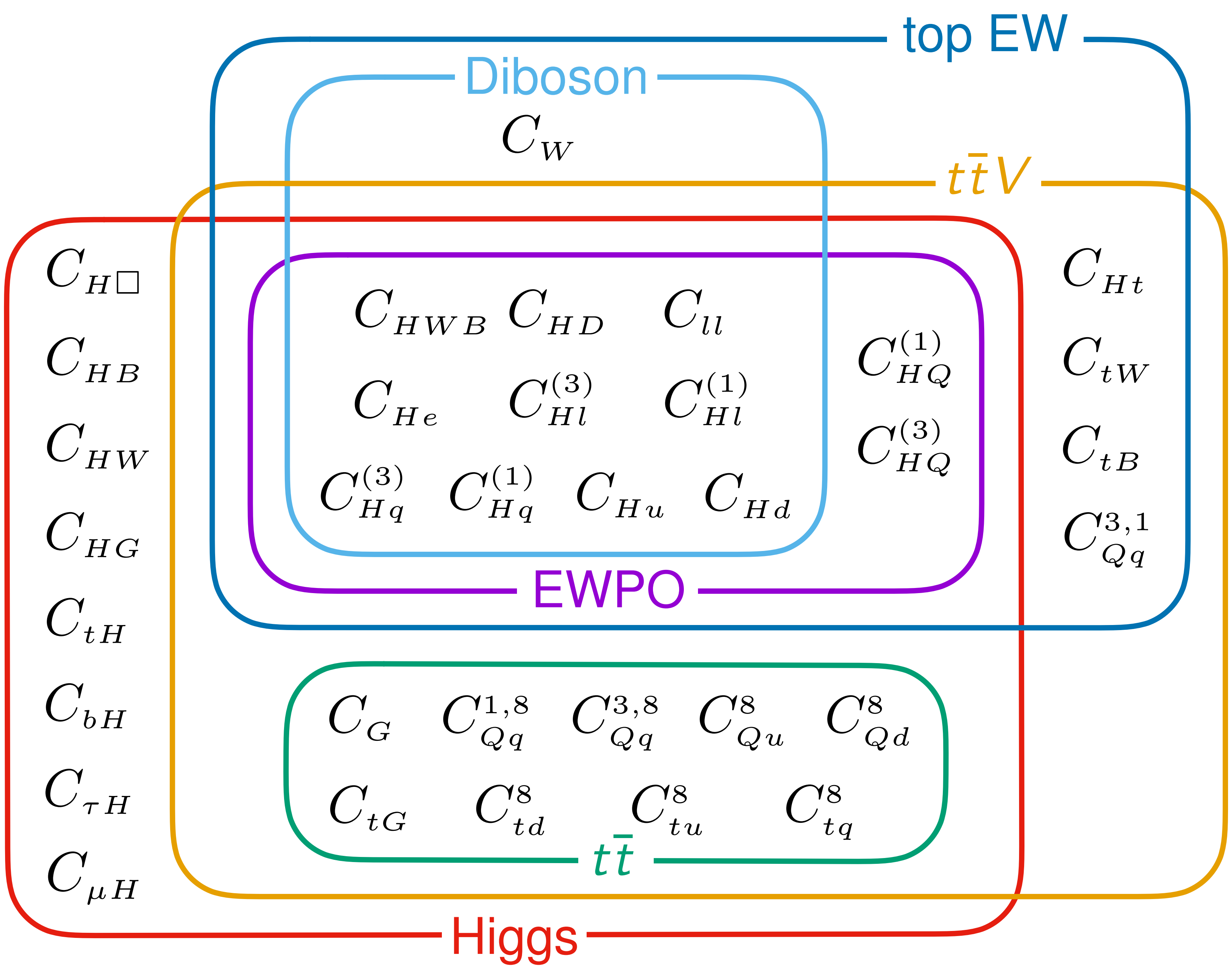
Dim6top conventions: [Aguilar-Saavedra et al.; arXiv:1802.07237]

Dictated by flavor symmetry & sensitivity of dataset

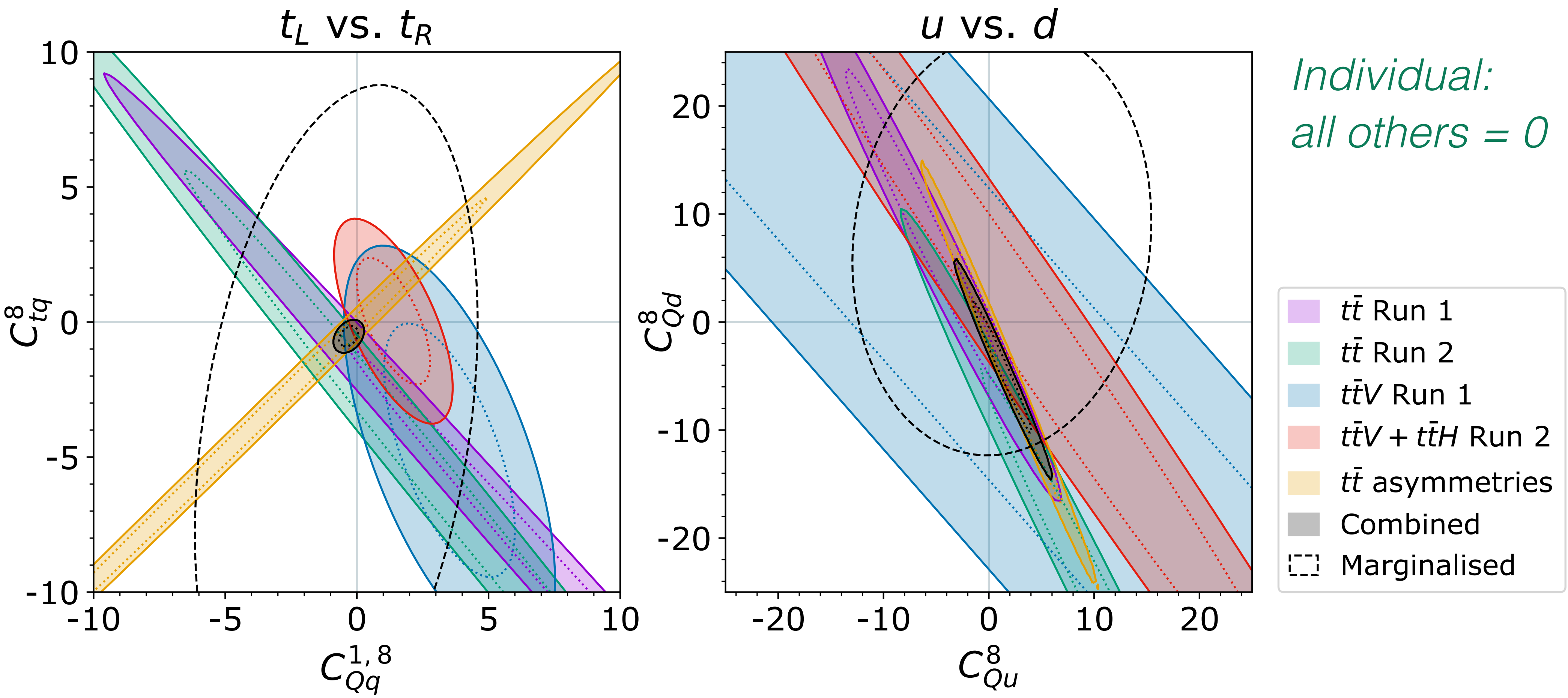
Linear EFT approximation precludes sensitivity to some ops

- 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}
$C_{HQ}^{(1)}$
$C_{HQ}^{(3)}$
EWPO
C_{Ht}
C_{tW}
C_{tB}
$C_{Qq}^{3,1}$
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

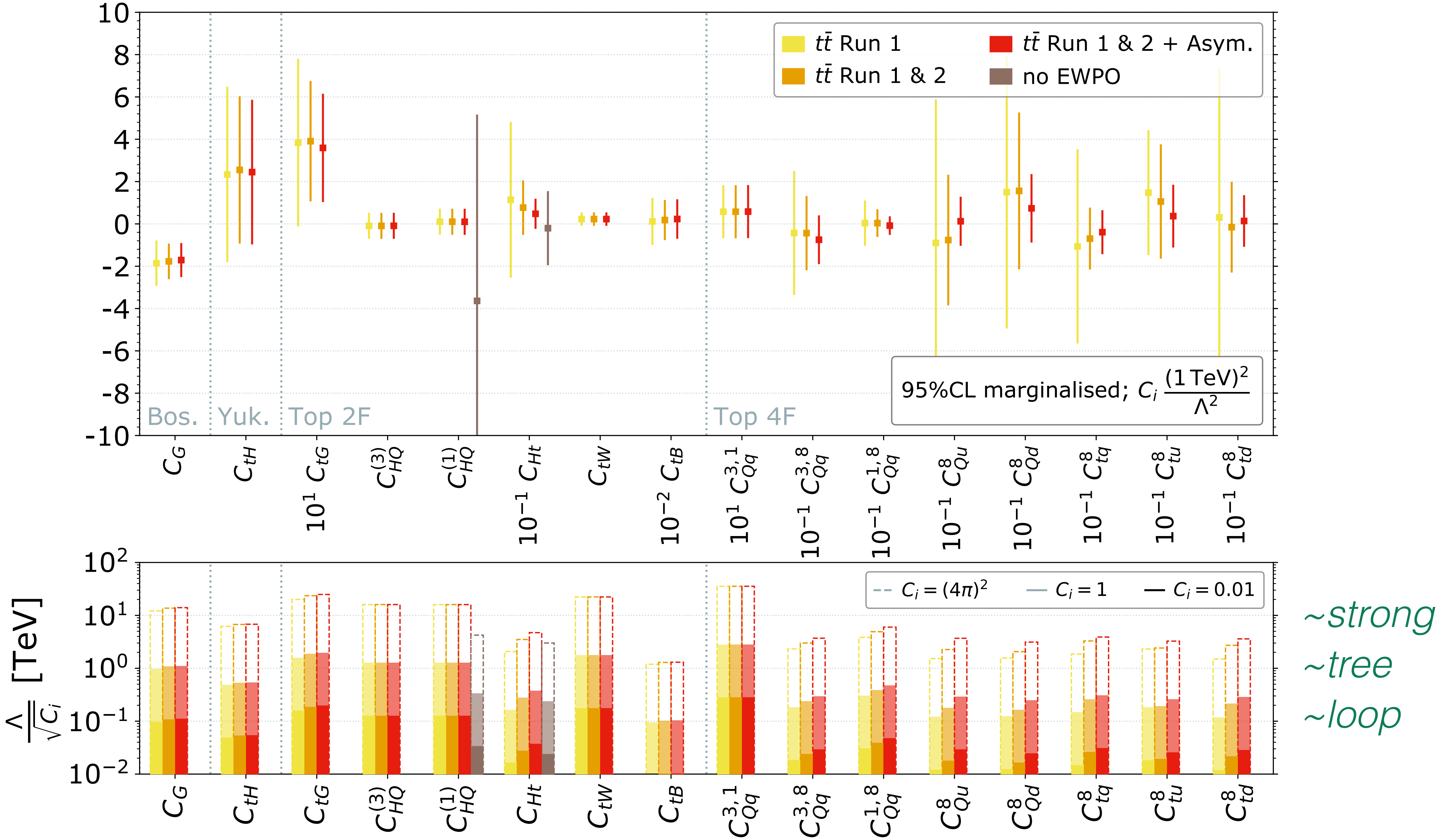
Top-only: breakdown



Individual: all others = 0

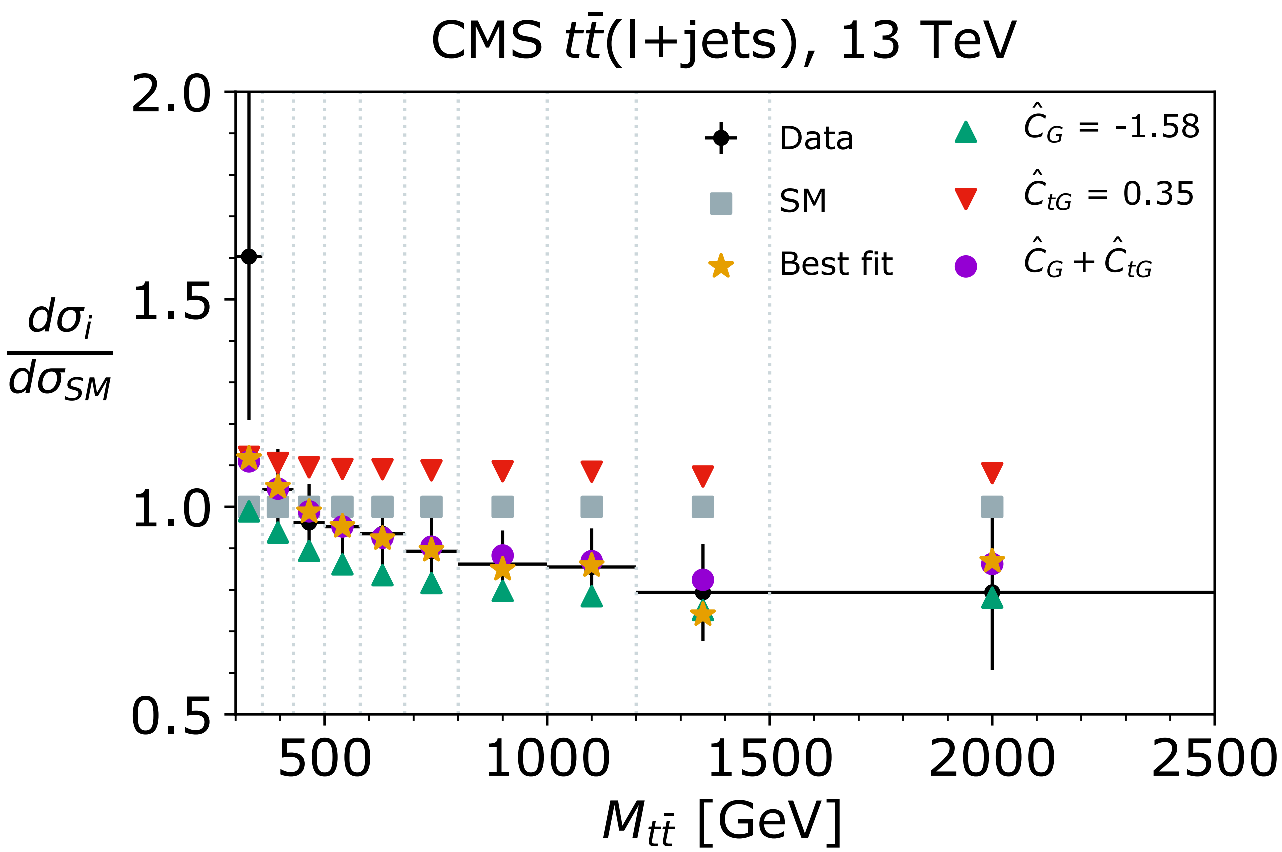
- $t\bar{t}$ asymmetries constrain orthogonal direction to cross section
- Large marginalisation effects: many similar operators
- $t\bar{t}V$ & $t\bar{t}H$ help to close the space
- Marginalised linear sensitivity: $C_{4F}\left[\frac{1\,\mathrm{TeV}^2}{\Lambda^2}\right] \sim (5-20)$ *significant* $\frac{1}{\Lambda^4}$ *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?)

$m_{t\bar{t}}$ tension



Example: CMS 13 TeV l+jets

- Data/SM tension at low $m_{t\bar{t}}$
- Pulls fit away from SM
- Mainly absorbed by C_{tG} & C_G

C_G has potentially strong multi-jet constraints

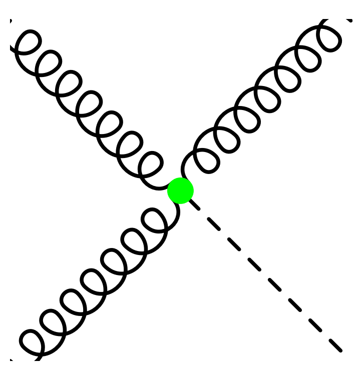
[Krauss et al.; PRD 95 (2017) 3, 035024]

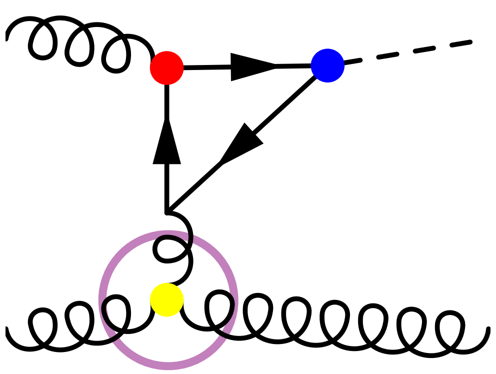
- Purely quadratic (non-interference due to helicity selection)
- Best existing linear constraint from $t\bar{t}$, other directions possible

[Goldouzian & Hildreth; PLB 811 (2020) 135889]

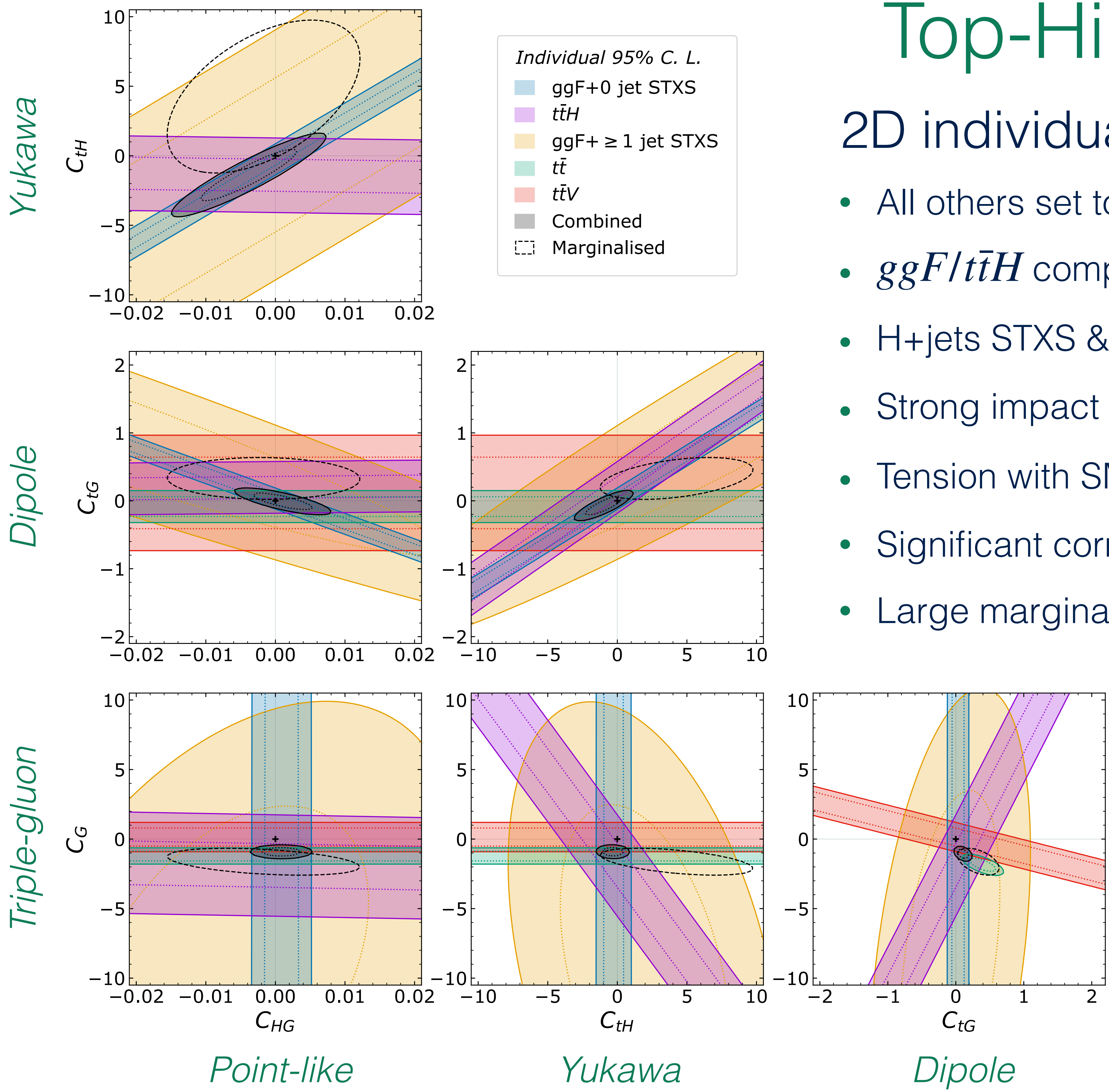
- Can also contribute to ggF $+ \geq 1$ jet

[Dixon & Shadmi; NPB 423 (1994) 3-32]
[Bardhan et al.; arXiv:2010.13402]
[Hirschi et al.; JHEP 07 (2018) 093]
[Degrande & M. Maltoni; arXiv:2012.06595]





Top-Higgs interplay

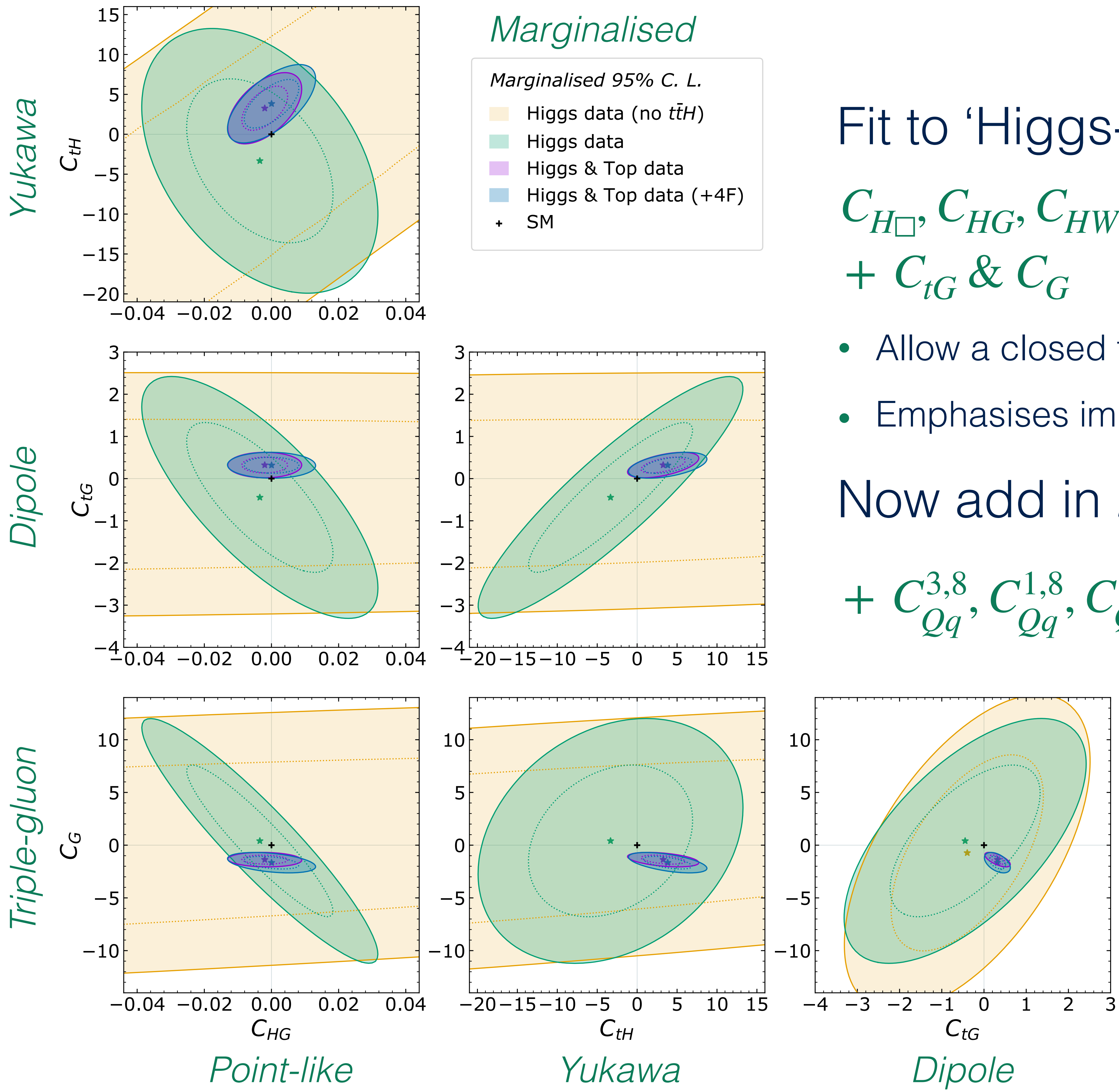


2D individual constraints

- 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 $> 2\sigma$
- Significant correlations remain
- Large marginalisation effects (including 4F)

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

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

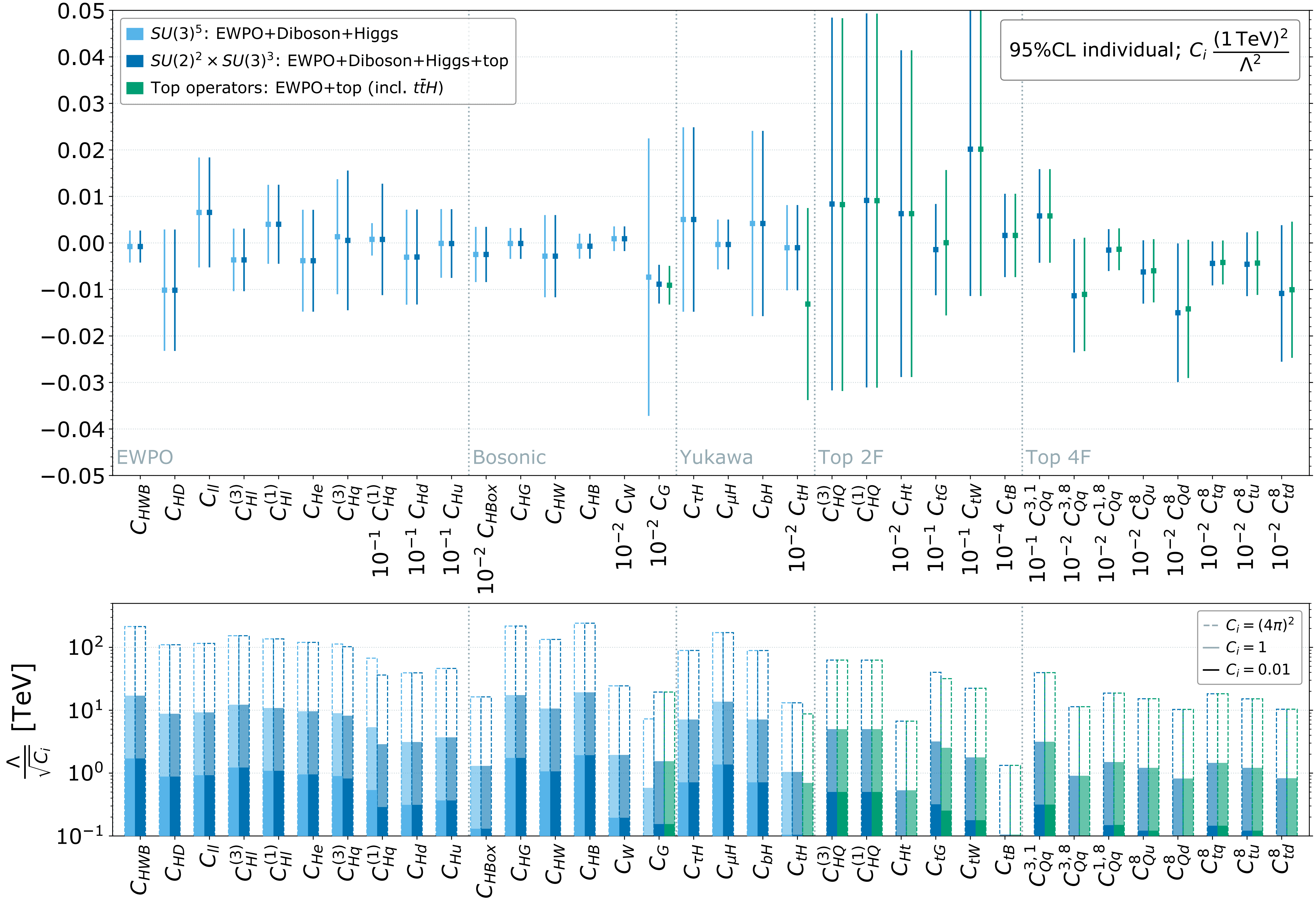
- Relatively mild impact
- Preferred $t\bar{t}$ phase space is different

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

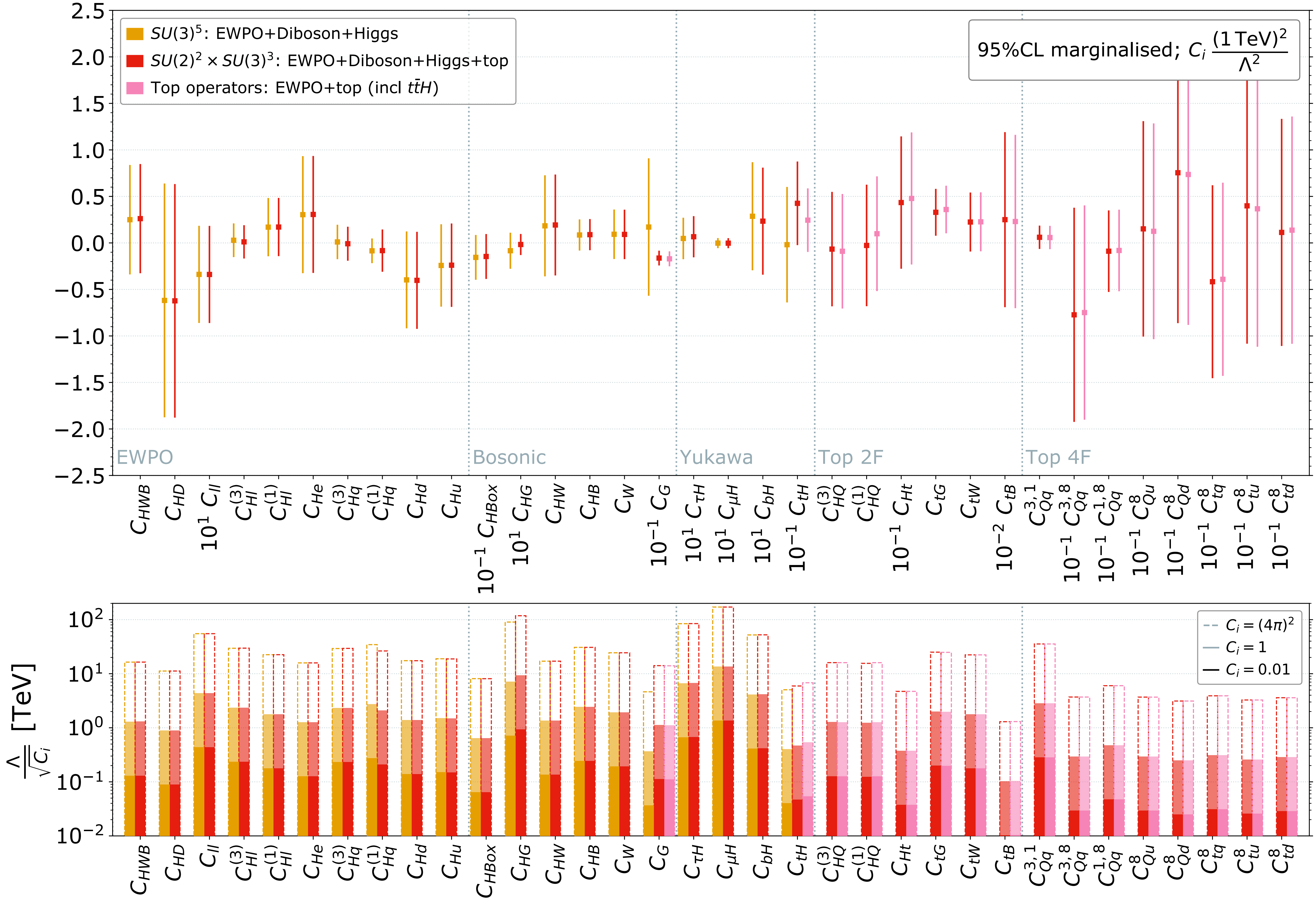
  $4F$: high $m_{t\bar{t}}$

- Able to constrain them independently

Full fit: individual



Full fit: marginalised



Correlations

Block diagonal: correlations *within* ‘sector’

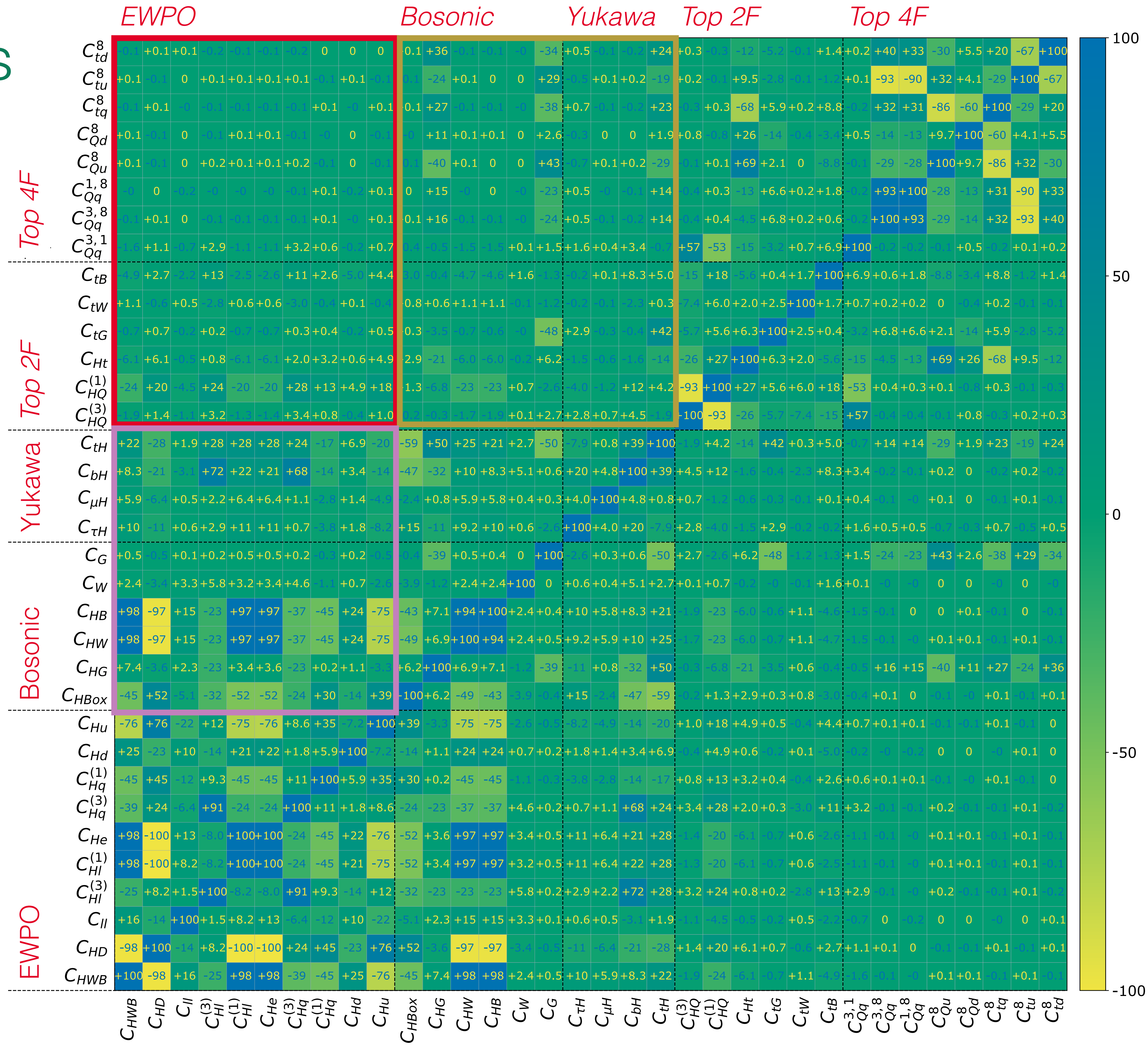
Block off-diagonal: correlations *among* ‘sectors’

EWPO & top ~uncorrelated

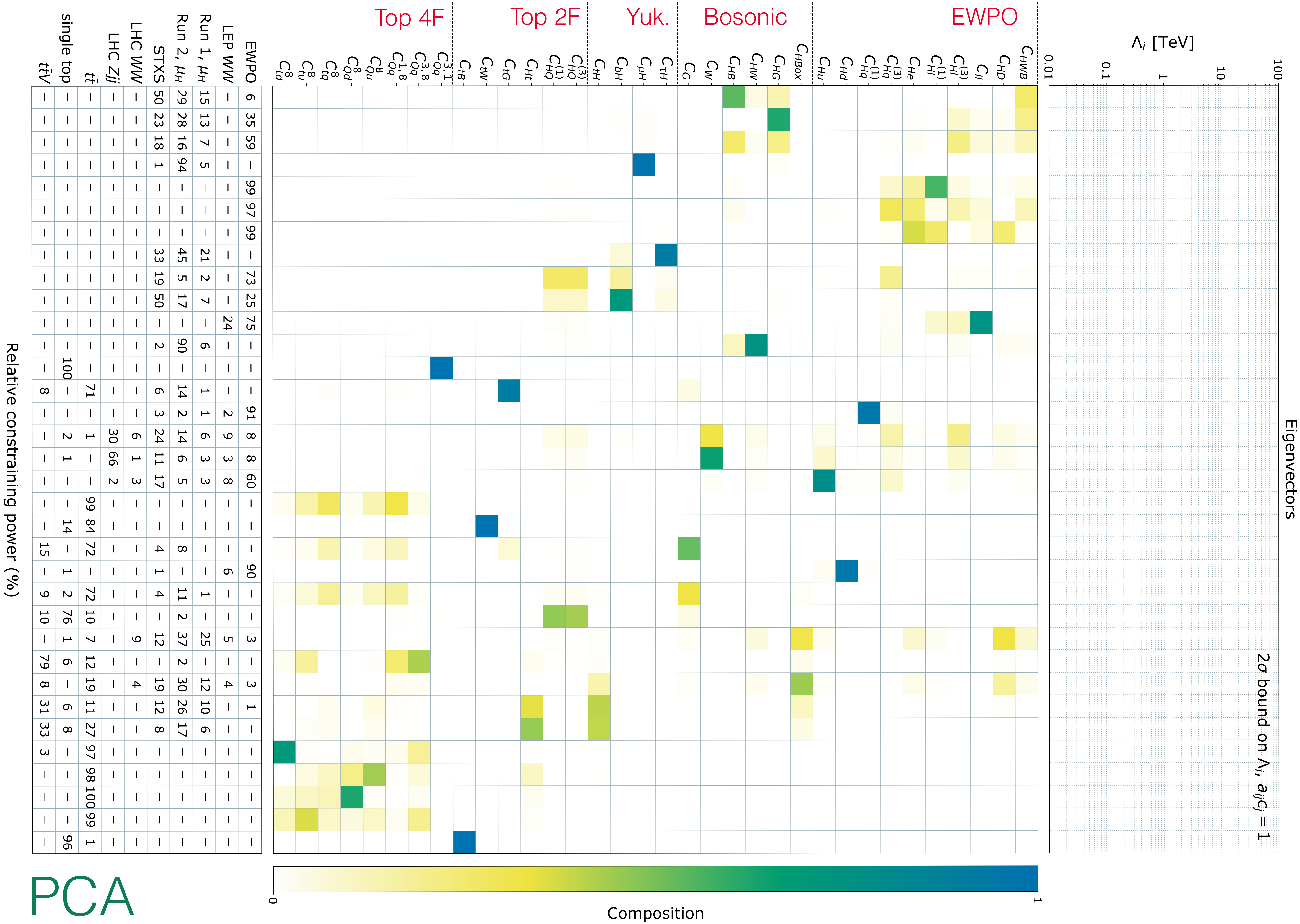
EWPO-Higgs
$C_{HB}, C_{HW}, C_{H\Box}$
& Yukawa
with EWPO

Higgs precision rivalling LEP

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



PCA



Top 4F
Top 2F
Yuk.
Bosonic
EWPO
Λ_i [TeV]
Eigenvectors
2σ bound on Λ_i, $a_{ij}c_j = 1$
Relative constraining power (%)
EWPO
LEP WW
Run 1, μ_H
Run 2, μ_H
STXS
LHC WW
LHC Zjj
$t\bar{t}$
single top
$t\bar{t}V$
Composition

Conclusions

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

- Include leading contributions from top operators in ggF (`SMEFTatNLO`)
- Top & Higgs are starting whisper to each other
- Measurement & prediction database + python fitting code (`fitmaker`)

https://gitlab.com/kenmimasu/fitrepo

Linear analysis has many benefits

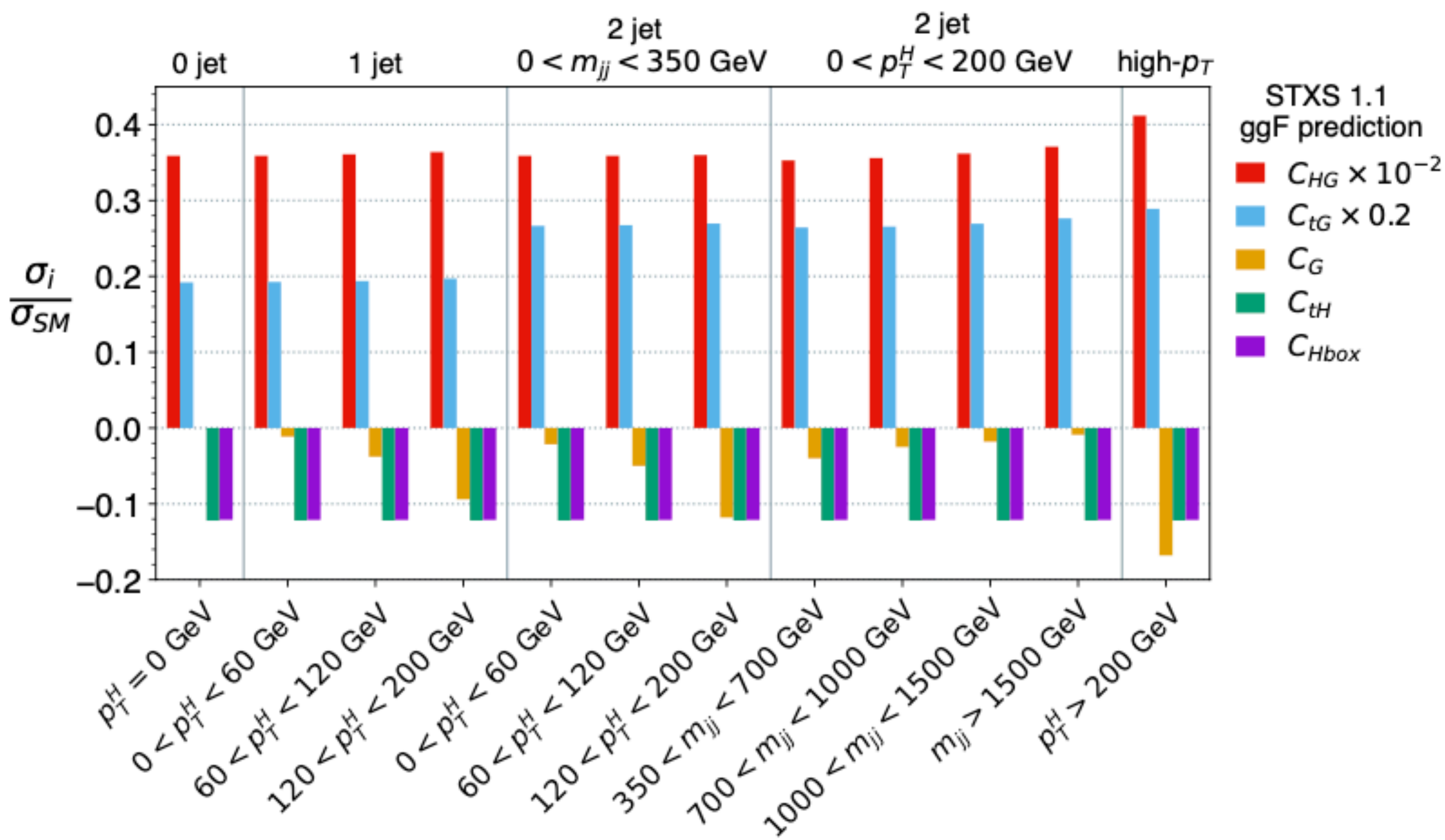
- Simple likelihood described by best fit+correlations, PCA exact
- Easy to interpret/combine with other likelihoods
- Fast: repeat for subsets, BSM interpretations (see paper)

& Drawbacks

- Potentially important quadratic effects, especially in top data
- Validity of EFT interpretation in question

Backup

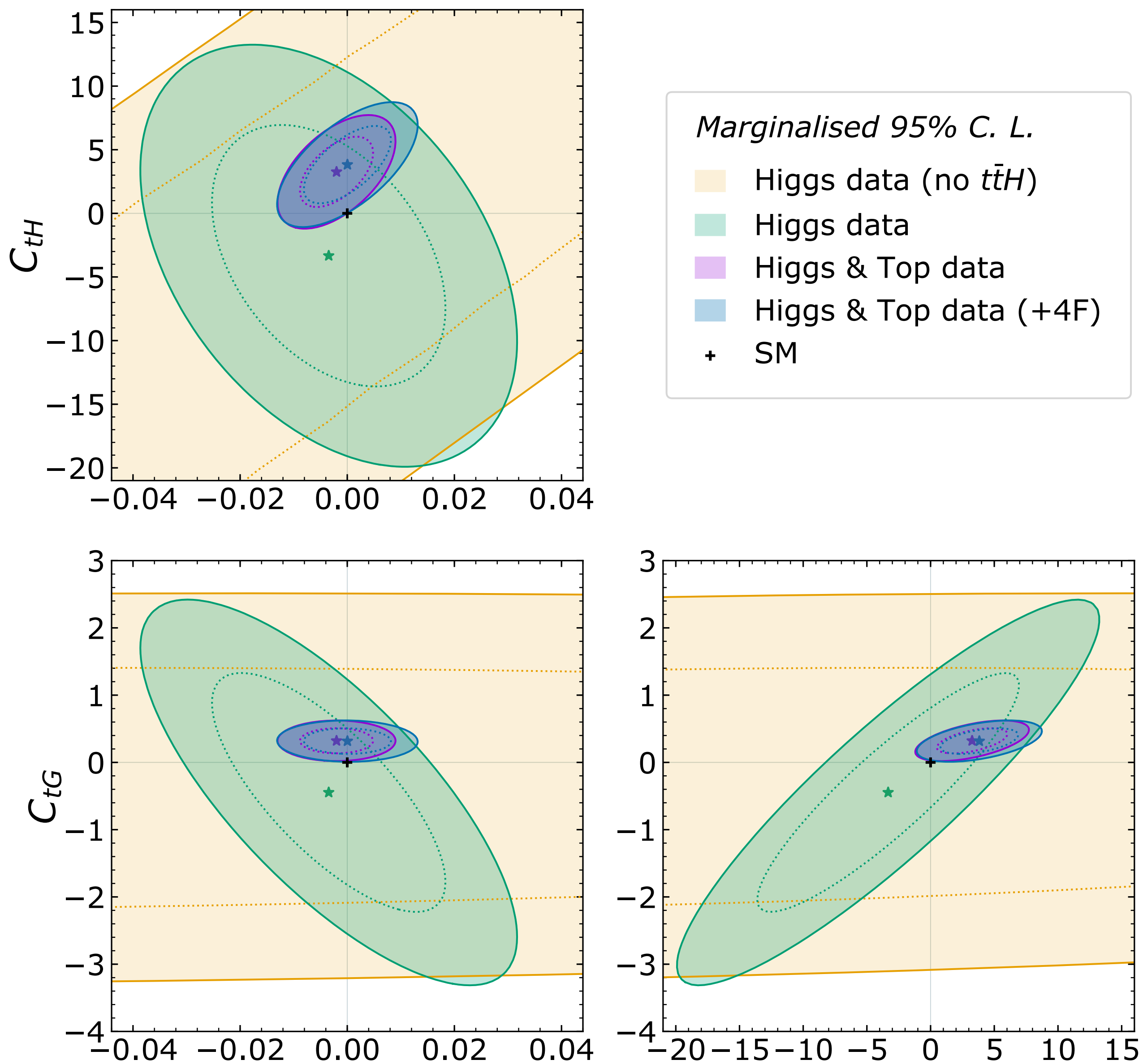
STXS with top loops



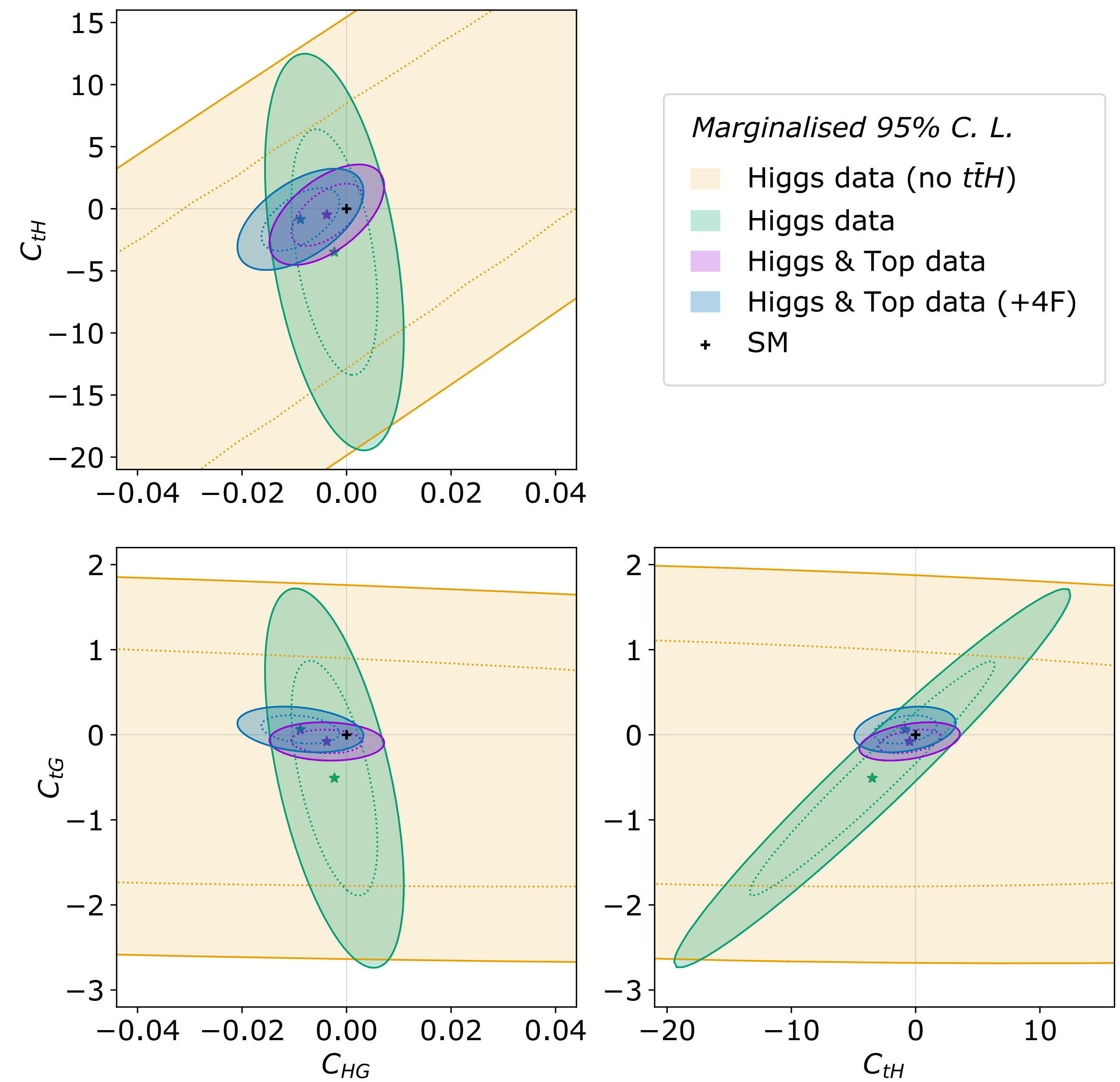
see also [ATLAS-CONF-2020-053]

Removing C_G

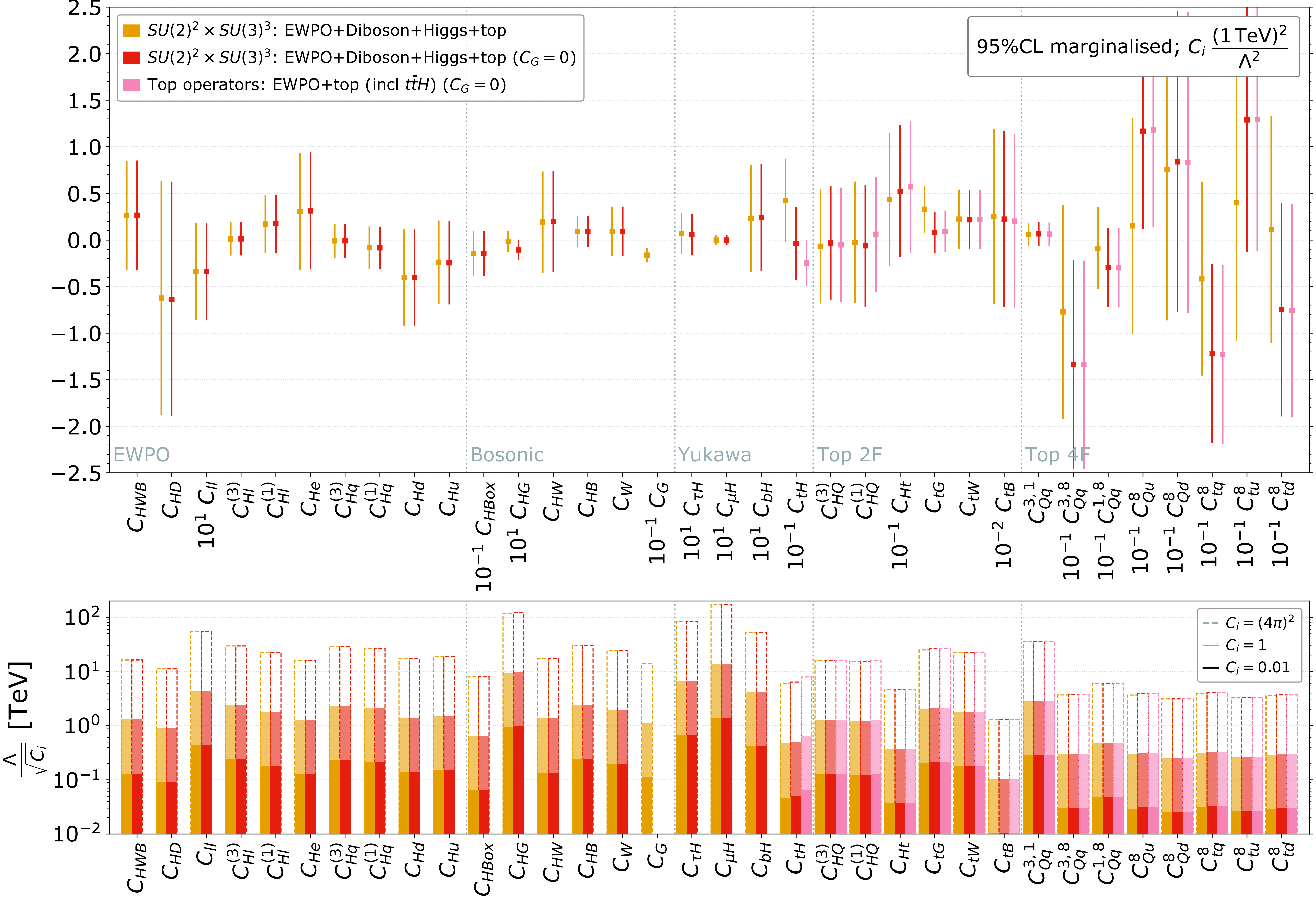
With



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; $C_i \frac{(1\,\mathrm{TeV})^2}{\Lambda^2}$
EWPO
Bosonic
Yukawa
Top 2F
Top 4F
$C_i = (4\pi)^2$
$C_i = 1$
$C_i = 0.01$
$\frac{\Lambda}{\sqrt{C_i}}$ [TeV]