

Top, Higgs, Diboson & Electroweak fit to the SMEFT

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Higgs 2021, SUNY & BNL

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[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>

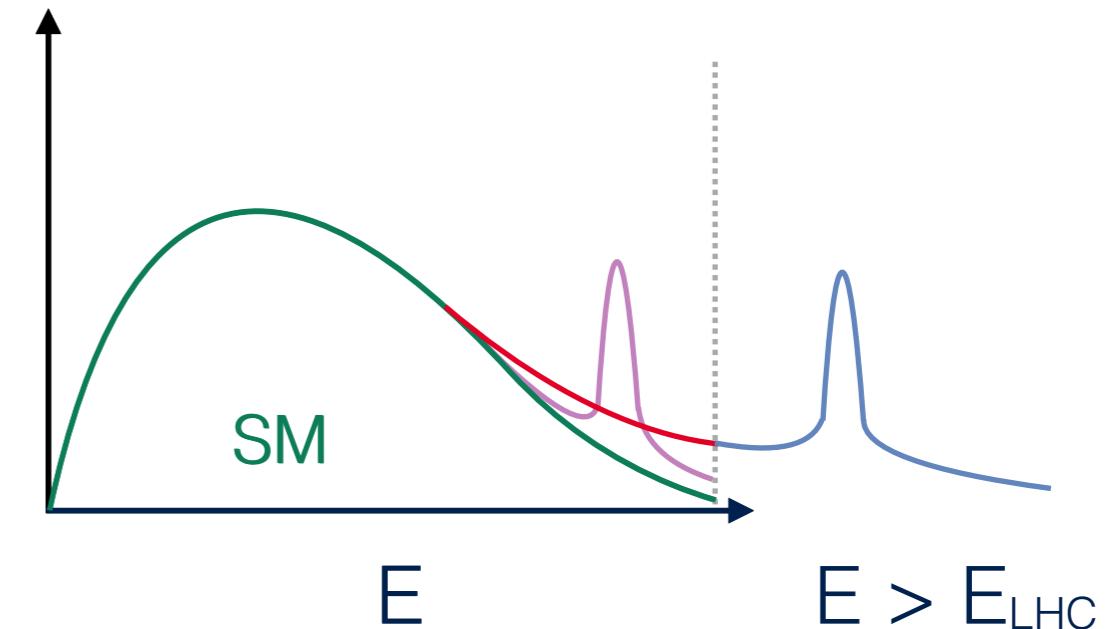
Energy & precision

Paradigm shift at the energy frontier for BSM searches

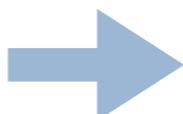
Direct (bumps)

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

Status in a nutshell

Global new physics searches via high precision/energy

- Z & W-pole data: handle on the EW gauge sector [Han & Skiba; PRD 71 (2005) 075009]
[Falkowski & Riva; JHEP 02 (2015) 039]
- LHC: thriving Higgs & top programmes
- Probing gauge interactions at high energy (VV, VBS, VVV, ...)

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]

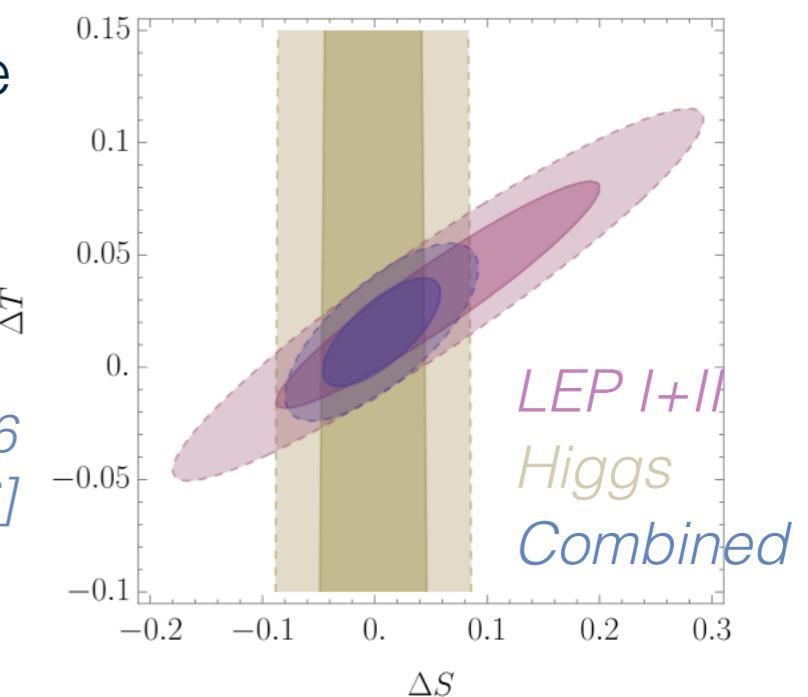
[Pomarol & Riva; JHEP 01 (2014) 151]

[Ellis, Sanz & You; JHEP 03 (2015) 157]

[Biekötter Corbett & Plehn; SciPost Phys 6 (2019) 6, 064]...

[Ellis et al.; JHEP 06

(2018) 146]



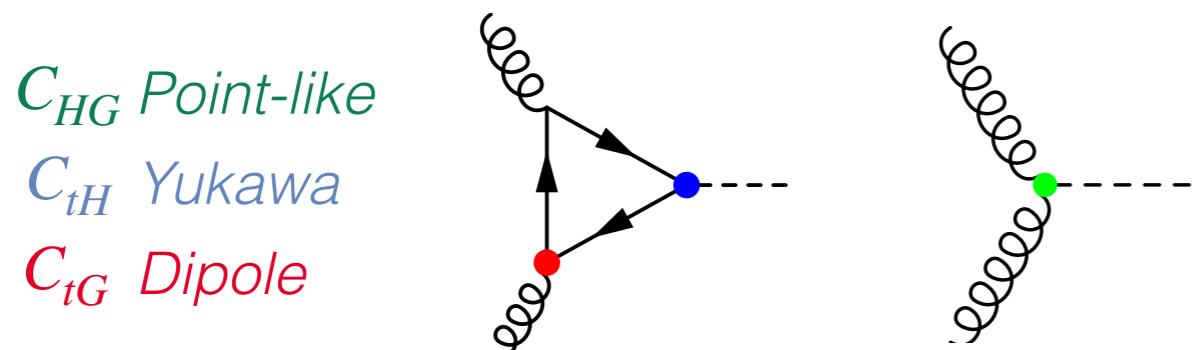
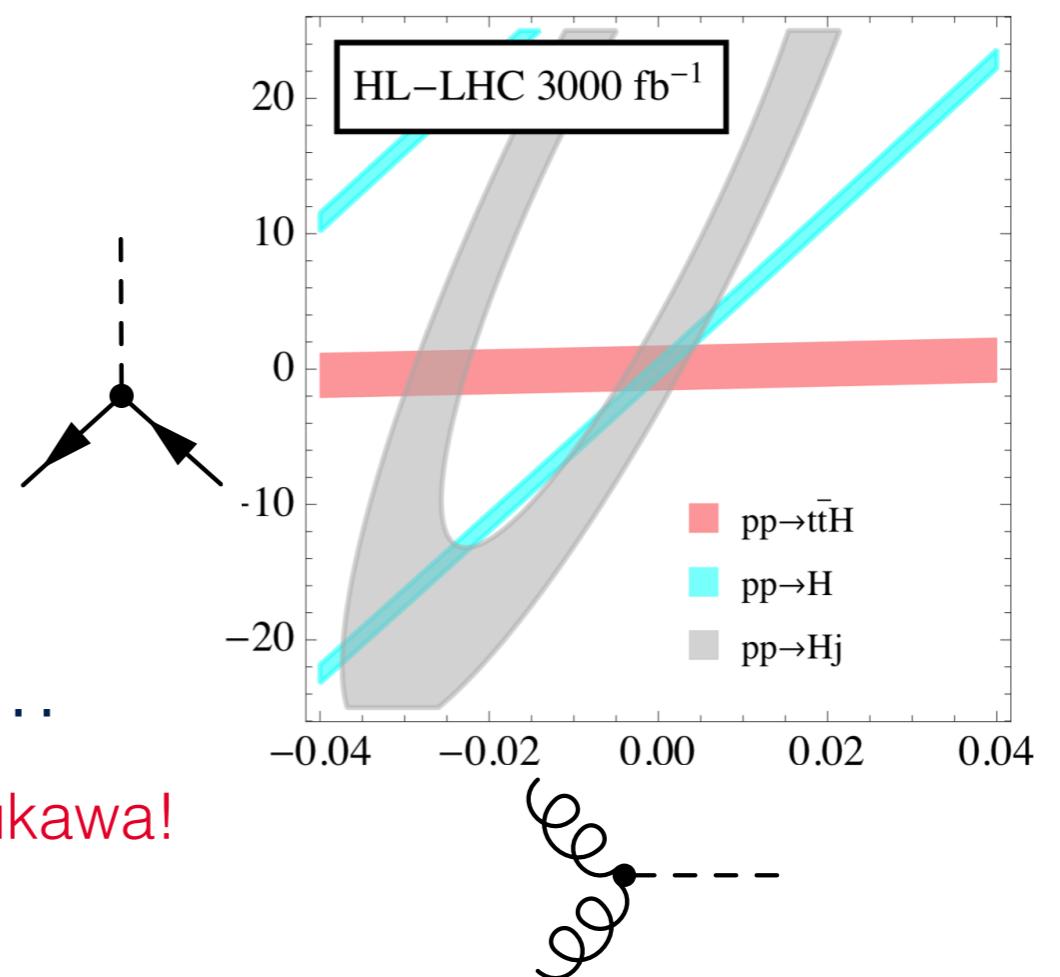
Top & Higgs

Inextricably linked in the SM

- Yukawa interaction mediates gluon fusion
- Strong BSM motivation to study tops

Gluon fusion is well measured now...

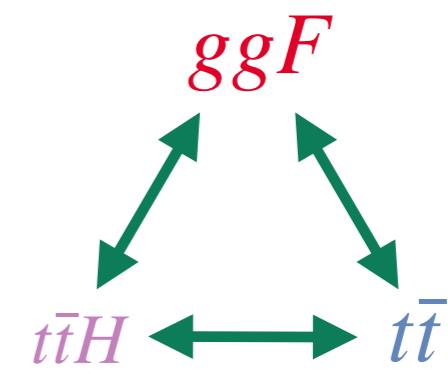
- Does not exclude top partners/anomalous Yukawa!



Need more data to break degeneracy

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

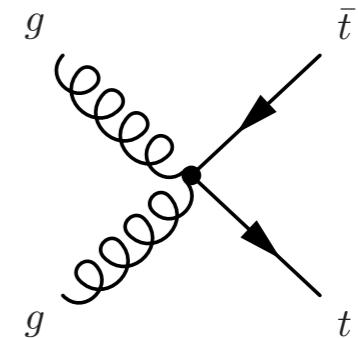
Effective coupling degeneracy
Blind direction in BSM scenarios



The role of top data

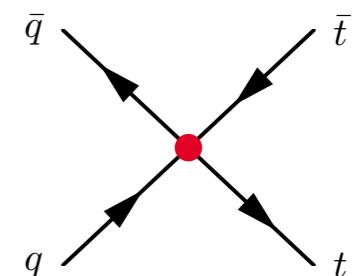
$t\bar{t}$ cross section measurements constrain C_{tG}

- 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**

SMEFTatNLO

- Beyond tree-level (at least for ggF)
- Identify other cross-talk (non-trivial correlations)
- Broaden range of applicability to UV models

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

[Degrade et al.; PRD 103 (2021) 9, 096024]

The fit

fitmaker <https://gitlab.com/kenmimasu/fitrepo>
public-friendly version w/ example notebooks in progress

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

- 14 • Electroweak Precision Observables (EWPO): Z-pole & W-mass [Ellis et al.; JHEP 06 (2018) 146]
- 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

Based on

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

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:	$\mathcal{O}_{H\square}, \mathcal{O}_{HG}, \mathcal{O}_{HW}, \mathcal{O}_{HB}, \mathcal{O}_W, \mathcal{O}_G,$
Yukawa:	$\mathcal{O}_{\tau H}, \mathcal{O}_{\mu H}, \mathcal{O}_{b H}, \mathcal{O}_{t H},$
Top 2F:	$\mathcal{O}_{HQ}^{(3)}, \mathcal{O}_{HQ}^{(1)}, \mathcal{O}_{Ht}, \mathcal{O}_{tG}, \mathcal{O}_{tW}, \mathcal{O}_{tB},$
Top 4F:	$\mathcal{O}_{Qq}^{3,1}, \mathcal{O}_{Qq}^{3,8}, \mathcal{O}_{Qq}^{1,8}, \mathcal{O}_{Qu}^8, \mathcal{O}_{Qd}^8, \mathcal{O}_{tQ}^8, \mathcal{O}_{tu}^8, \mathcal{O}_{td}^8.$

20

+ 14

SMEFT: Warsaw basis

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

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

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

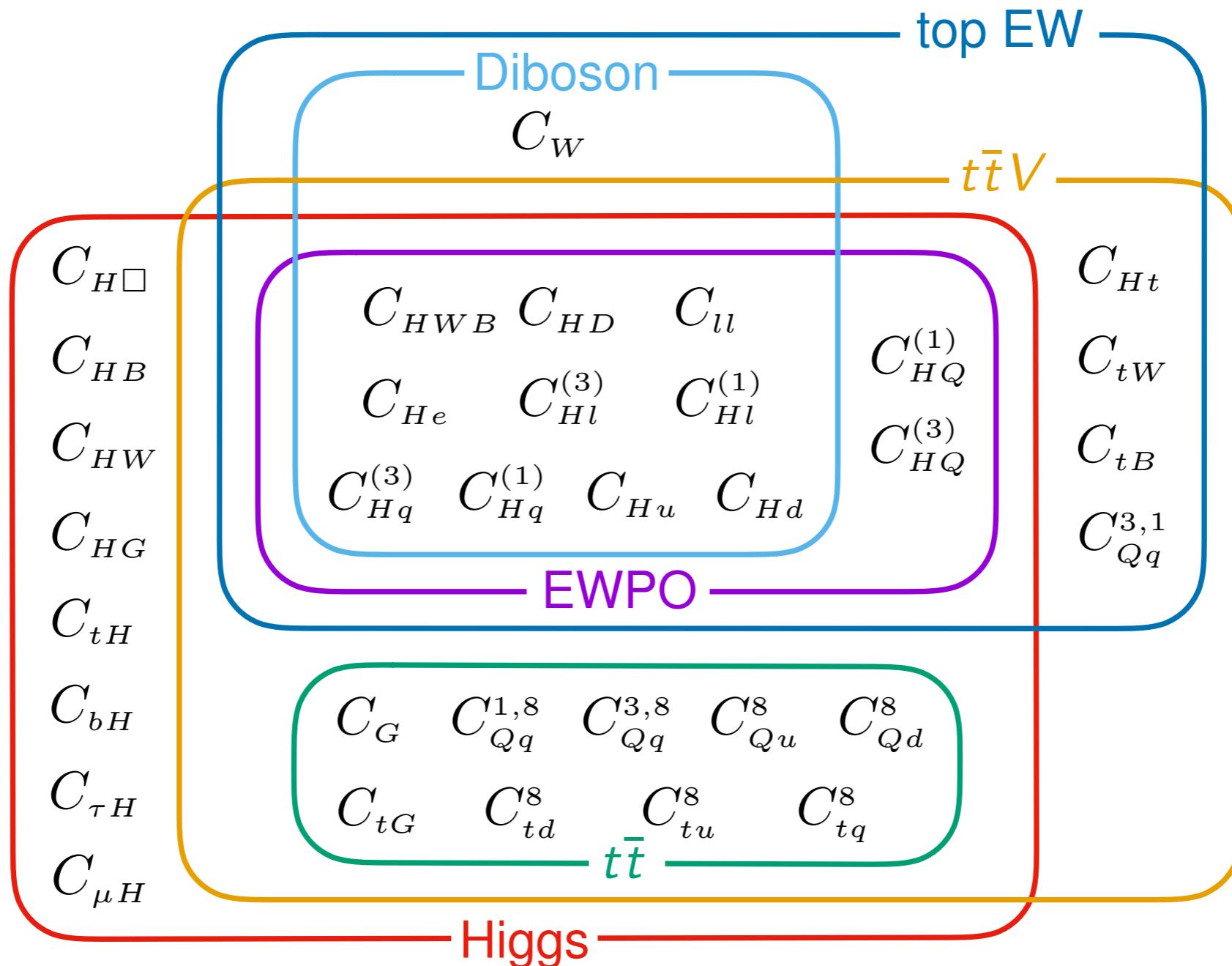
'Universal'
'Top-specific'

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)

Interplay

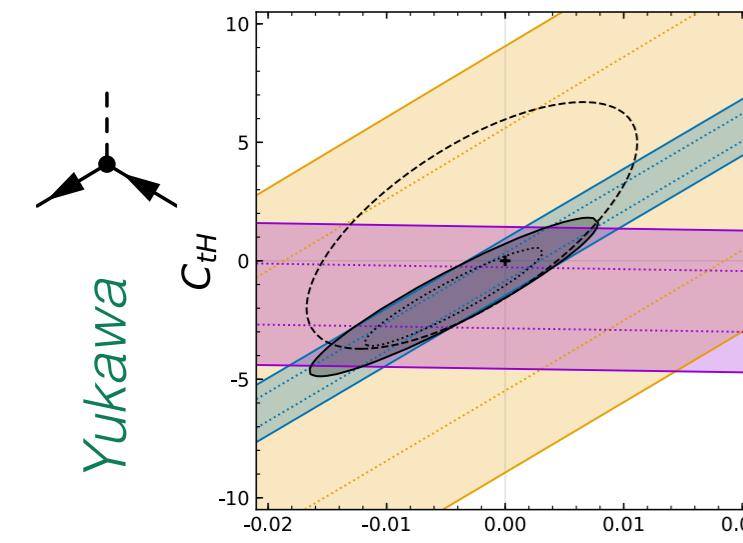


Top-Higgs interplay

2D individual constraints

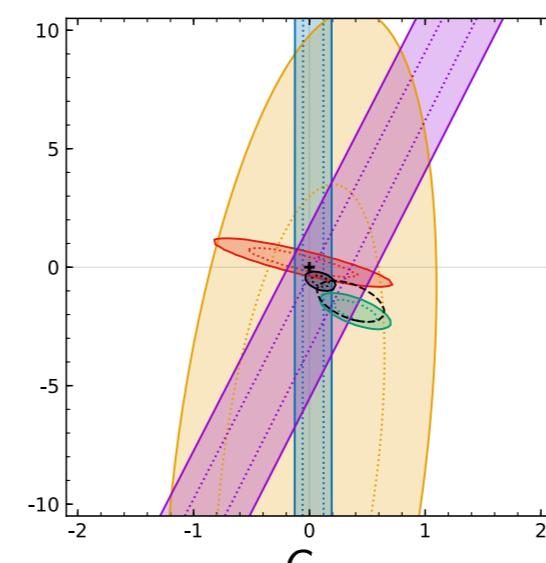
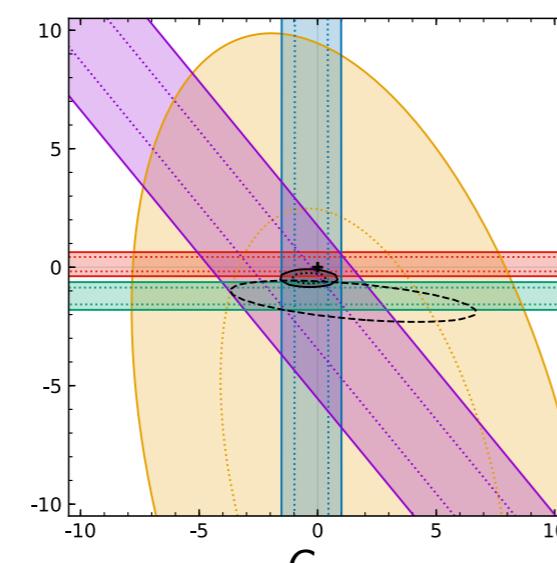
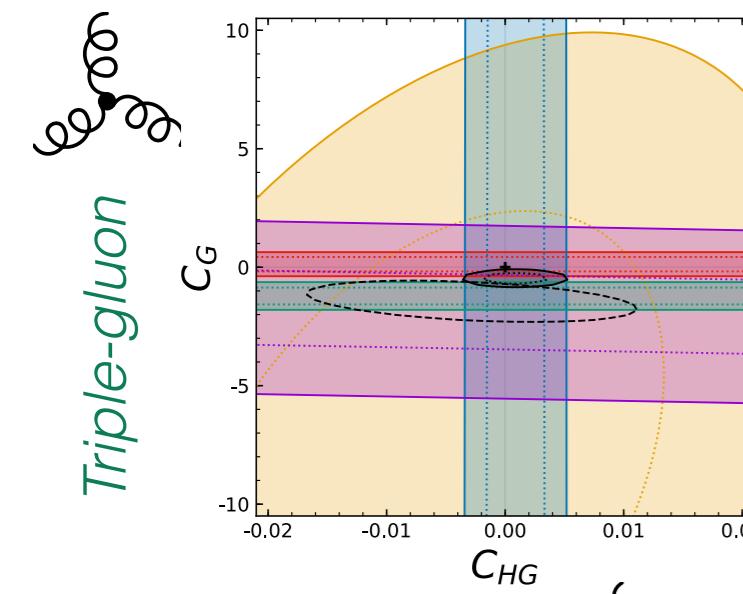
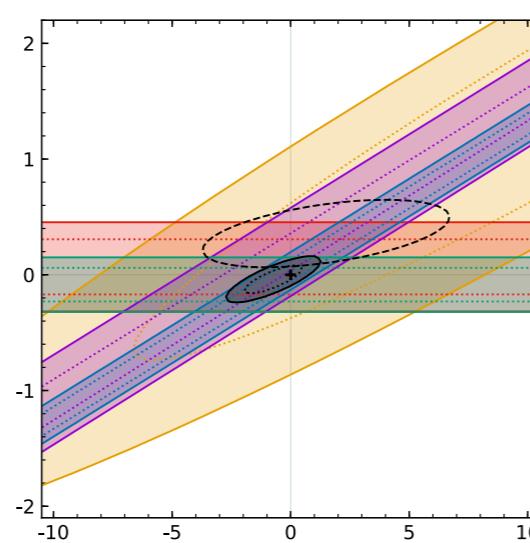
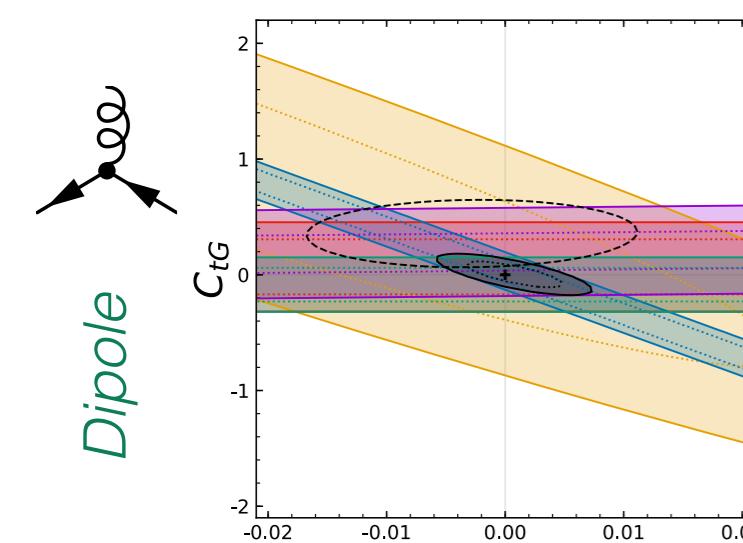
- All others set to 0
- $ggF/t\bar{t}H$ complementarity for (C_{HG}, C_{tH})
- H+jets STXS & $t\bar{t}V$ not yet competitive
- Strong impact of $t\bar{t}$ evident for (C_{tG}, C_G)
- Tension with SM $\sim 2\sigma$
- Significant correlations remain
- Large marginalisation effects

What is the concrete impact of 4F?



Individual 95% C. L.

- ggF+0 jet STXS
- $t\bar{t}H$
- ggF+ ≥ 1 jet STXS
- $t\bar{t}$
- $t\bar{t}V$
- Combined
- Marginalised



Point-like

Yukawa

Dipole

4F impact

Fit to ‘Higgs-only’ subspace

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

- 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

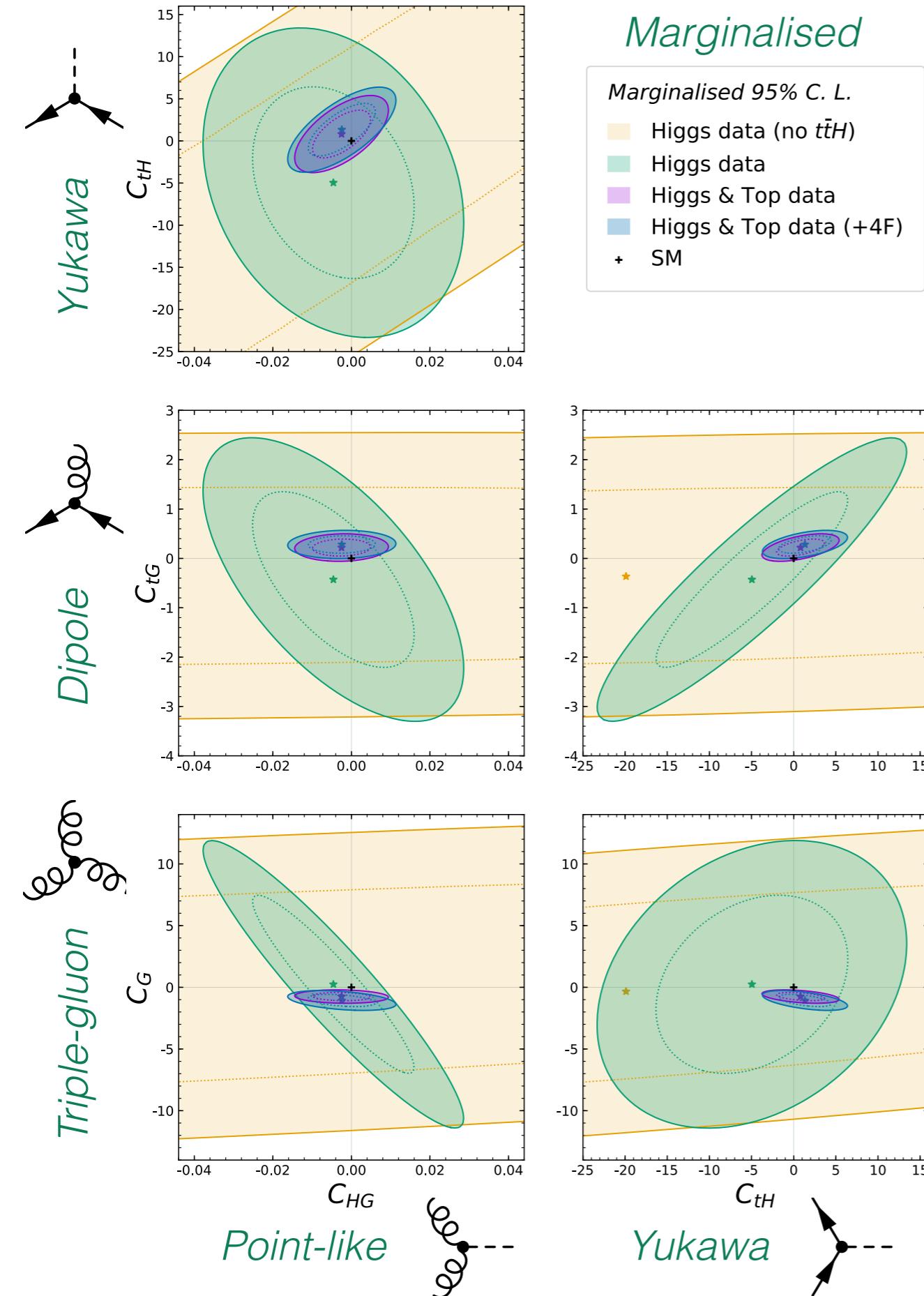
$$+ C_{Qq}^{3,8}, C_{Qq}^{1,8}, C_{Qu}^8, C_{Qd}^8, C_{tq}^8, C_{tu}^8, C_{td}^8$$

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

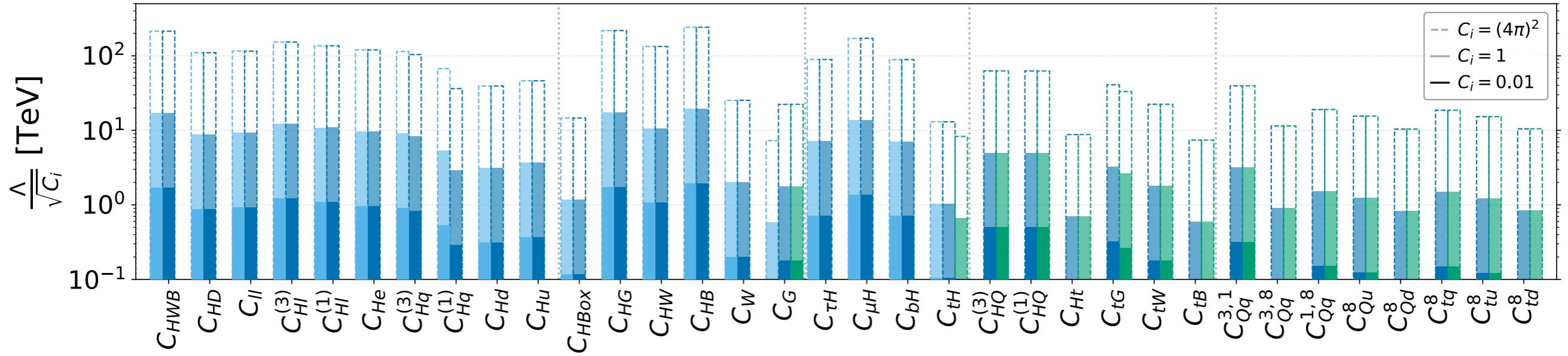
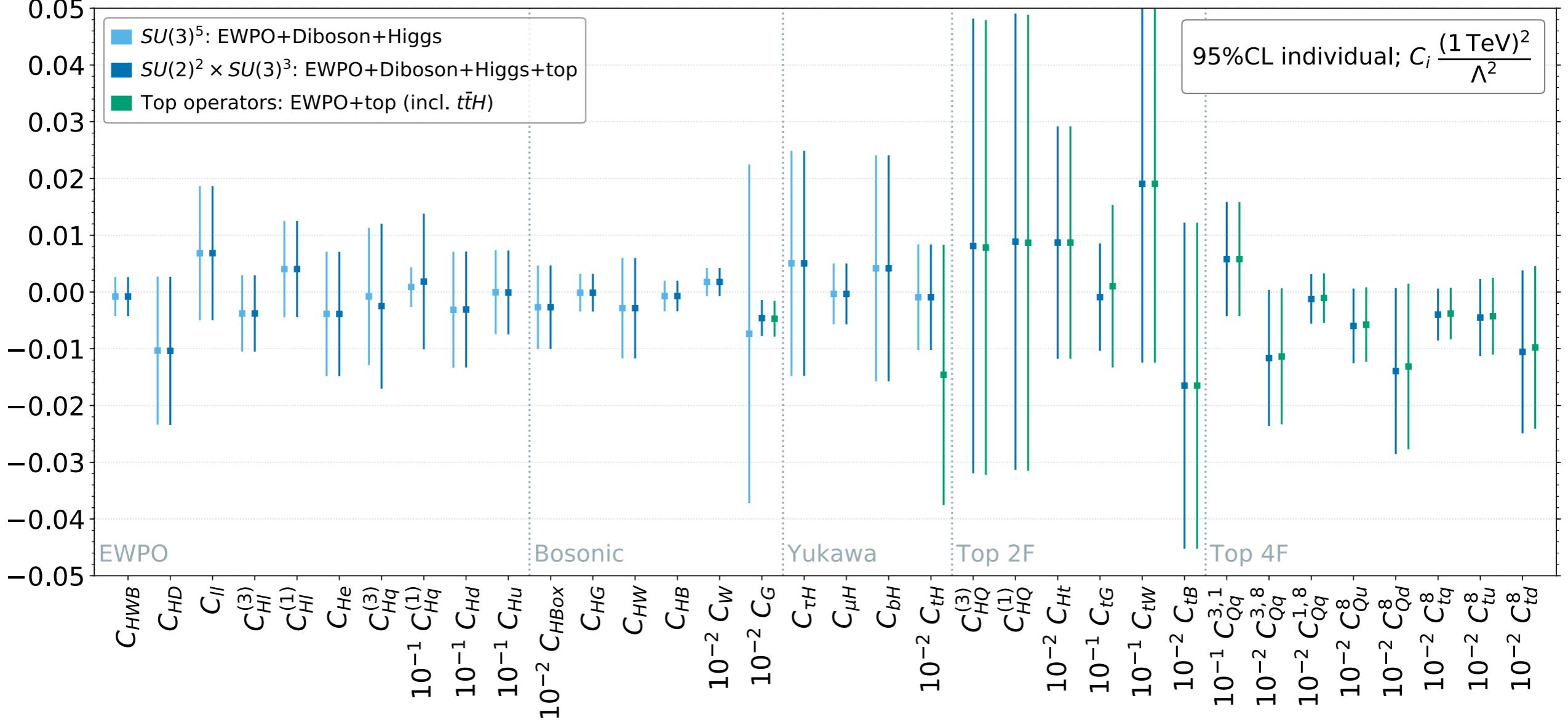
C_{tG} : low $m_{t\bar{t}}$

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

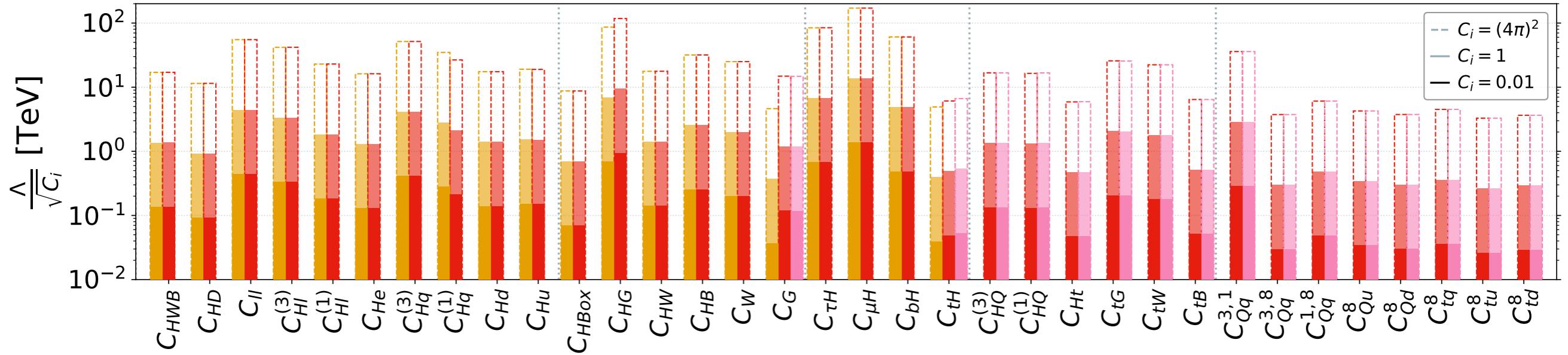
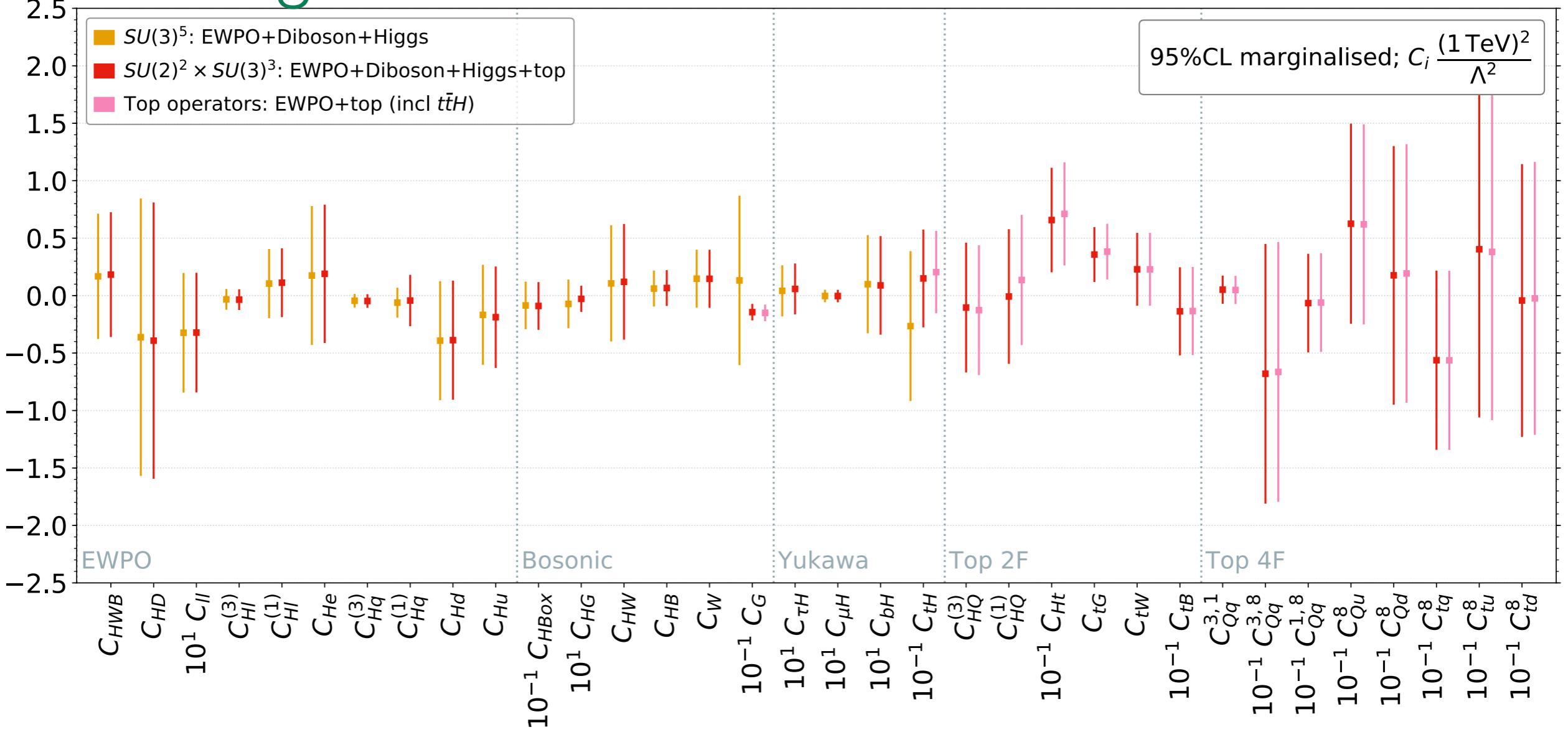
- Able to constrain them independently



Full fit: individual

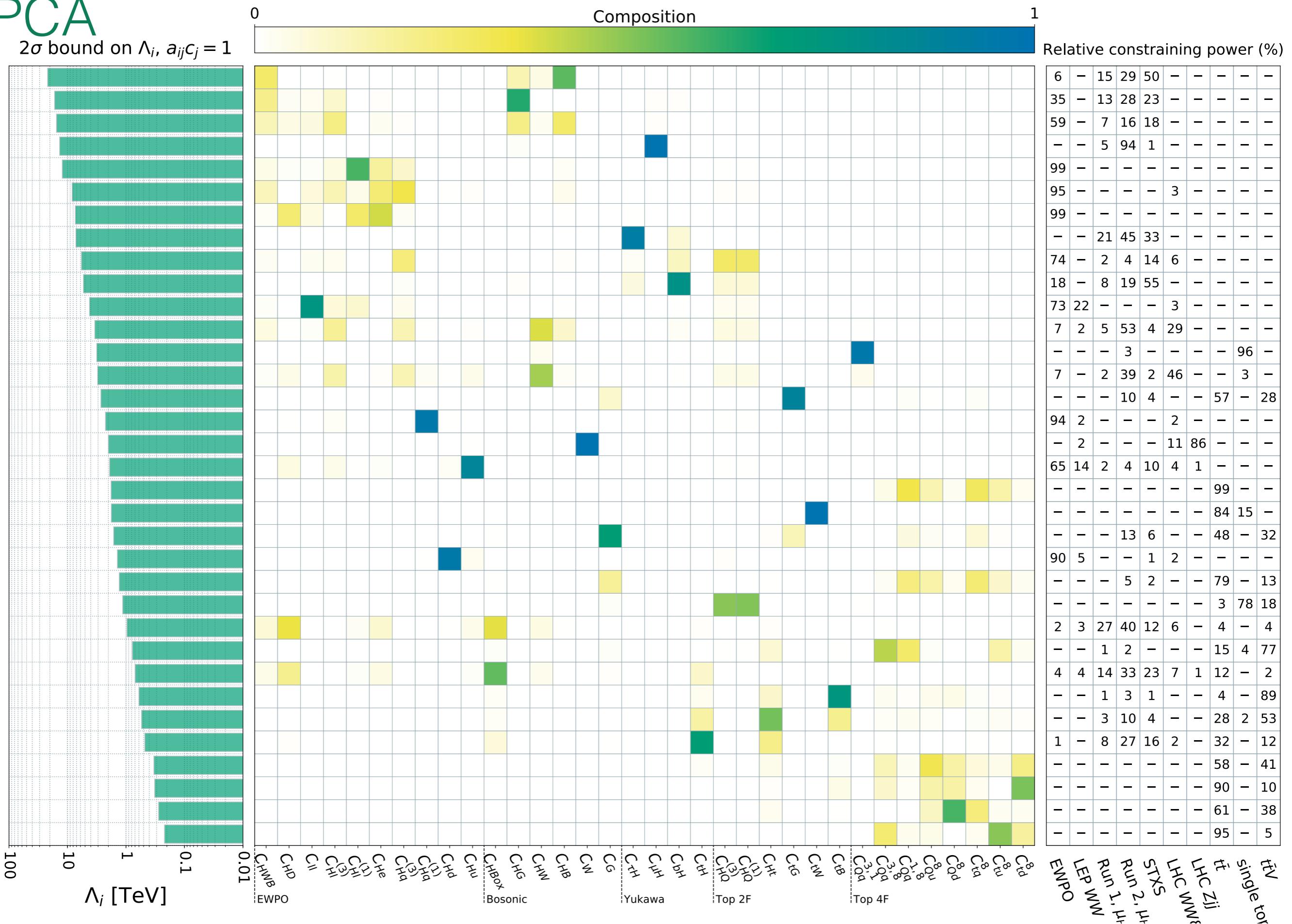


Full fit: marginalised

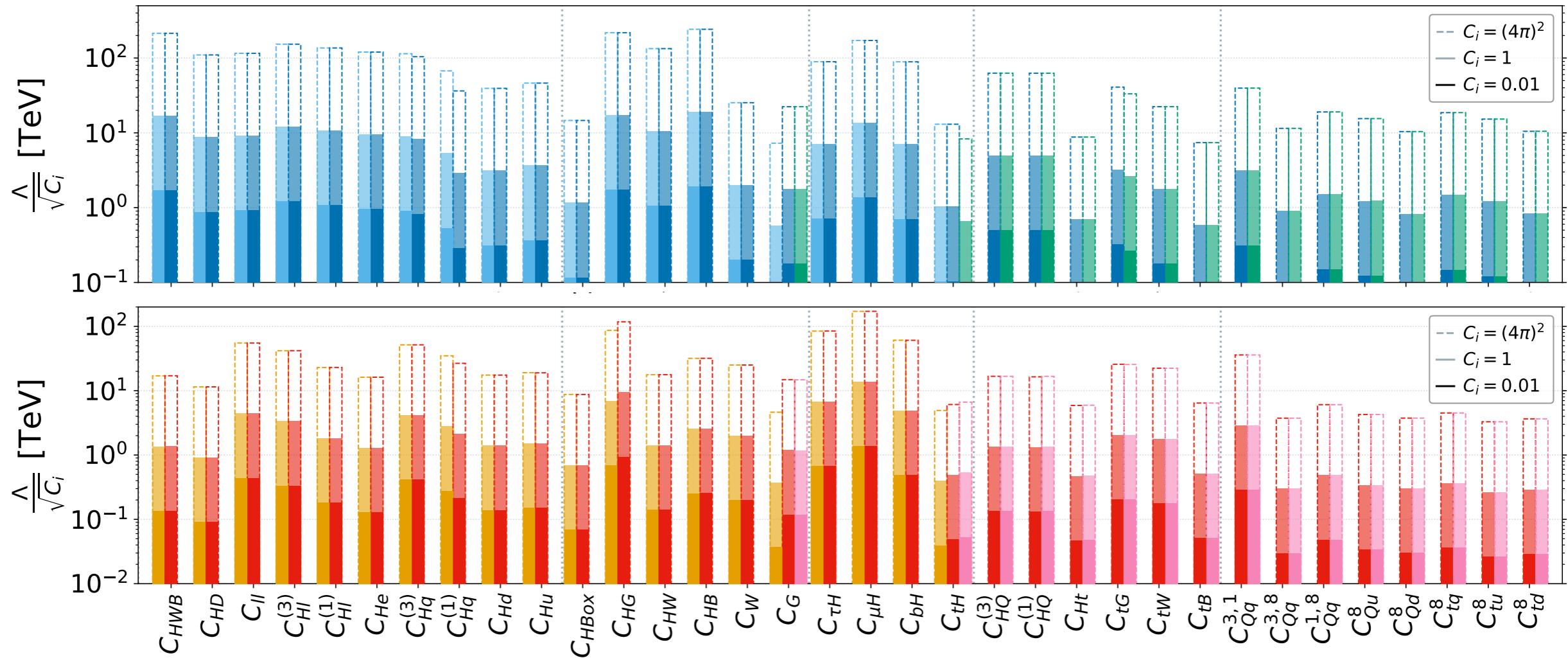


PCA

2σ bound on Λ_i , $a_{ij}c_j = 1$



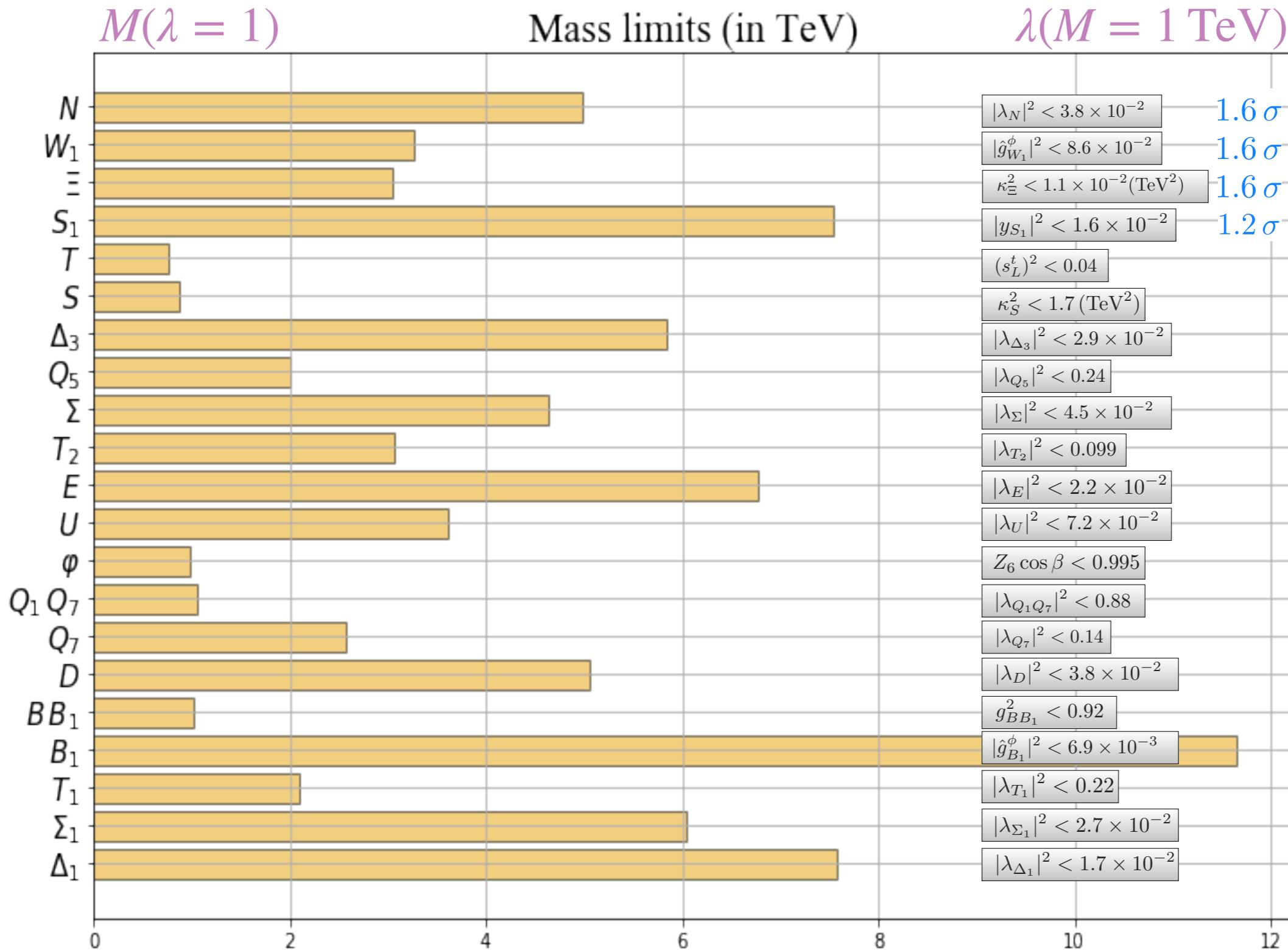
BSM implications



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

One parameter models



Conclusions & Outlook

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

- LHC data sensitivity rivals that of LEP
- 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 & public **fitmaker** code

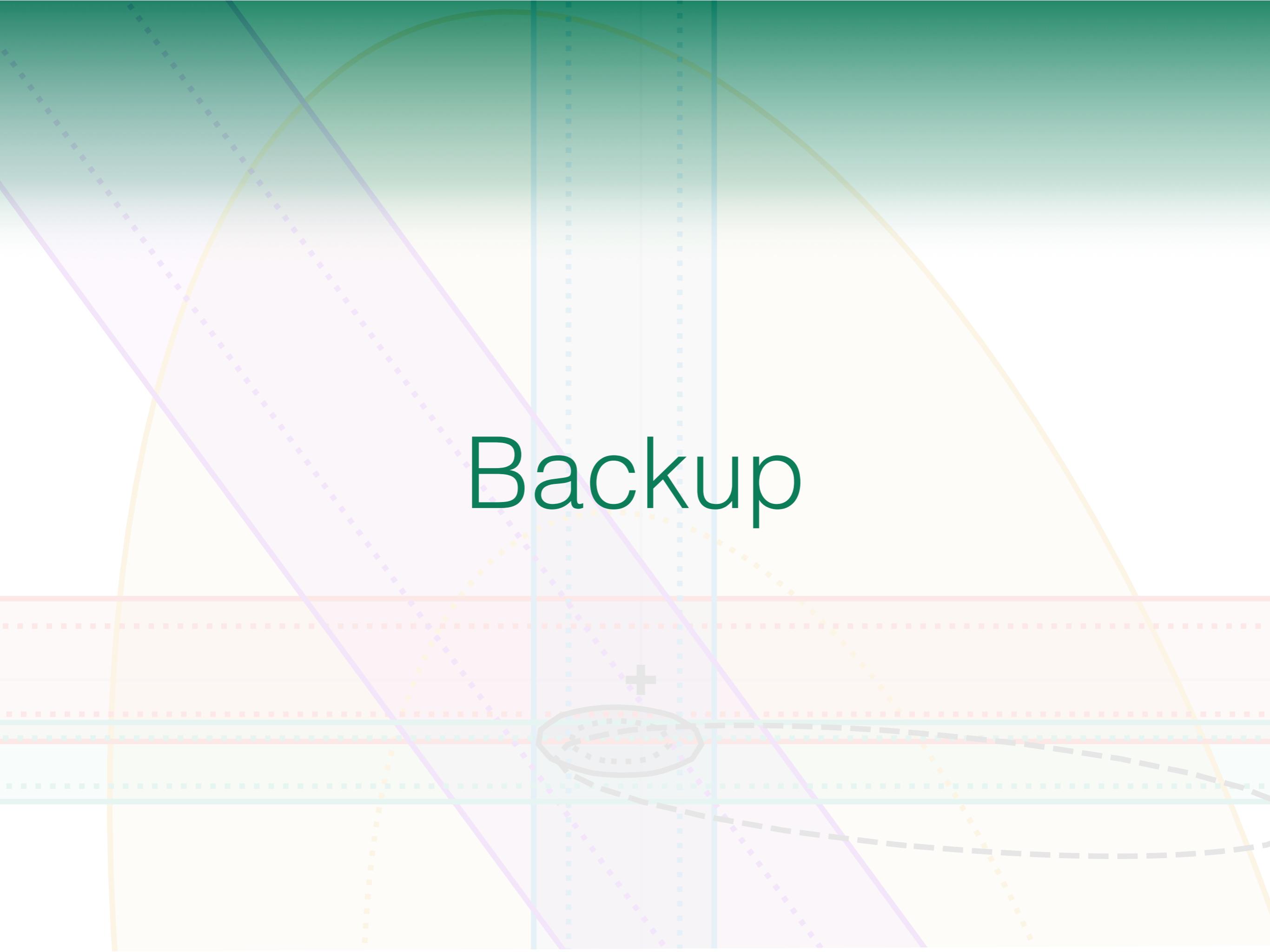
- Easy to interpret/combine with other likelihoods
- Fast: repeat for subsets, BSM interpretations
- Potentially important quadratic effects, especially in top data

Next steps...

- Quadratic level fit, SMEFT theory errors & EFT validity
- More impact of loops: full NLO & top operators in Higgs decays, EWPO
- Go beyond 1 particle UV scenarios towards realistic models

[Ethier et al.; arXiv:2105.00006]

Backup



Data: EWPO & Diboson

EW precision observables	n_{obs}
Precision electroweak measurements on the Z resonance.	12
Γ_Z , $\sigma_{\text{had.}}^0$, R_ℓ^0 , A_{FB}^ℓ , $A_\ell(\text{SLD})$, $A_\ell(\text{Pt})$, R_b^0 , R_c^0 , A_{FB}^b , A_{FB}^c , A_b & A_c	
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, $\frac{d\sigma}{dp_{\ell_1}^T}$, $p_T > 120$ GeV overflow bin	1
ATLAS $W^+ W^-$ fiducial differential cross section in the $e\nu\mu\nu$ channel, $\frac{d\sigma}{dp_{\ell_1}^T}$	14
ATLAS $W^\pm Z$ fiducial differential cross section in the $\ell^+\ell^-\ell^\pm\nu$ channel, $\frac{d\sigma}{dp_Z^T}$	7
CMS $W^\pm Z$ normalised fiducial differential cross section in the $\ell^+\ell^-\ell^\pm\nu$ channel, $\frac{1}{\sigma} \frac{d\sigma}{dp_Z^T}$	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 & tH 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 $H \rightarrow 4\ell$ 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 & tH Decay: $\gamma\gamma$, ZZ , W^+W^- , $\tau^+\tau^-$, $b\bar{b}$ & $\mu^+\mu^-$	23
CMS stage 1.0 STXS measurements for $H \rightarrow \gamma\gamma$. 13 parameter fit 7 parameter fit	13 7
CMS stage 1.0 STXS measurements for $H \rightarrow \tau^+\tau^-$	9
CMS stage 1.1 STXS measurements for $H \rightarrow 4\ell$	19
CMS differential cross section measurements of inclusive Higgs production in the $WW^* \rightarrow \ell\nu\ell\nu$ final state. $\frac{d\sigma}{dn_{\text{jet}}} \quad \quad \frac{d\sigma}{dp_H^T}$	5 6
ATLAS $H \rightarrow Z\gamma$ signal strength.	1
ATLAS $H \rightarrow \mu^+\mu^-$ signal strength.	1

Data: Tevatron, LHC Run 1 & 2 top

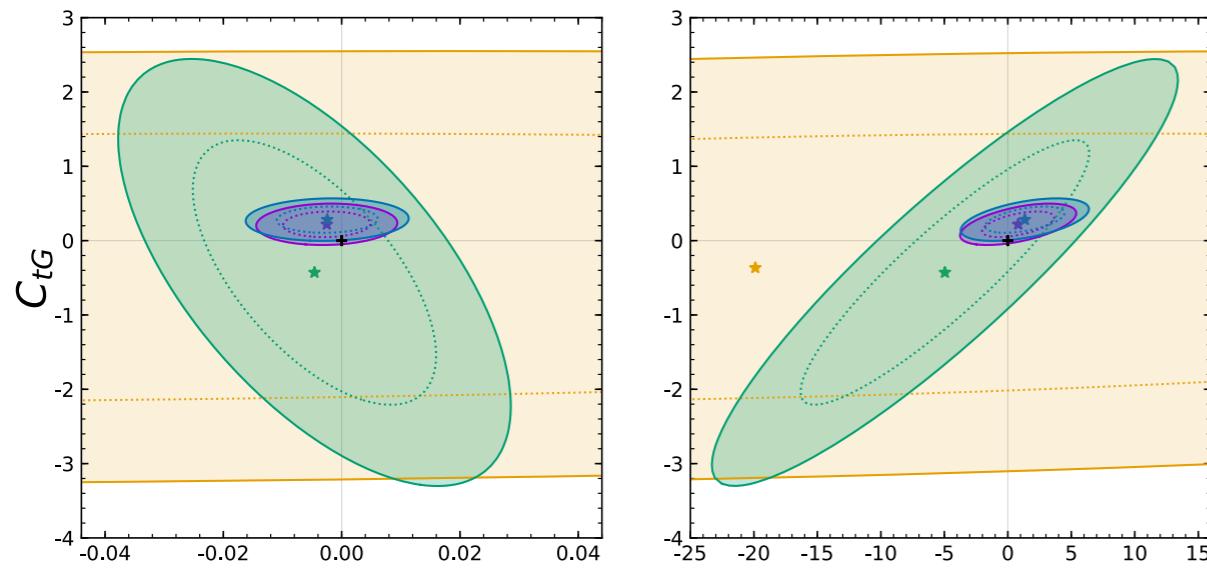
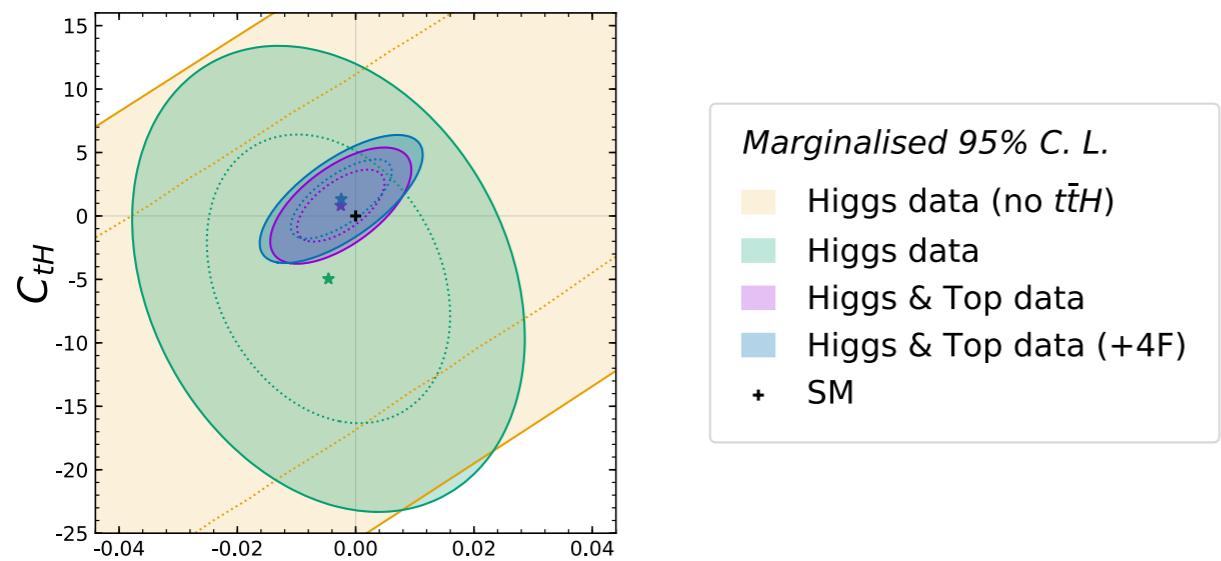
Tevatron & Run 1 top	n_{obs}	Ref.	Run 2 top	n_{obs}	Ref.
Tevatron combination of differential $t\bar{t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar{t}})$.	4	[7]	CMS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	6	[46, 50]
ATLAS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	6	[31]	CMS $t\bar{t}$ differential distributions in the $\ell+\text{jets}$ channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	10	[53]
ATLAS $t\bar{t}$ differential distributions in the $\ell+\text{jets}$ channel. $\frac{d\sigma}{dm_{t\bar{t}}} \mid \frac{d\sigma}{d y_{t\bar{t}} } \mid \frac{d\sigma}{dp_t^T} \mid \frac{d\sigma}{d y_t }$.	7 5 8 5	[24]	ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$. $\frac{d\sigma}{dp_z^T} \mid \frac{d\sigma}{d\cos\theta^*}$	5	[55]
CMS $t\bar{t}$ differential distributions in the $\ell+\text{jets}$ channel. $\frac{d\sigma}{dm_{t\bar{t}}} \mid \frac{d\sigma}{d y_{t\bar{t}} } \mid \frac{d\sigma}{dp_t^T} \mid \frac{d\sigma}{d y_t }$.	7 10 8 10	[25, 34]	ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	2	[58]
CMS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$ in the dilepton channel.	3	[33]	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	[48]
ATLAS inclusive measurement $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$ in the dilepton channel.	1	[32]	CMS $t\bar{t}Z$ differential distributions. $\frac{d\sigma}{dp_\gamma^T}$	4 4	[60]
ATLAS & CMS combination of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$, in the $\ell+\text{jets}$ channel.	6	[38]	ATLAS $t\bar{t}\gamma$ differential distribution. $\frac{d\sigma}{dp_{t+\bar{t}}^T} \mid R_t(p_{t+\bar{t}}^T)$	11	[62]
CMS $t\bar{t}$ double differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}} dy_t} \mid \frac{d\sigma}{dm_{t\bar{t}} dy_{t\bar{t}}} \mid \frac{d\sigma}{dm_{t\bar{t}} dp_{t\bar{t}}^T} \mid \frac{d\sigma}{dy_t dp_t^T}$.	16 16 16 16	[18, 35]	CMS measurement of differential cross sections and charge ratios for t -channel single-top quark production. $\sigma_t \mid \sigma_{\bar{t}} \mid \sigma_{t+\bar{t}} \mid R_t$.	5 5	[56]
ATLAS & CMS Run 1 combination of W -boson helicity fractions in top decay. f_0, f_L & f_R	3	[40]	CMS measurement of t -channel single-top and anti-top cross sections. $\sigma_t, \sigma_{\bar{t}}, \sigma_{t+\bar{t}} \& R_t$.	4	[42]
ATLAS measurement of W -boson helicity fractions in top decay. f_0, f_L & f_R	3	[30]	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	[45]
CMS measurement of W -boson helicity fractions in top decay. f_0, f_L & f_R	3	[29]	CMS t -channel single-top differential distributions. $\frac{d\sigma}{dp_{t+\bar{t}}^T} \mid \frac{d\sigma}{d y_{t+\bar{t}} }$	4 4	[44]
ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	2	[23]	ATLAS tW cross section measurement.	1	[43]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	2	[26]	CMS tZ cross section measurement.	1	[47]
ATLAS $t\bar{t}\gamma$ cross section measurement in the $\ell+\text{jets}$ channel.	1	[36]	CMS tW cross section measurement.	1	[52]
CMS $t\bar{t}\gamma$ cross section measurement in the $\ell+\text{jets}$ channel.	1	[37]	ATLAS tZ cross section measurement.	1	[49]
ATLAS t -channel single-top differential distributions. $\frac{d\sigma}{dp_t^T} \mid \frac{d\sigma}{dp_{\bar{t}}^T} \mid \frac{d\sigma}{d y_t } \mid \frac{d\sigma}{d y_{\bar{t}} }$	4 4 4 5	[39]	CMS tZ ($Z \rightarrow \ell^+\ell^-$) cross section measurement	1	[54]
CMS s -channel single-top cross section measurement.	1	[28]	ATLAS four-top search in the multi-lepton and same-sign dilepton channels.	1	[63]
CMS t -channel single-top differential distributions. $\frac{d\sigma}{dp_{t+\bar{t}}^T} \mid \frac{d\sigma}{d y_{t+\bar{t}} }$	6 6	[19]	ATLAS four-top search in the single-lepton and opposite-sign dilepton channels.	1	[51]
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	[20]	CMS four-top search in the multi-lepton and same-sign dilepton channels.	1	[61]
ATLAS s -channel single-top cross section measurement.	1	[27]	CMS four-top search in the single-lepton and opposite-sign dilepton channels.	1	[59]
CMS tW cross section measurement.	1	[21]	CMS $t\bar{t}b\bar{b}$ cross section measurement in the all-jet channel.	1	[57]
ATLAS tW cross section measurement in the single lepton channel.	1	[41]	CMS $t\bar{t}b\bar{b}$ cross section measurement in the dilepton channel.	1	[64]
ATLAS tW cross section measurement in the dilepton channel.	1	[22]			

Fisher information breakdown

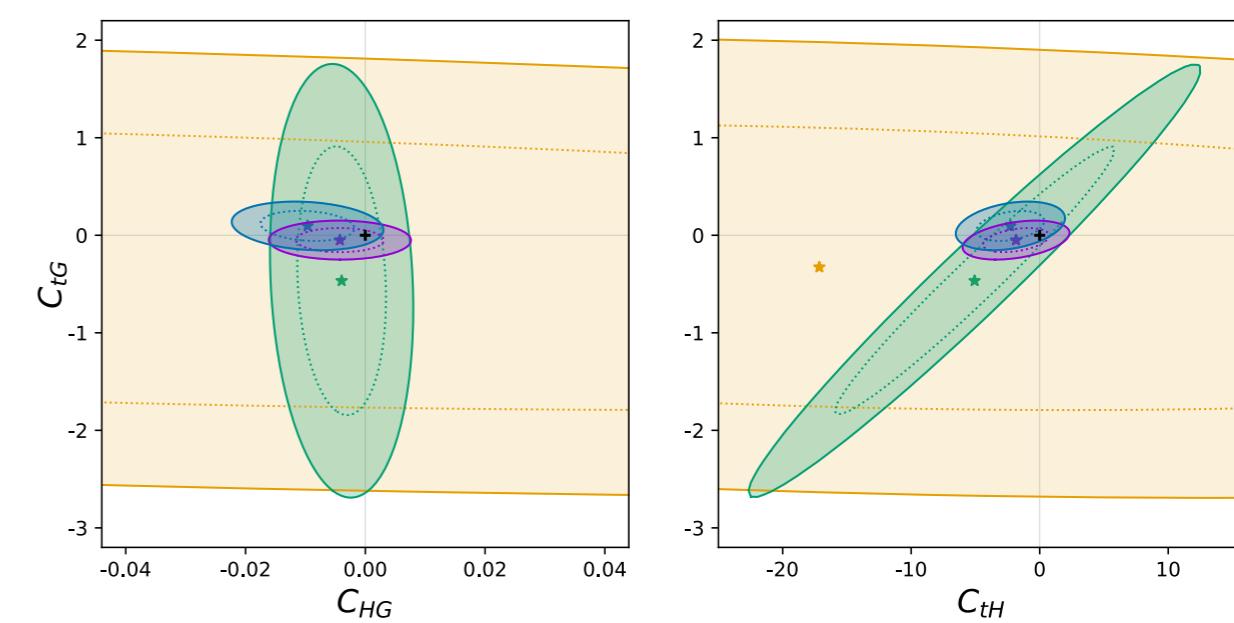
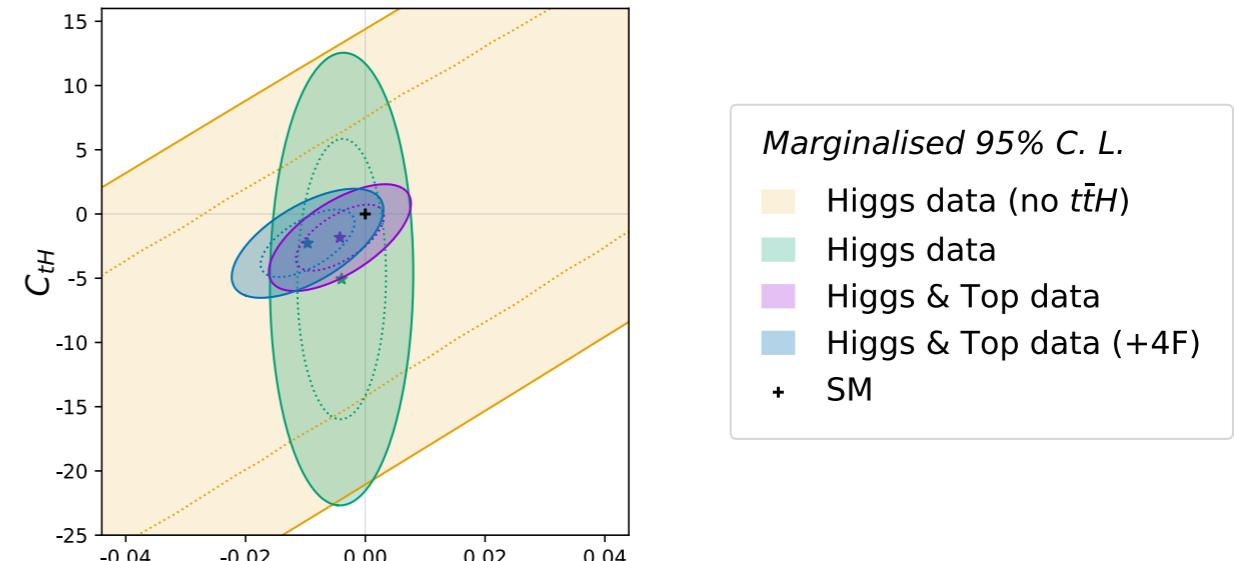
C_i	EWPO	LEP WW	Run 1 SS	Run 2 SS	STXS	LHC WW	WZ	Zjj	$t\bar{t}$	$W_{\text{hel.}}$	tX	$t\bar{t}V$
C_{HWB}	51	—	7	14	28	—	—	—	—	—	—	—
C_{HD}	100	—	—	—	—	—	—	—	—	—	—	—
C_{ll}	99	—	—	—	—	—	—	—	—	—	—	—
$C_{Hl}^{(3)}$	99	—	—	—	—	—	—	—	—	—	—	—
$C_{Hl}^{(1)}$	100	—	—	—	—	—	—	—	—	—	—	—
C_{He}	100	—	—	—	—	—	—	—	—	—	—	—
$C_{Hq}^{(3)}$	89	1	—	—	2	—	6	—	—	—	—	—
$C_{Hq}^{(1)}$	99	—	—	—	—	—	—	—	—	—	—	—
C_{Hd}	99	—	—	—	—	—	—	—	—	—	—	—
C_{Hu}	98	—	—	—	1	—	—	—	—	—	—	—
$C_{H\square}$	—	—	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

Removing C_G

With



Without



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