Interpretation of Higgs data within the SMEFT

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

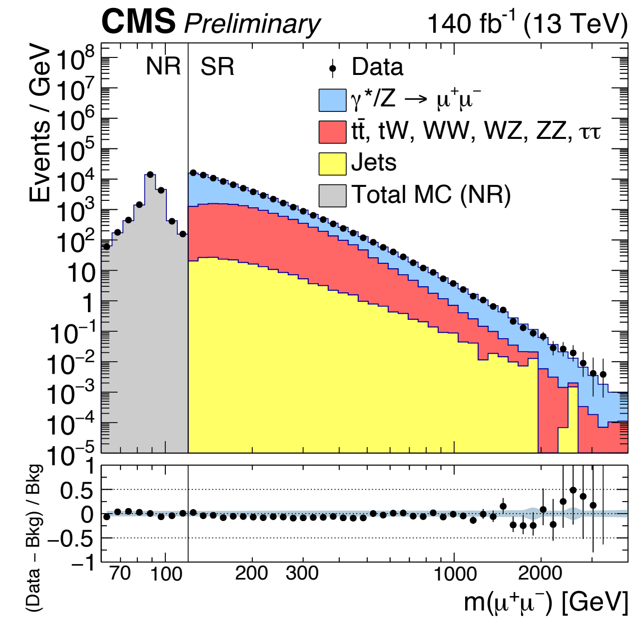
`fitmaker` *https://gitlab.com/kenmimasu/fitrepo*

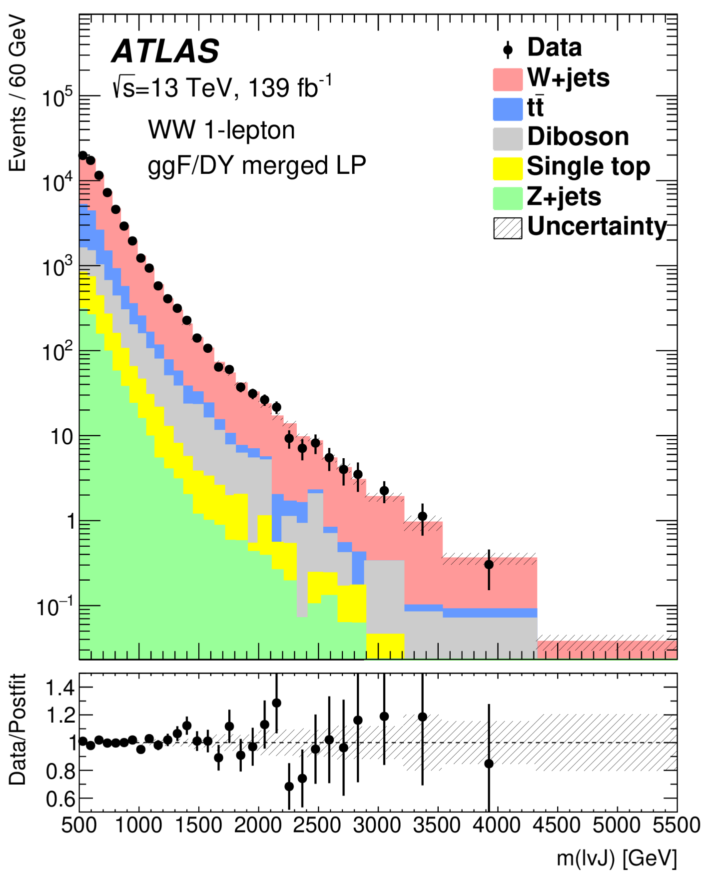
[CMS-PAS-EXO-19-019]

Where are we?

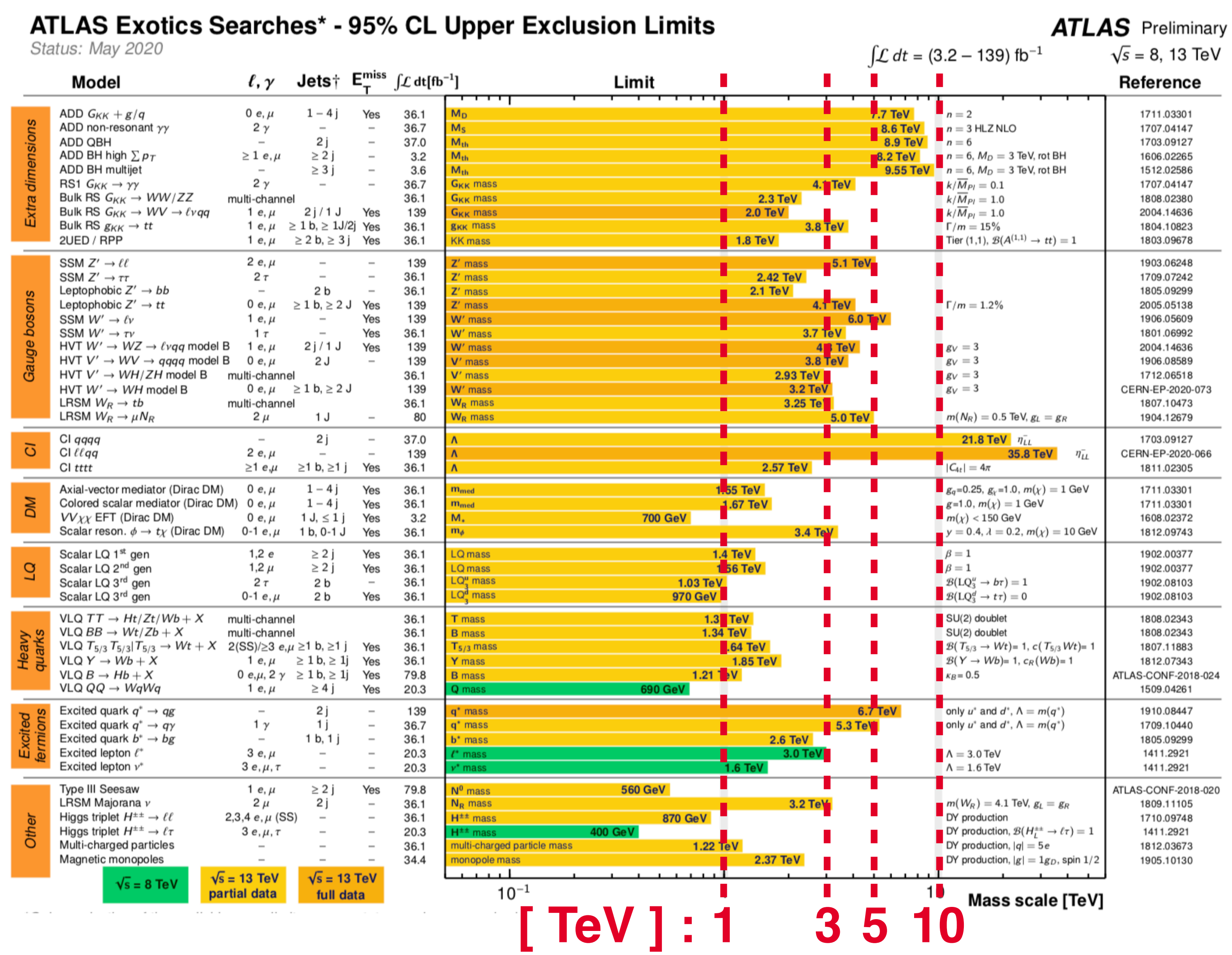
10 years since the Higgs discovery

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





[CERN-EP-2020-049]



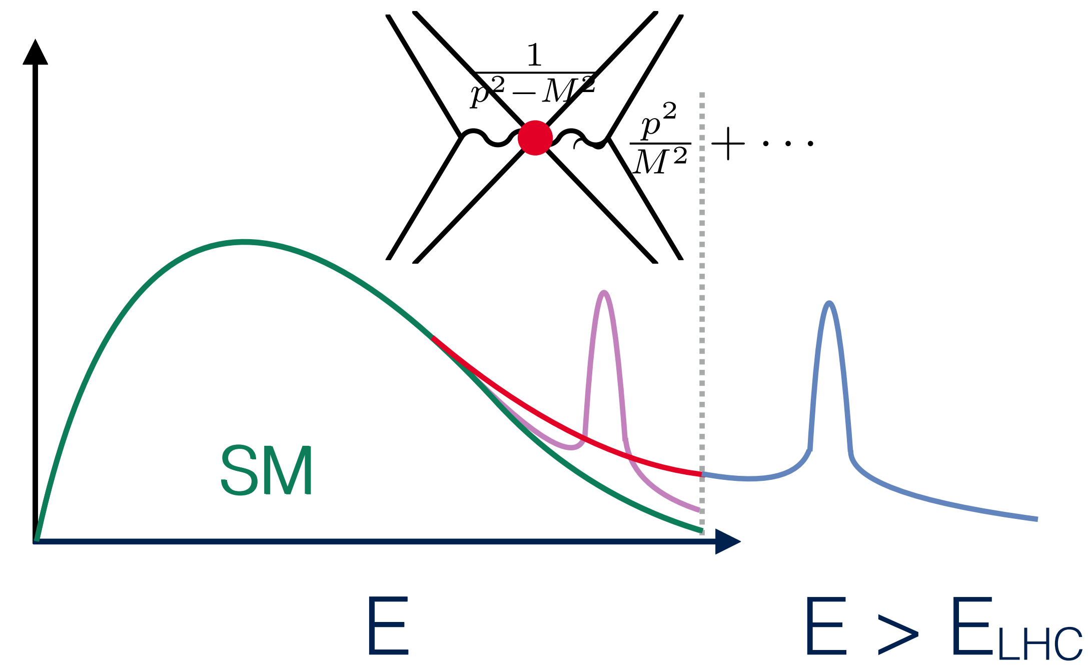
Energy & precision

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

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

SM is low energy effective description

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

SU(3)$_C$ x SU(2)$_L$ x 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 ($\sim\Lambda$)
- Renormalisable QFT (order-by-order)
- Well defined matching procedure

SMEFT is…

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

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 operators & 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:

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

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

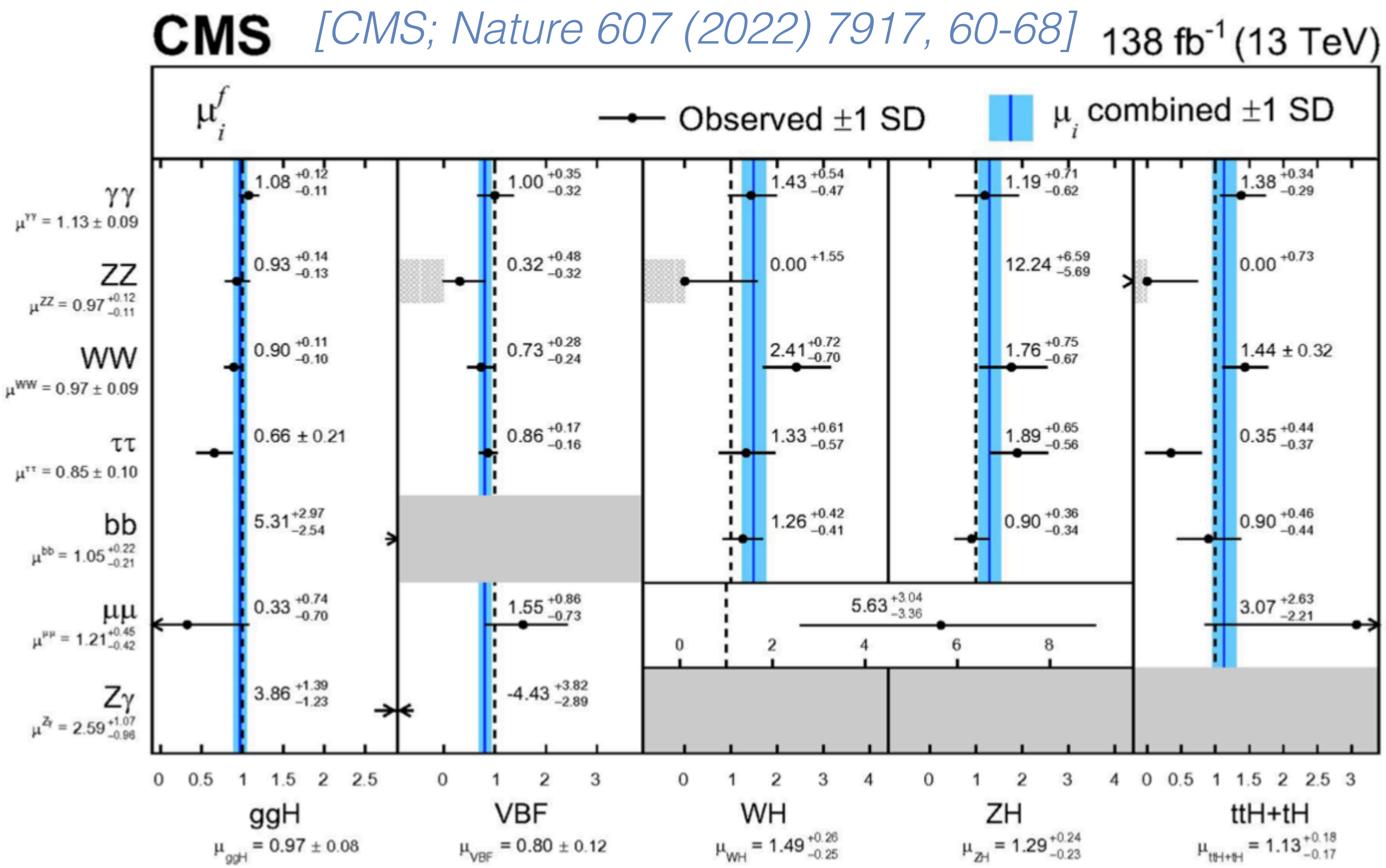
Determining $c_i^{(6)}$ requires most precise available SMEFT predictions

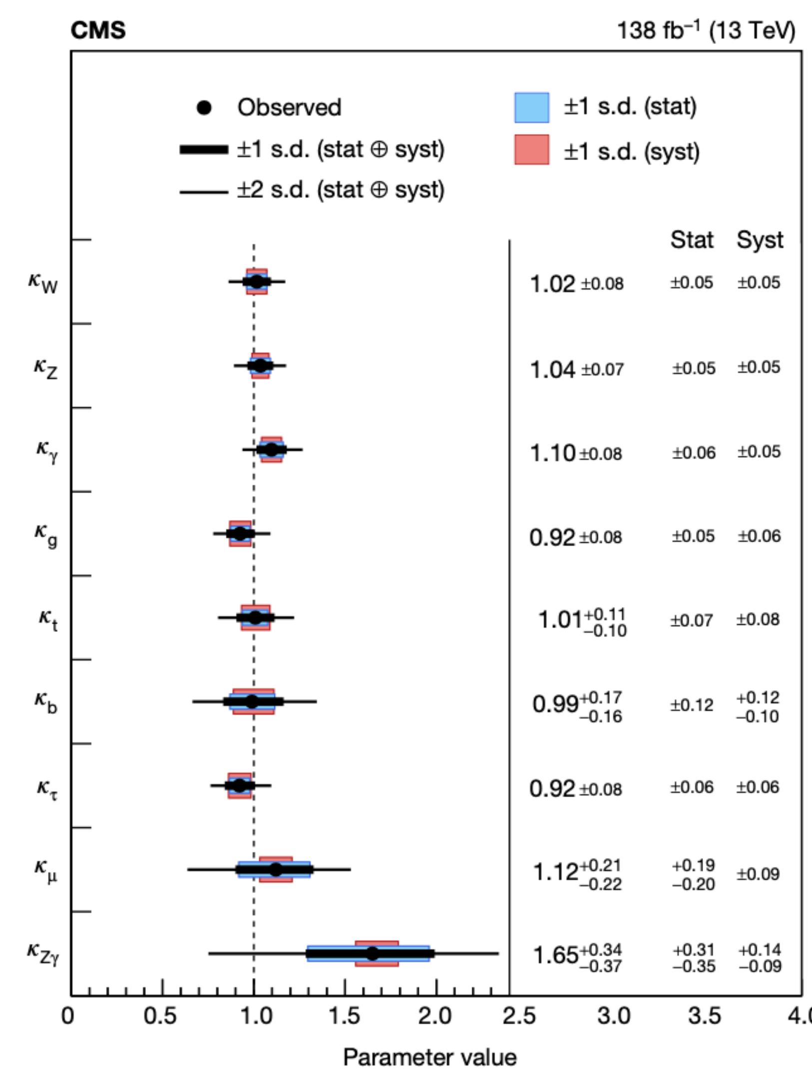
Higgs data

Signal strengths, $\mu_{i\to f} \sim \dfrac{\sigma_{i\to H} \times \mathrm{BR}_{\mathrm{H}\to\mathrm{f}}}{\sigma^{\mathrm{SM}}_{i\to H} \times \mathrm{BR}^{\mathrm{SM}}_{\mathrm{H}\to\mathrm{f}}}$

κ-framework interpretation

[CMS; Nature 607 (2022) 7917, 60-68]





+ correlations

$$\mu_{\rm tot} = 1.002 \pm 0.057$$

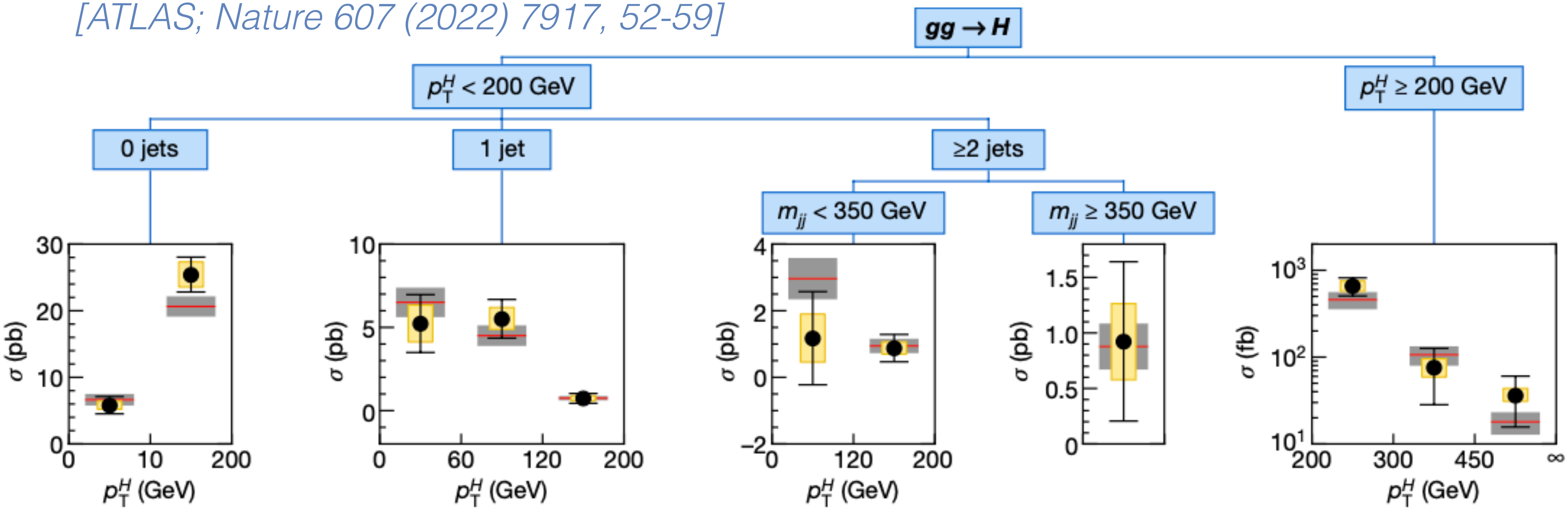
$$\mu_{i\to f} \propto \kappa_i^2 \kappa_f^2$$

Higgs data

[CMS-HIG-19-010]
[ATLAS; PRD 101 (2020) 012002]
[ATLAS; EPJC 80 (2020) 957]
[ATLAS; JHEP 08 (2022) 175]
...

Simplified Template Cross Sections (STXS)

[ATLAS; Nature 607 (2022) 7917, 52-59]



- Production binned in Higgs/associated particle kinematics (unfolded to SM)

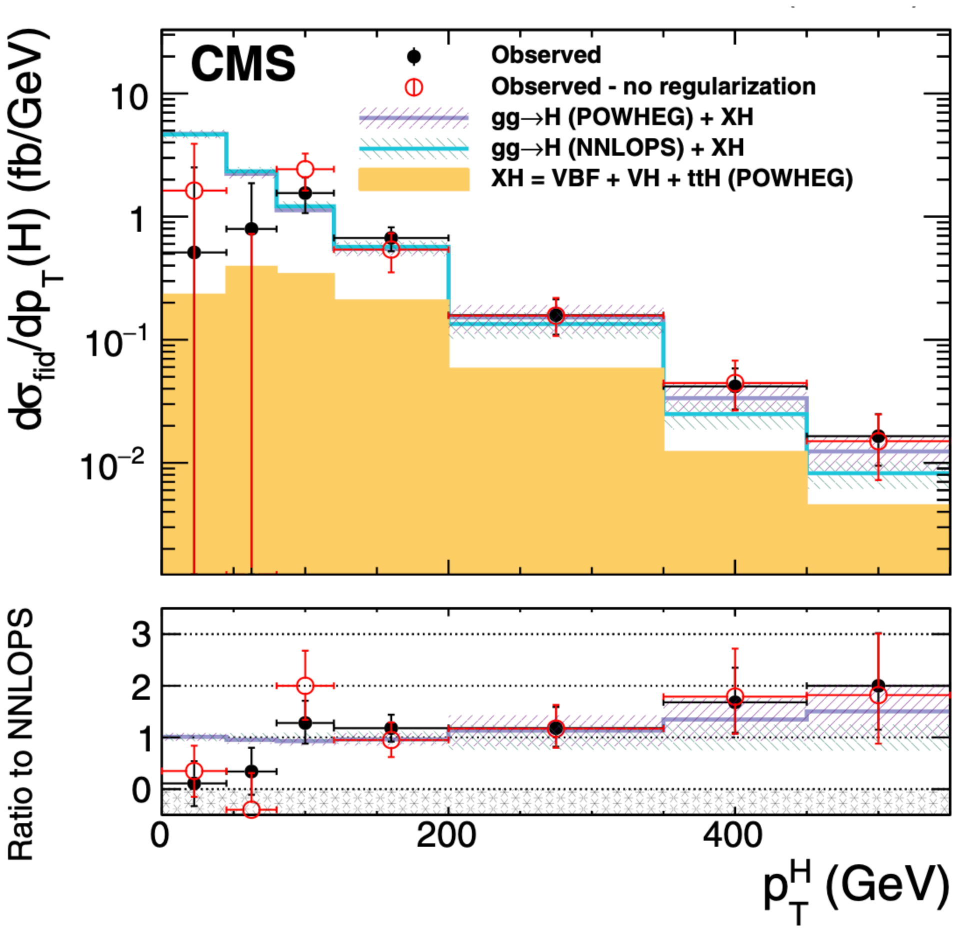
$\mathrm{ggF}: \{p_T^{\mathrm{H}}, n_{\mathrm{jet}}, m_{jj}, \ldots\}$ $\quad \mathrm{EW}\ qqH: \{p_T^{\mathrm{H}}, n_{\mathrm{jet}}, m_{jj}, \ldots\}$ $\quad VH \to \mathrm{leptons}: \{p_T^{\mathrm{V}}, n_{\mathrm{jet}}, \ldots\}$ $\quad t\bar{t}H: \{p_T^{\mathrm{H}}, \ldots\}$

- Measured for each decay mode: $b\bar{b}, \gamma\gamma, \tau\tau, 4\ell, \ldots$
- Detailed correlation information for consistent combination

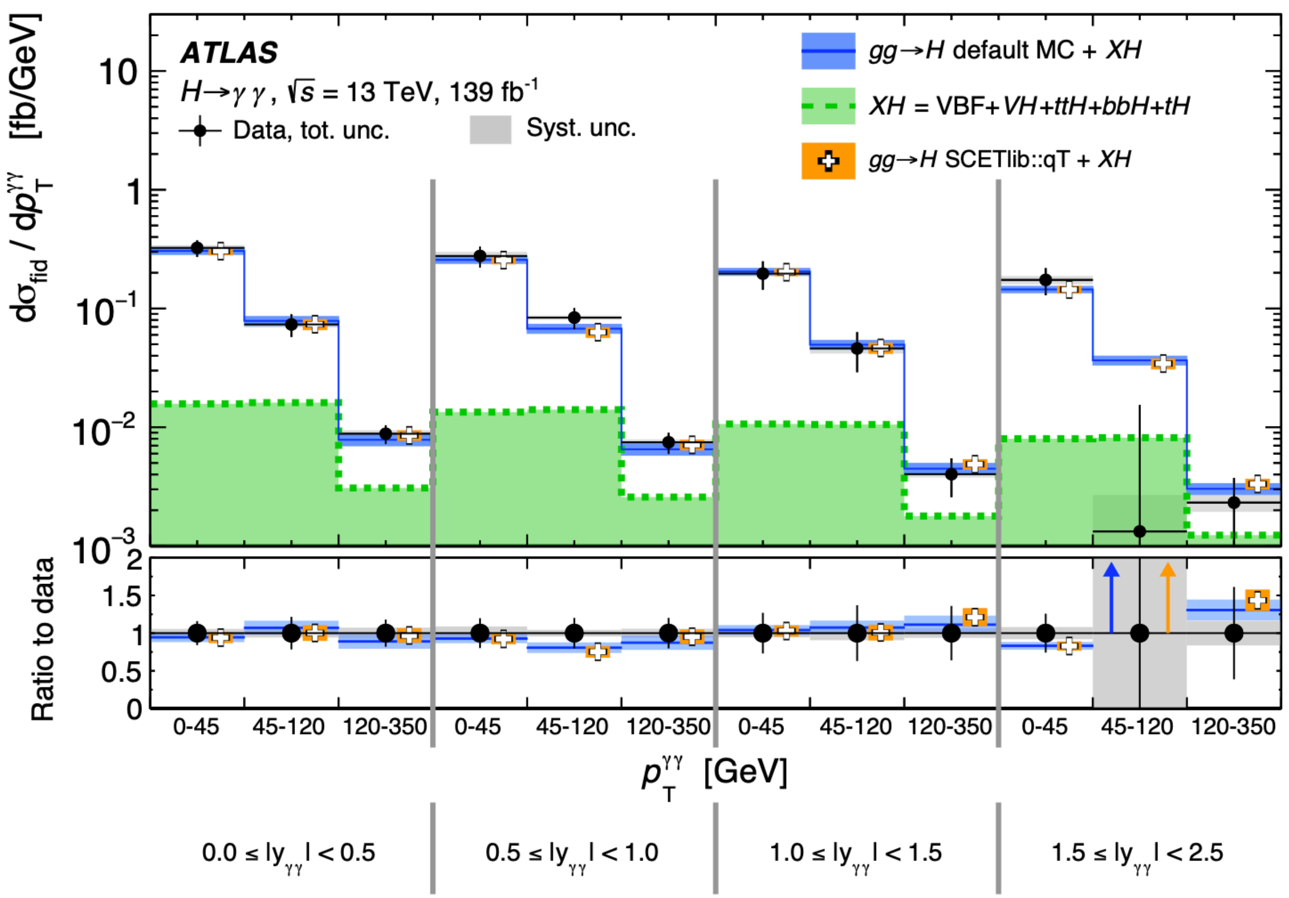
Higgs data

Differential cross sections

[CMS; PRL128 (2022) 081805]



[ATLAS; JHEP 08 (2022) 027]

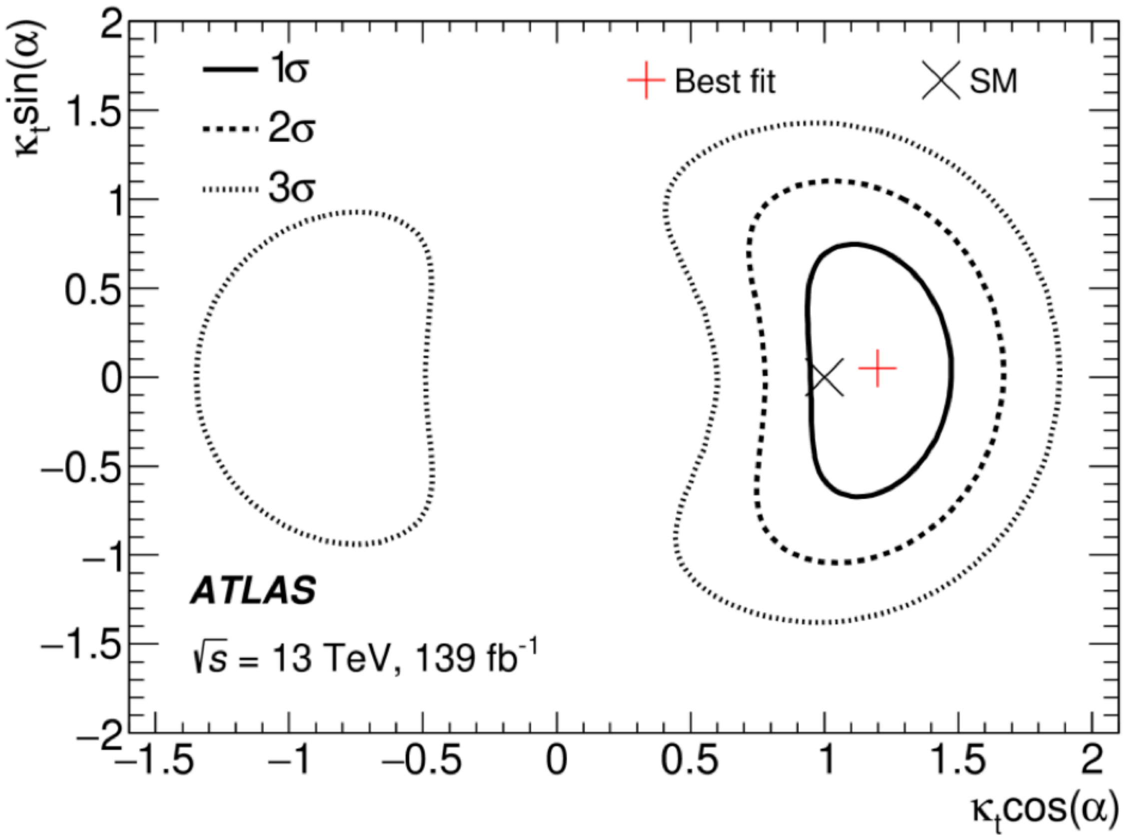


- Most fine-grained binning → best individual sensitivity
- No correlation information with other channels
- Statistical overlap with, e.g., STXS

Higgs data

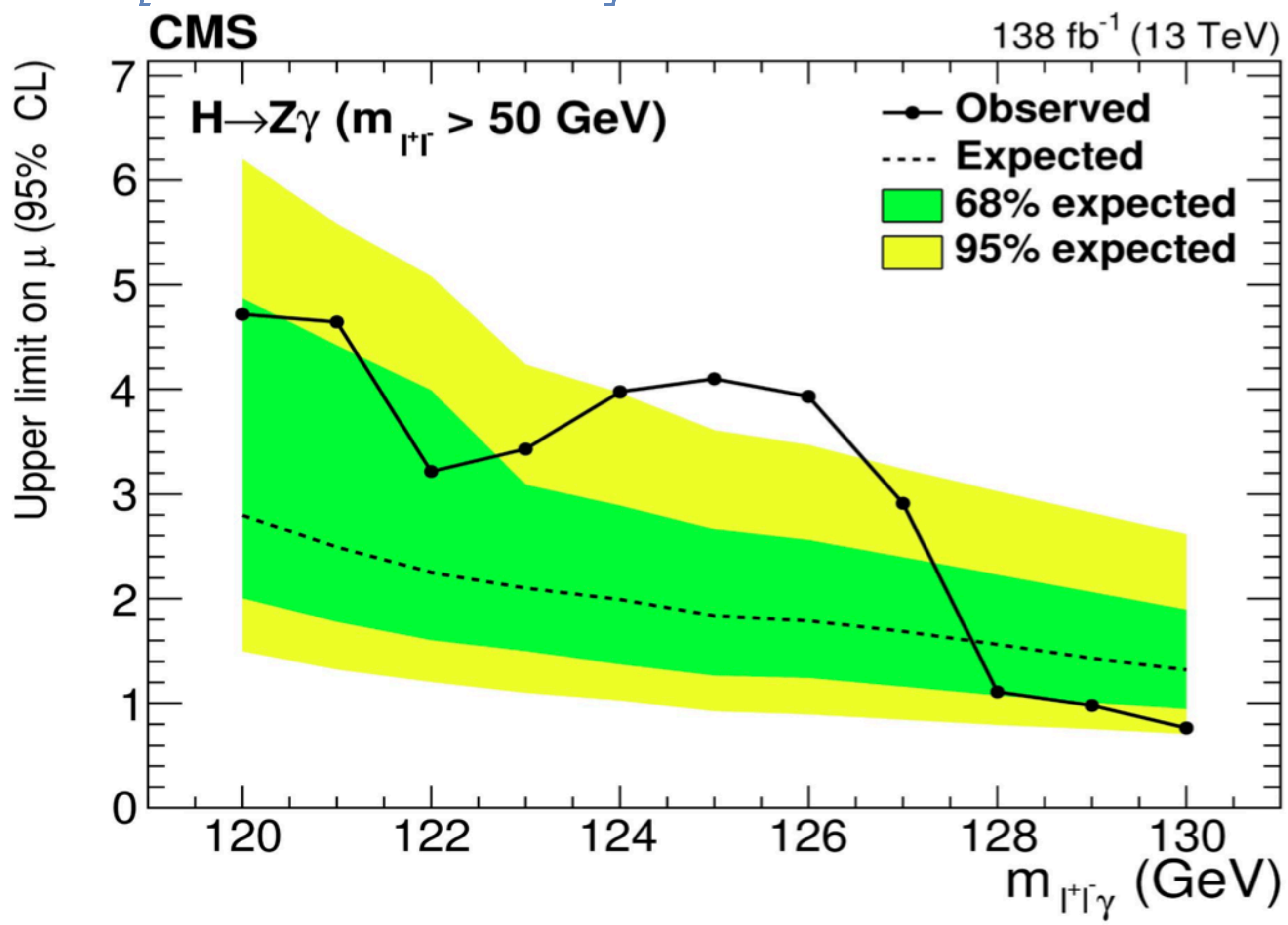
CP properties

[ATLAS; PRL 125 (2020) 061802]



Rare decays

[CMS-HIG-19-014]



Breadth of SMEFT framework

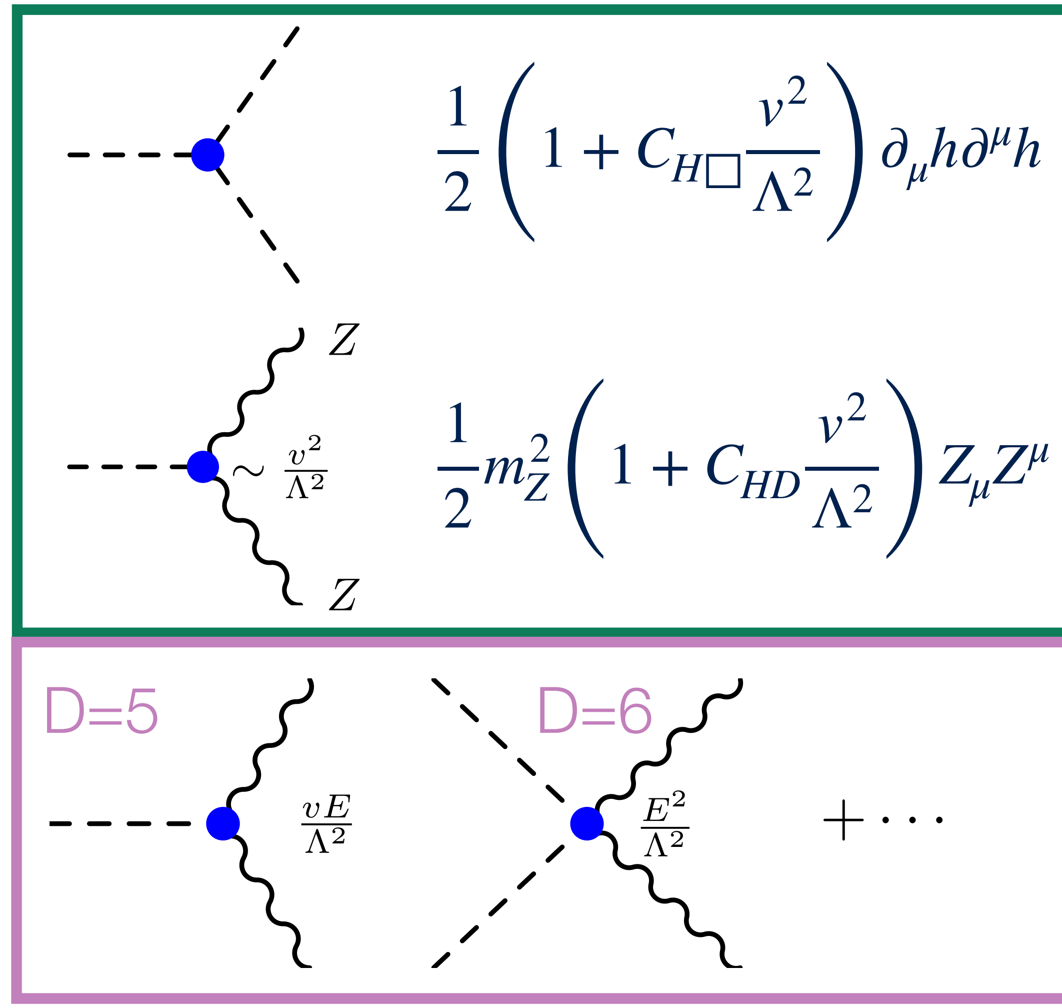
- All measurements can be interpreted in a global analysis
- Data ⇔ Wilson coefficients: search of hints of heavy new physics

Bosonic operators

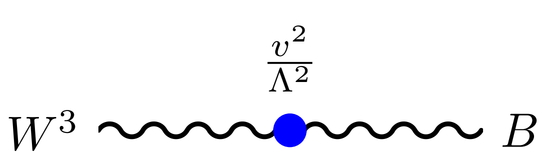
[Grzadkowski et al.; JHEP 10 (2010) 085]

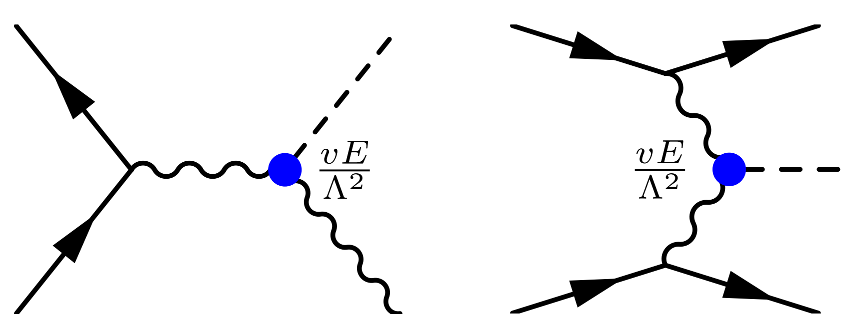
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

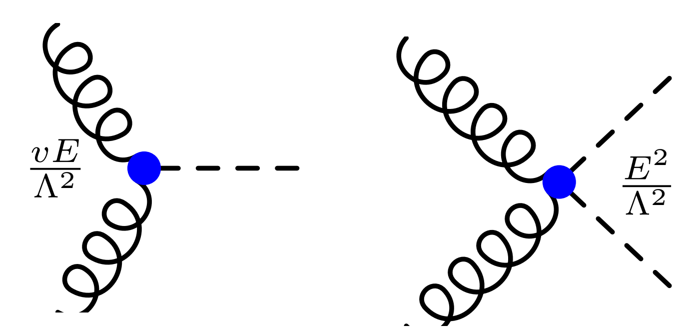
$\phi^n D^m$



$\phi^2 X_{\mu\nu}^2$







EW precision tests

EW Higgs production & decay

Gluon fusion: Higgs, di-Higgs

Yukawa/dipole operators

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

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
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Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
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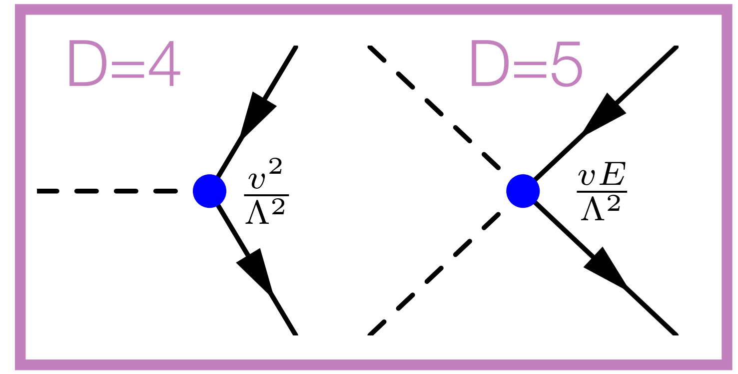
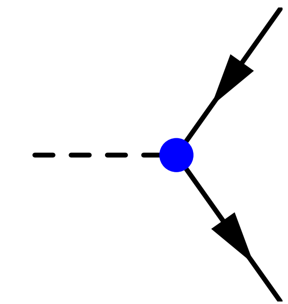
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

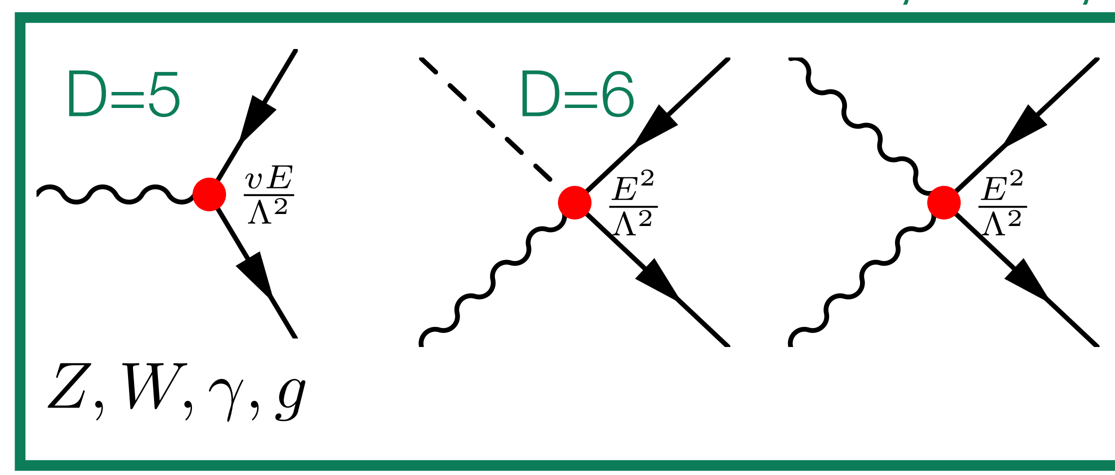
$\phi^3\bar\psi_L\psi_R$





$H\to f\bar f$

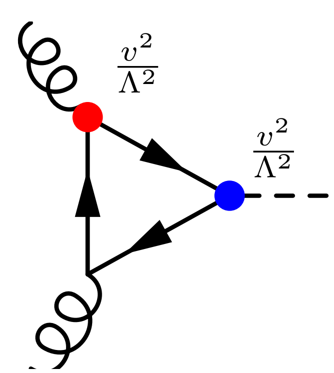
$\phi\bar\psi_L\sigma_{\mu\nu}\psi_R X_{\mu\nu}$



Chiral flip: $f_L f_R$

⇒ Leading effects ∝ m_f

⇒ 3rd generation couplings



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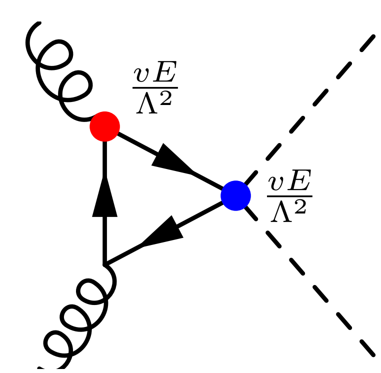

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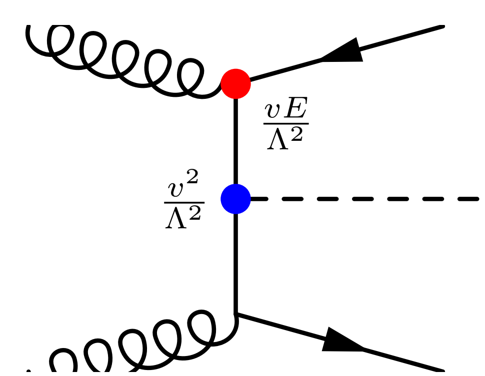

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Current operators

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

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
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$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
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$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
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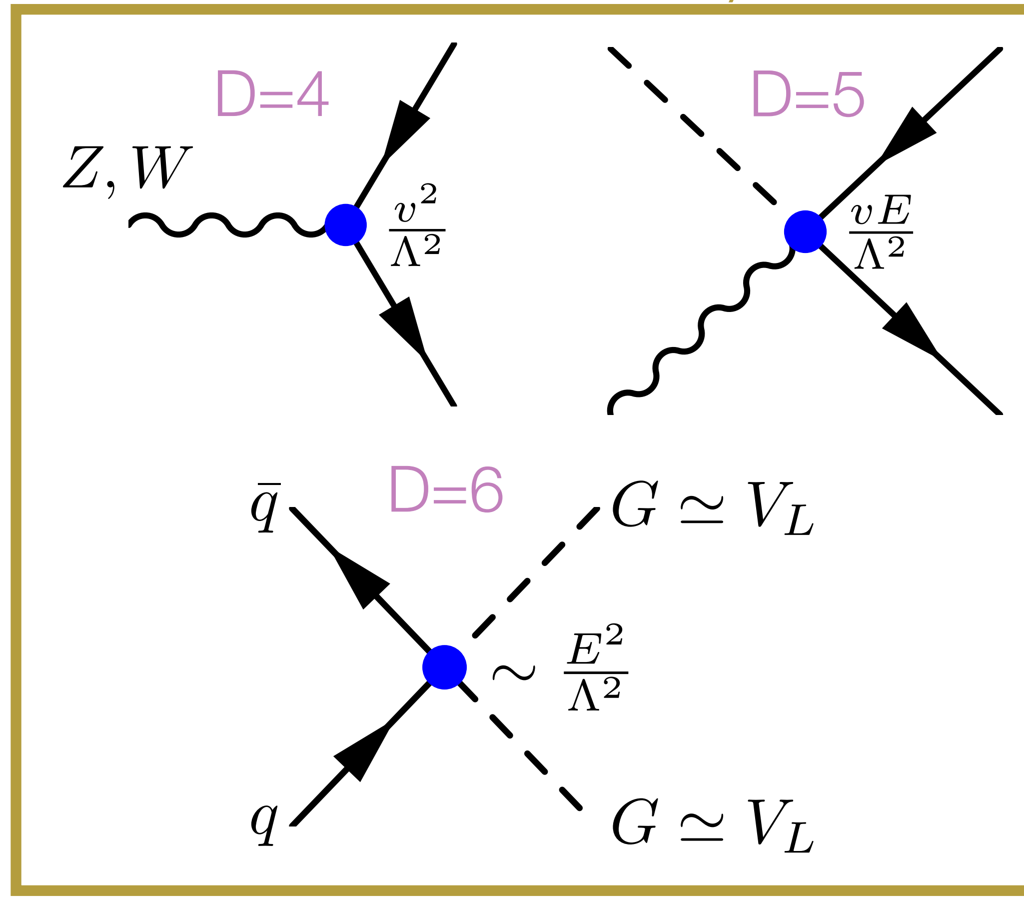
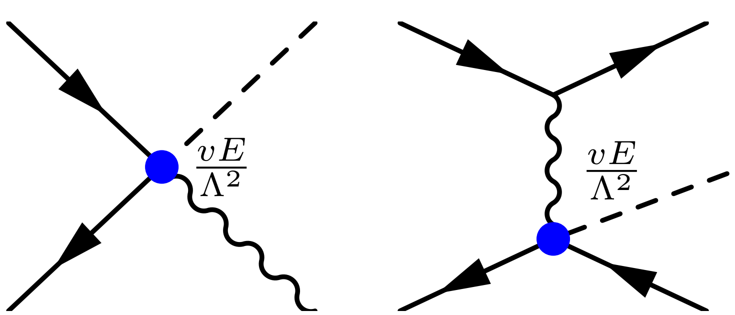
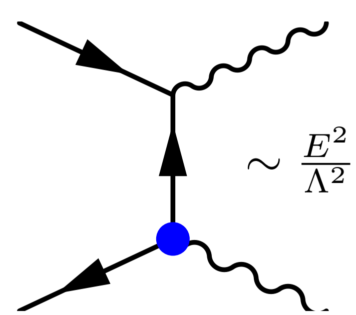
$(\phi^\dagger D_\mu\phi)(\bar\psi\gamma^\mu\psi)$

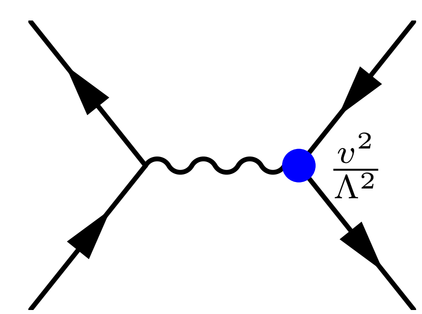




EW Higgs production

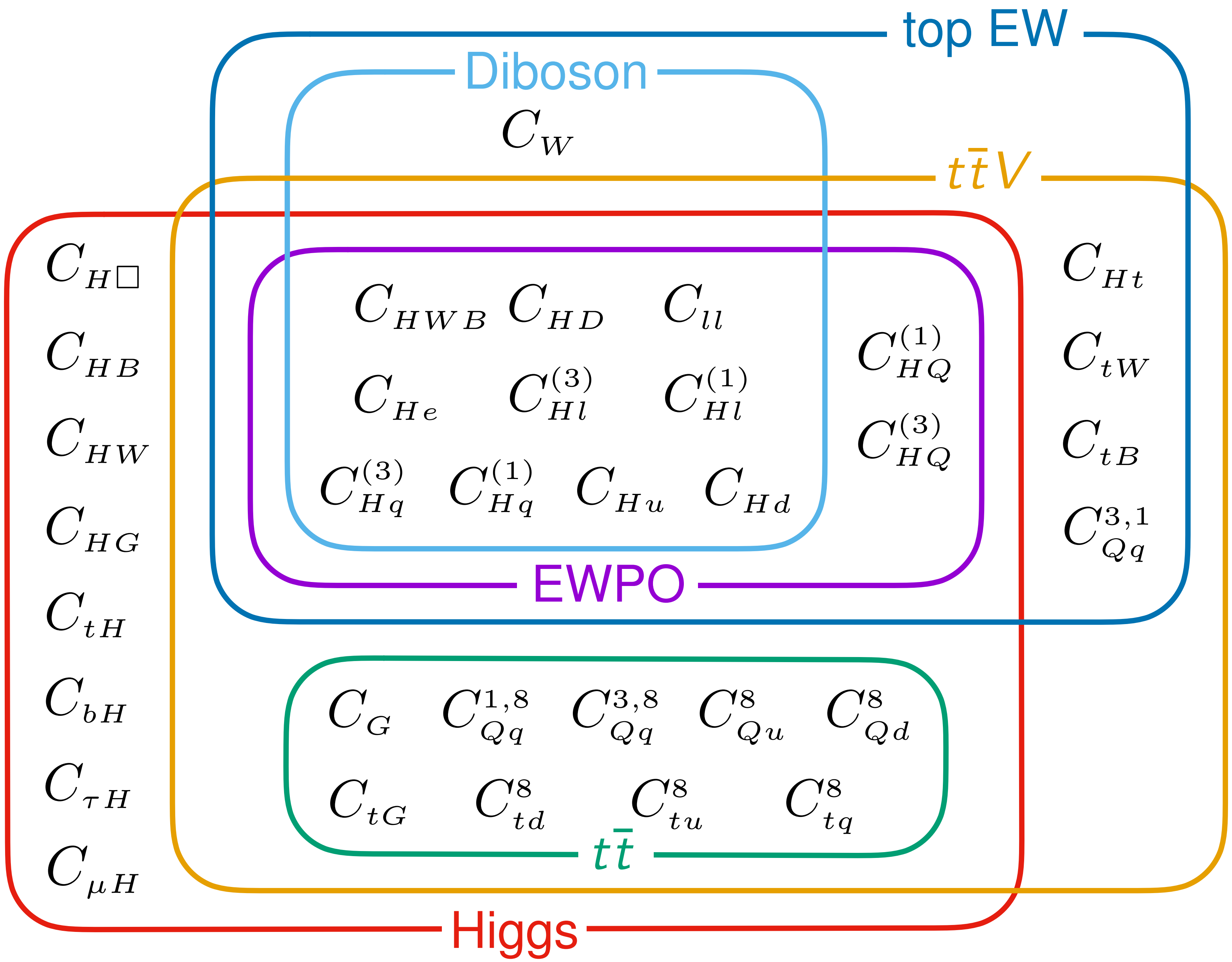


Diboson production



Precision EW on the Z peak (LEP)

Interplay



[Ellis, Madigan, KM, Sanz & You; JHEP 04 (2021) 279]

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]

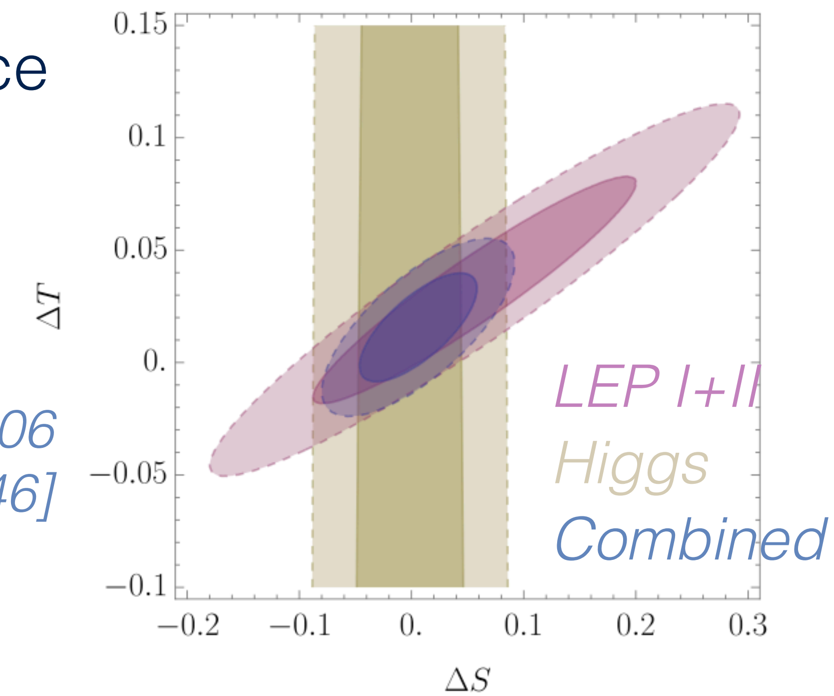
How much cross-talk? Where does being global matter?

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]
[Anisha et al; arXiv:2111.05876]……

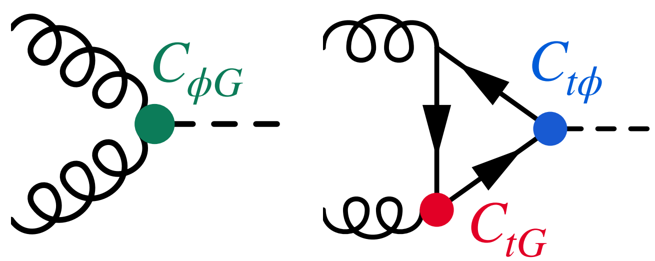
[Ellis et al.; JHEP 06 (2018) 146]

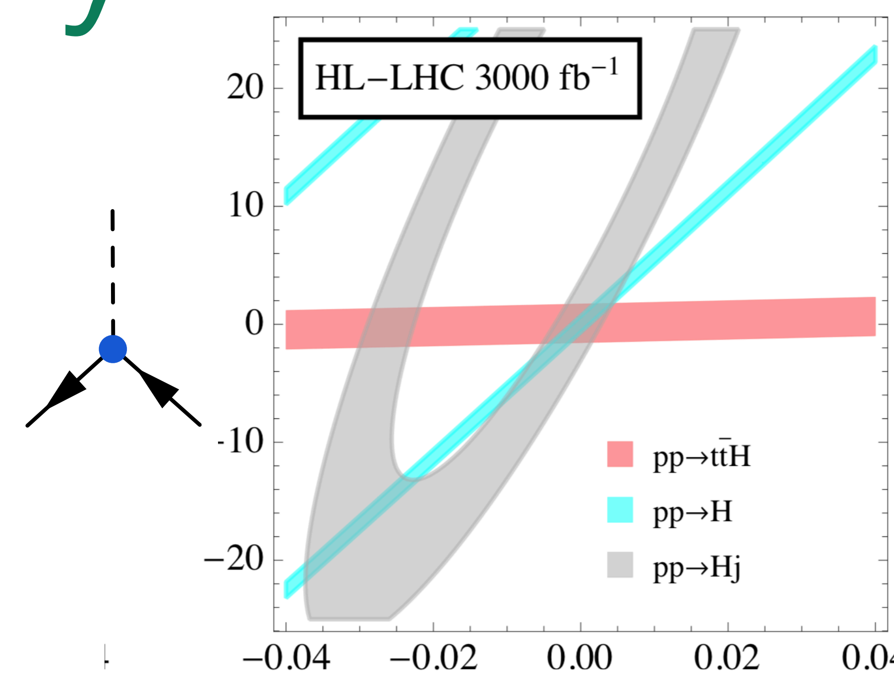


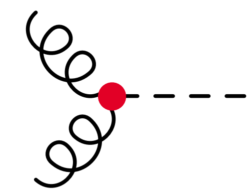
Top/Higgs interplay

[Maltoni, Vryonidou &

$C_{\phi G}$ *Point-like*
$C_{t\phi}$ *Yukawa*
C_{tG} *Dipole*







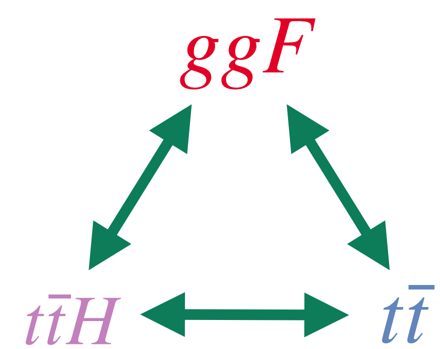
$gg \to h$ is well measured now…

⚠ Can't exclude top partners/anomalous Yukawa

- Degeneracy in coefficient/model space

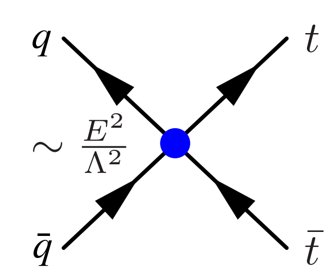
Need more data!

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



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?



Answer: do 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

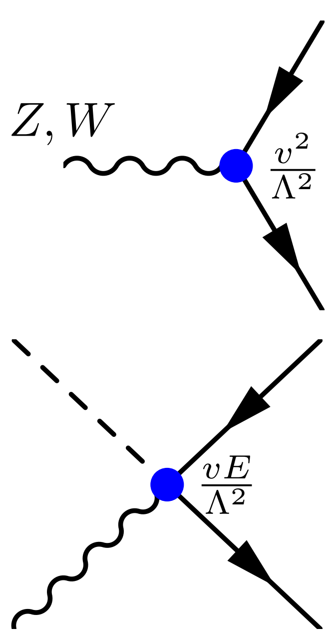
- Chosen to be statistically independent & maximise reach
- Correlations included when publicly available (mostly are)

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

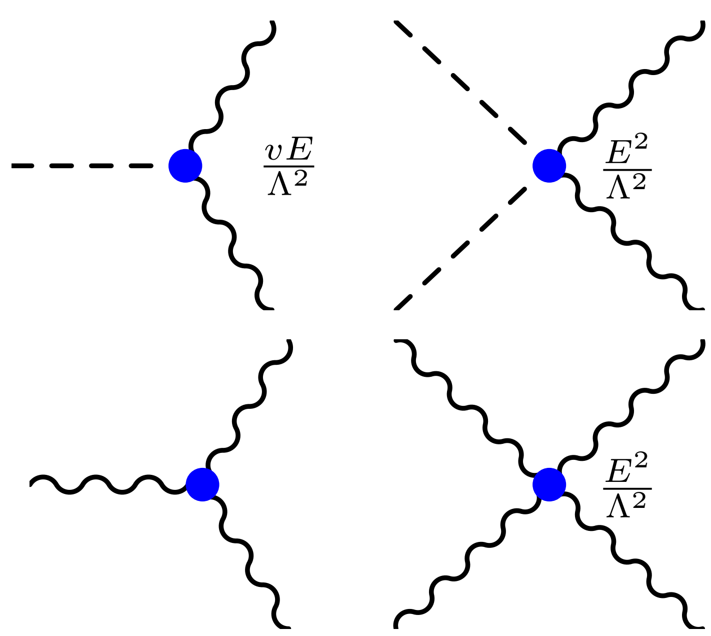
Degrees of freedom

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

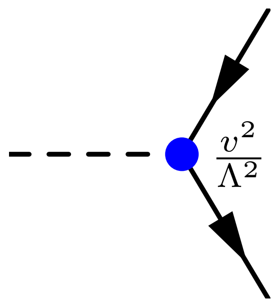
EWPO



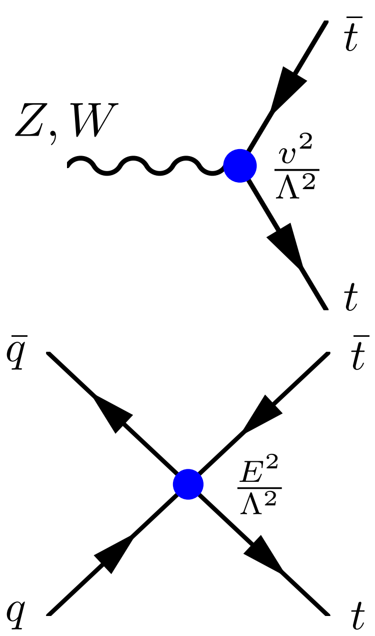
Bosonic



Yukawa

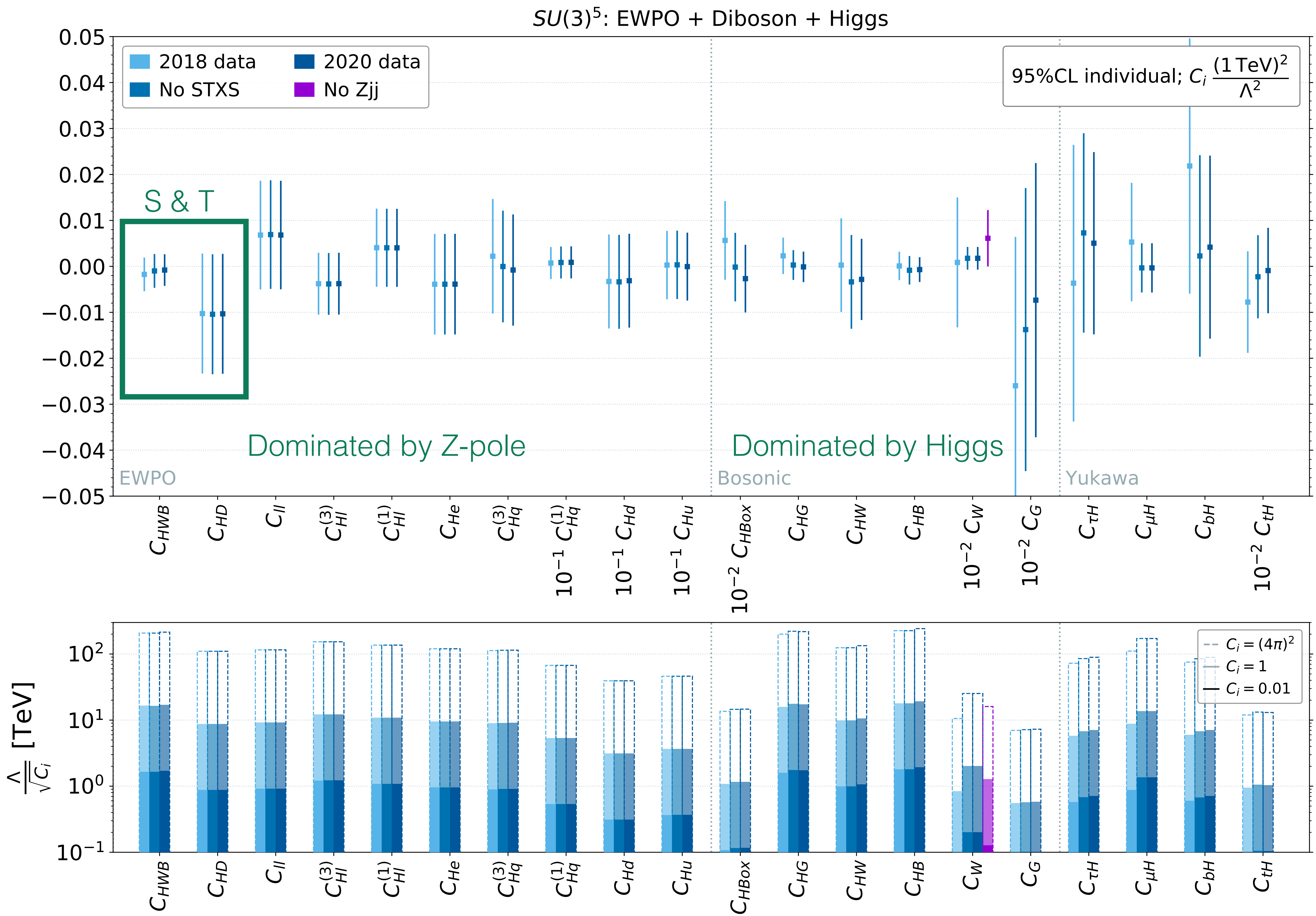


Top 2F/4F



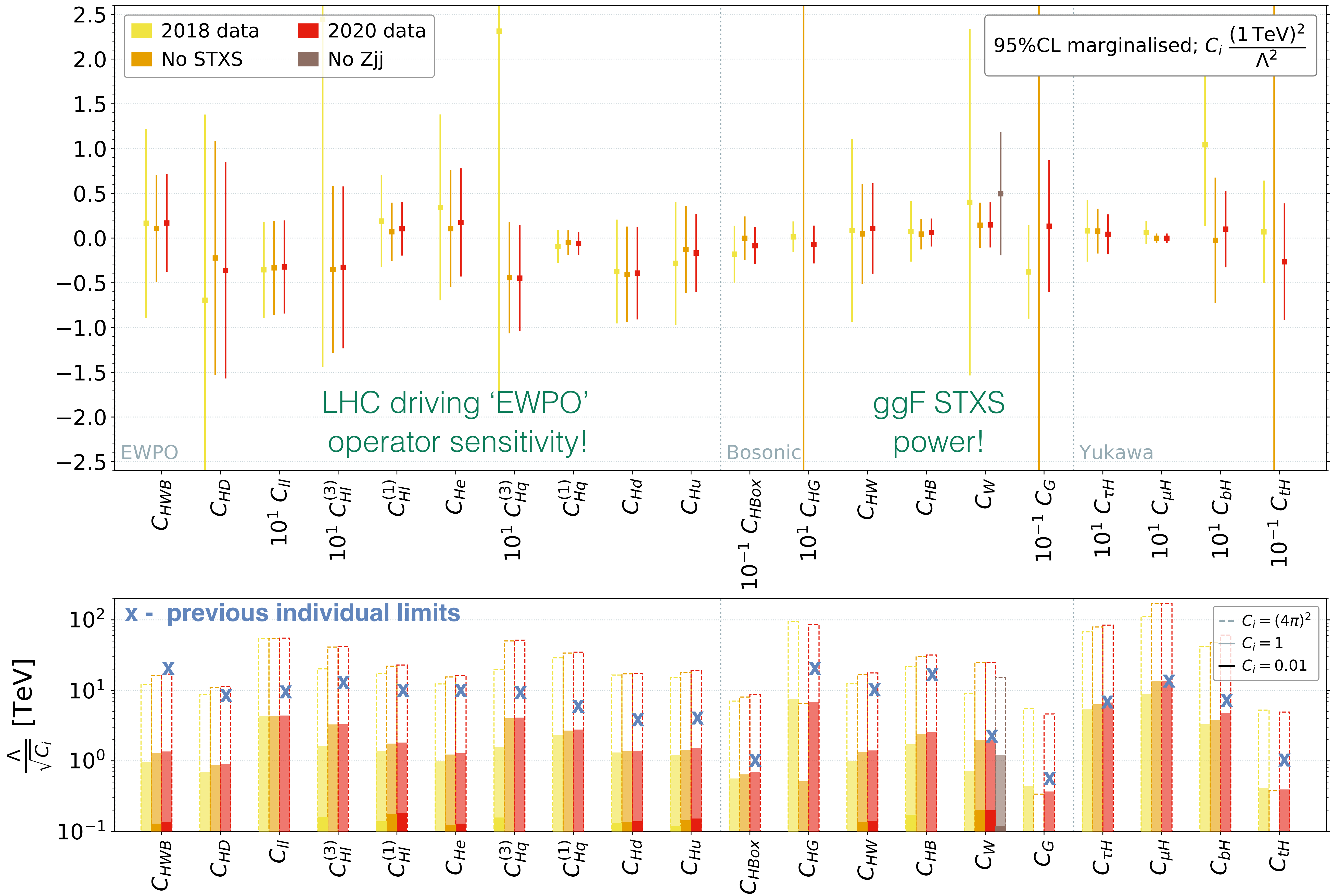
Individual limits: $U(3)^5$

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



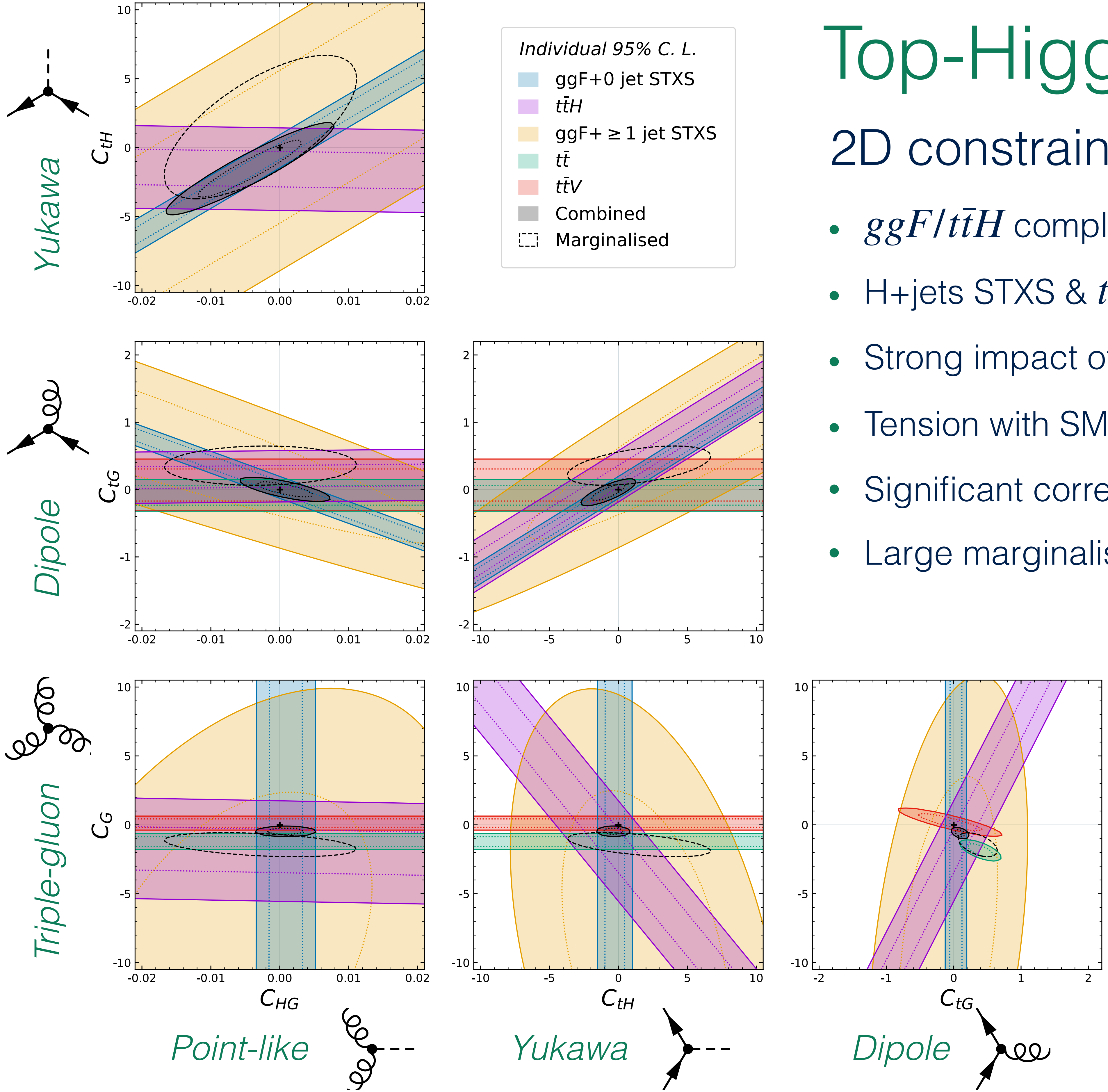
Marginalised limits: U(3)^5

2018 ⇒ 2020: only LHC data changed



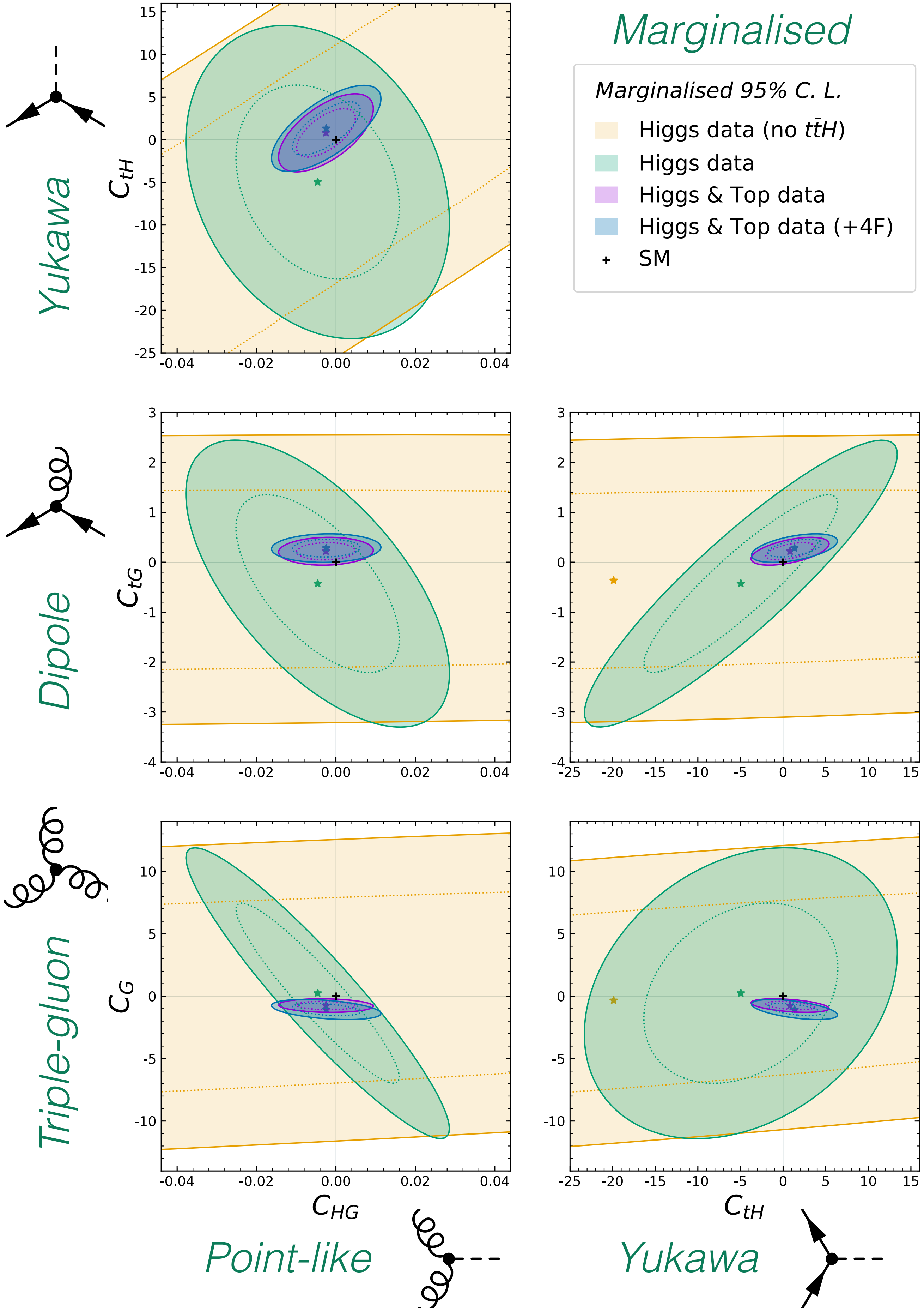
Top-Higgs interplay

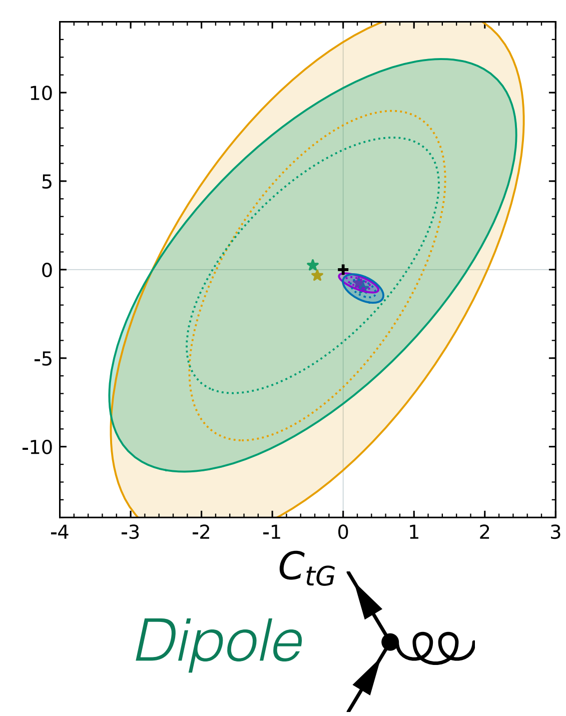
2D constraints



- $ggF/t\bar{t}H$ 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 $m_{t\bar{t}}$

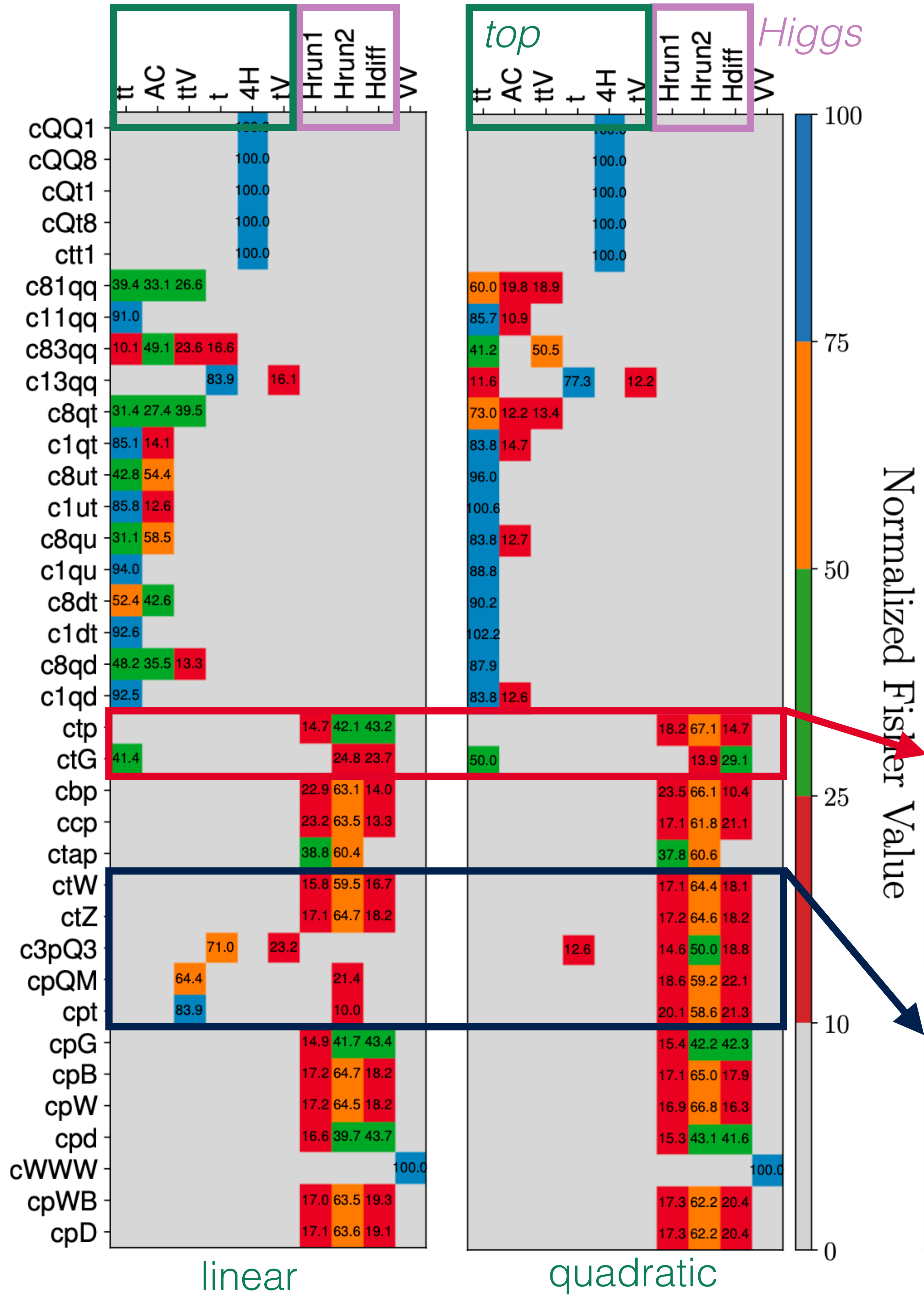
  $4F$: high $m_{t\bar{t}}$

- Able to constrain them independently

[ATLAS-CONF-2021-031]

More top/Higgs interplay

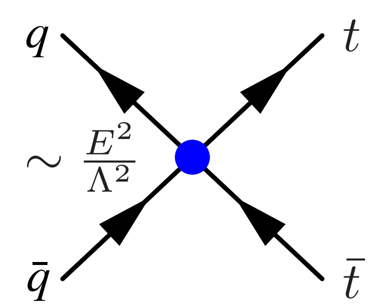
[Ethier et al.; JHEP 11 (2021) 089]



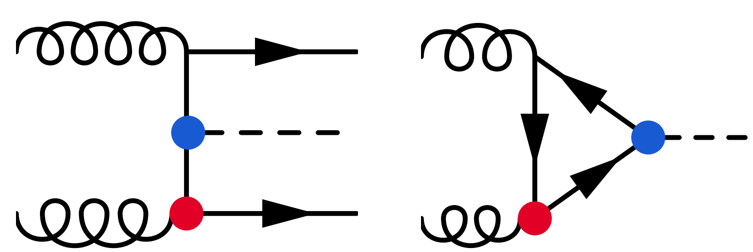
Fisher Information:

Hessian of Log-likelihood at the best-fit point

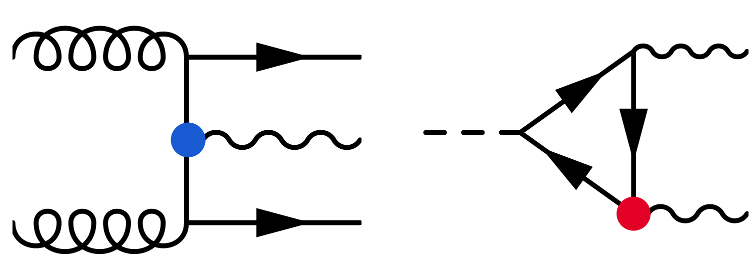
4F operators: mostly top data



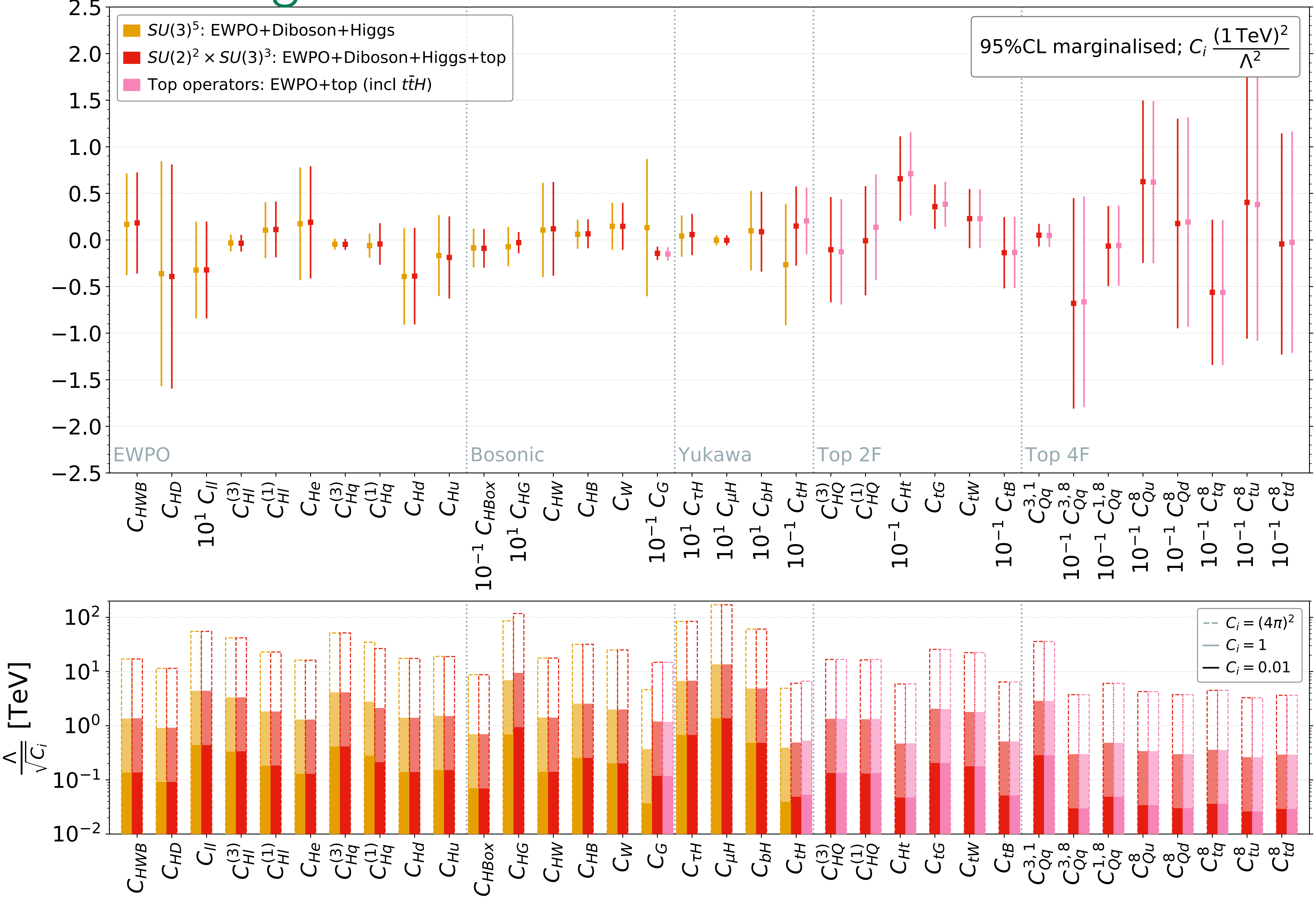
Yukawa & Chromo-dipole



$t\bar{t}V$ couplings



Full fit: marginalised



Correlations

Block diagonal: correlations *within* 'sector'

Block off-diagonal: correlations *among* 'sectors'

EWPO & top ~uncorrelated

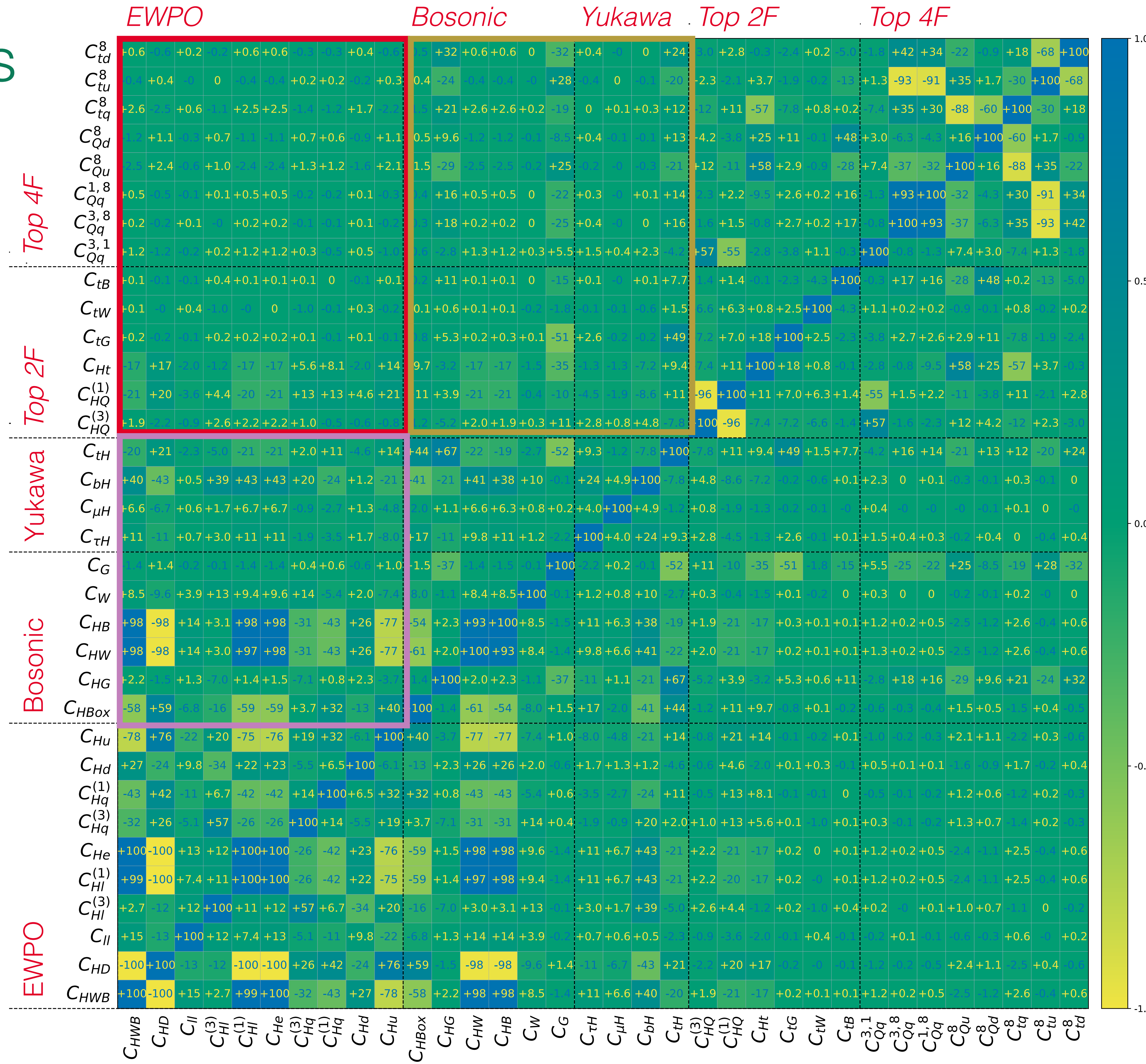
EWPO-Higgs

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

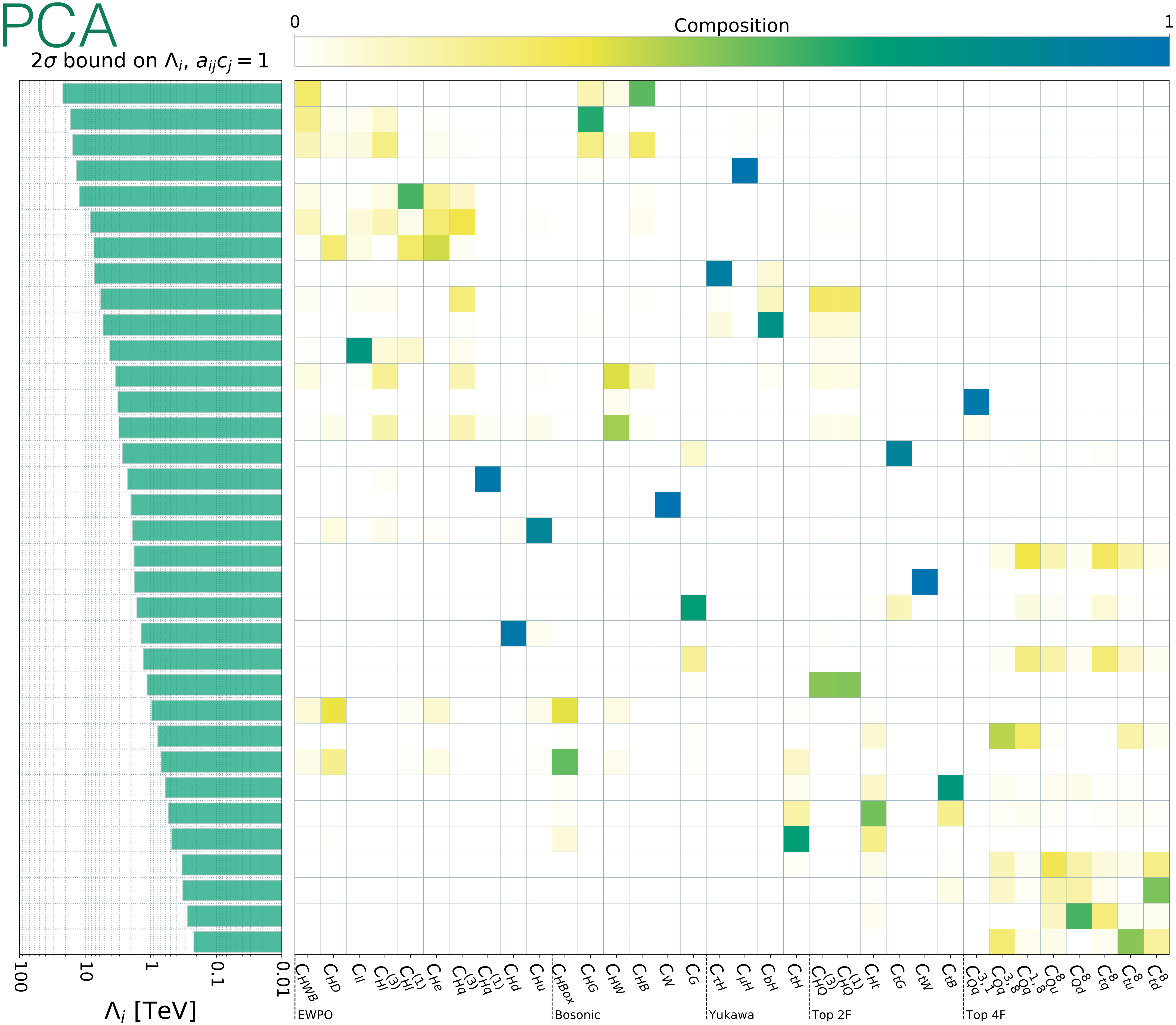
Higgs precision rivalling LEP

Top-Higgs

C_{HG}, C_G, C_{tH} with 4F



PCA



Relative constraining power (%)

EWPO	LEP WW	Run 1, μ	Run 2, μ	STXS	LHC WW	LHC Zjj	$t\bar{t}$	single top	$t\bar{t}V$
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

Higgs

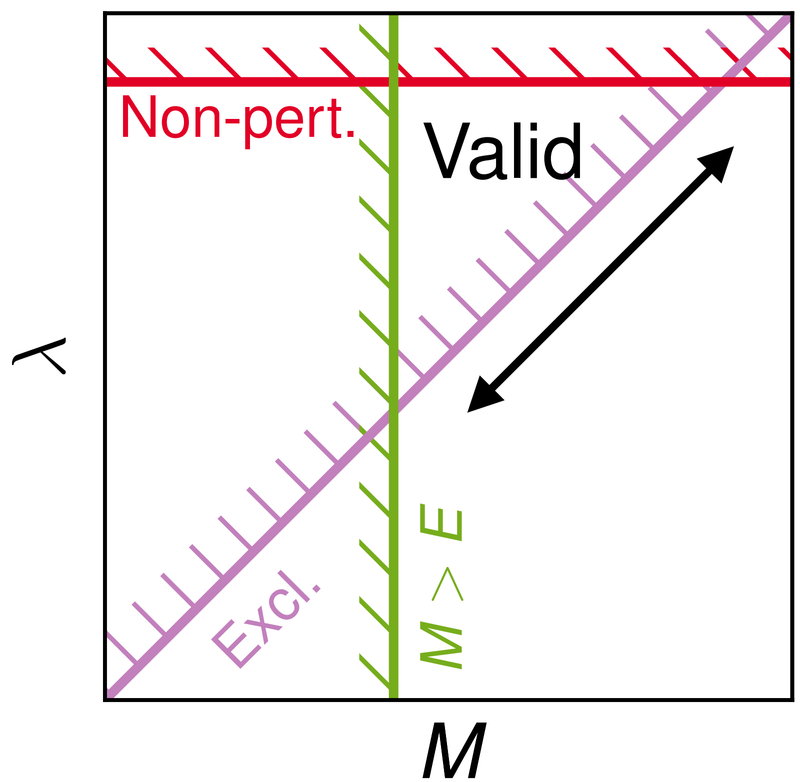
BSM implications

SMEFT-UV connection is model dependent by construction

- New physics implications & EFT validity are ***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*

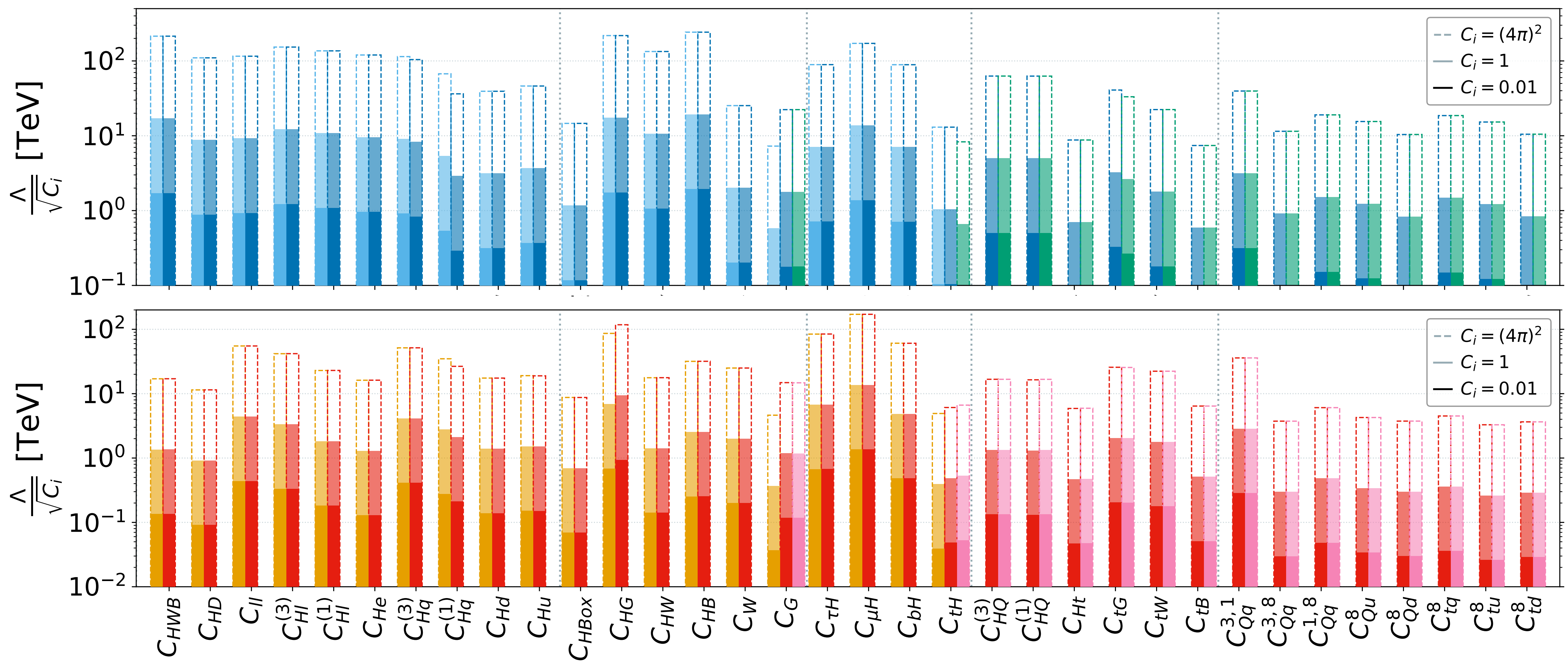
constraint: $c/\Lambda^2 < X$



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

	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	$-\frac{1}{2}$	$(M_{\Delta_3},\lambda_{\Delta_3})$	
Scalars	φ	0	1	2	$\frac{1}{2}$	$(M_\varphi,Z_6\cos\beta)$	Σ	$\frac{1}{2}$	1	3	0	$(M_\Sigma,\lambda_\Sigma)$	VLL
	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)	
Z’	B	1	1	1	0	$(M_B,\hat{g}_H^B)$	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$	(M_D,λ_D)	
W’	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})	VLQ
	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})	
VLL	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})	
VLQ	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

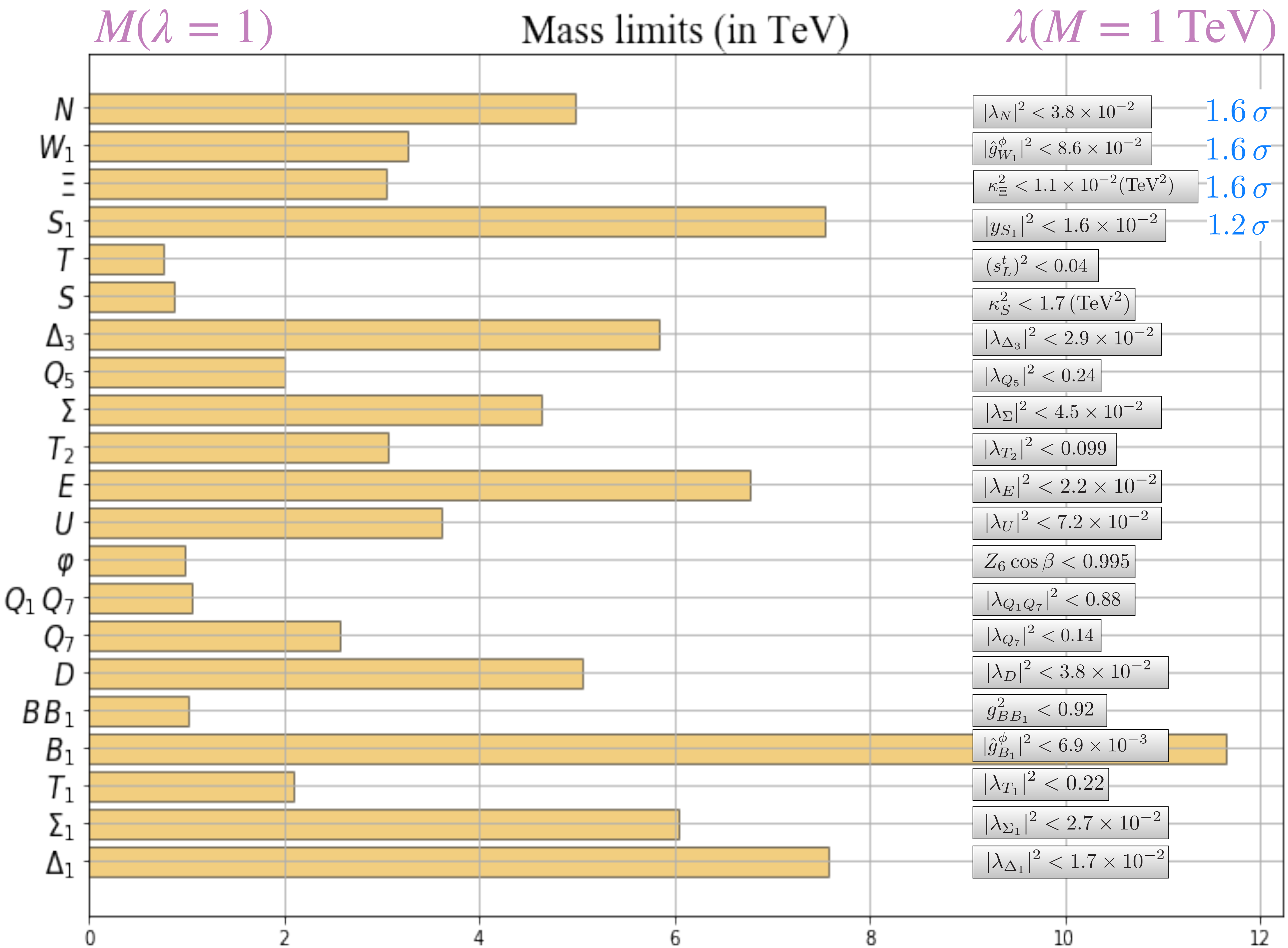
One parameter models

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

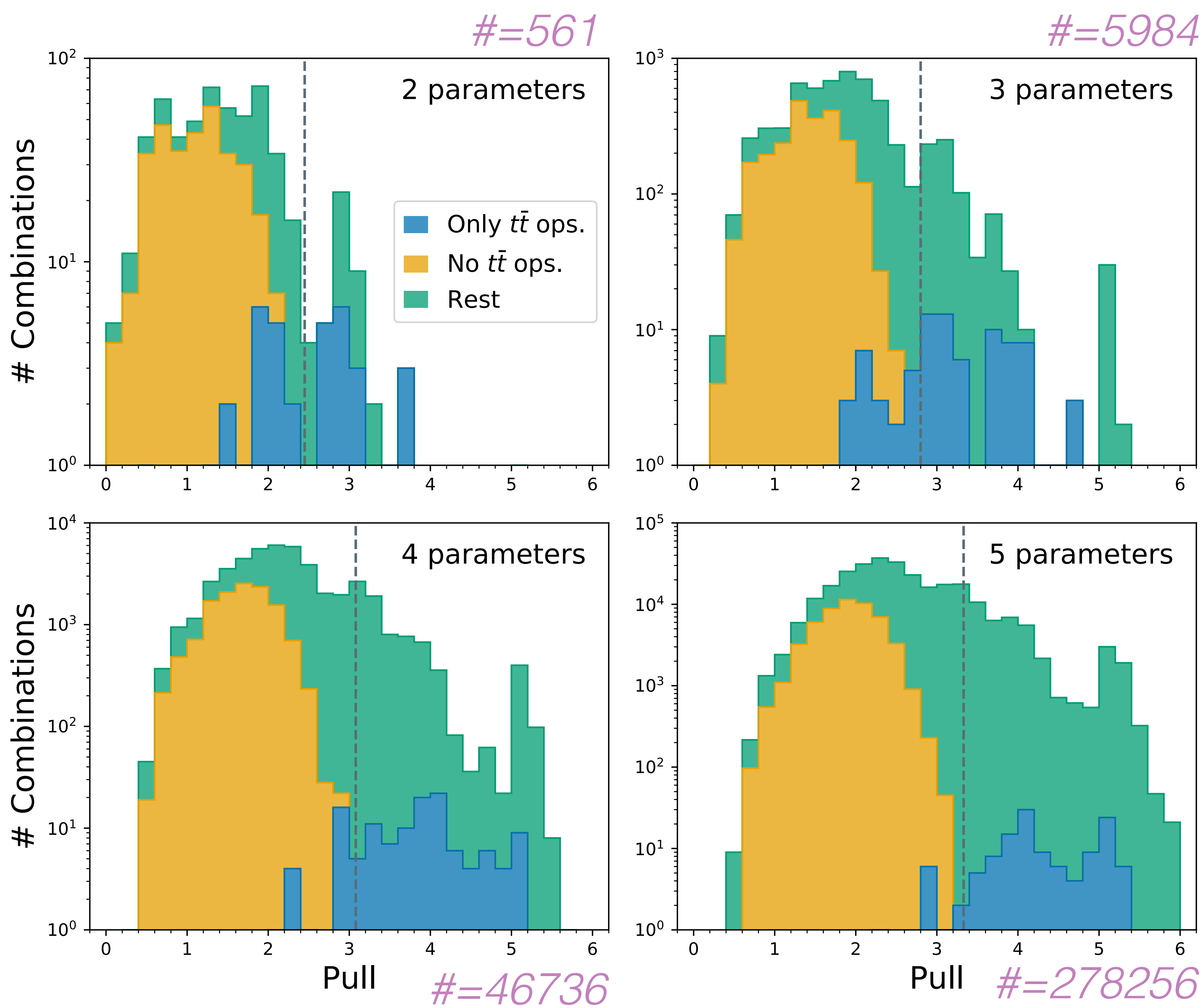


Pull-ology

Brute force: fit to all combinations of n-coefficients

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

- 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…



Conclusions

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

- Higgs data are driving global sensitivity beyond EWPO
- Top & Higgs sector are starting to talk to each other
- Interplay is robust against 4F operators in $t\bar{t}$

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

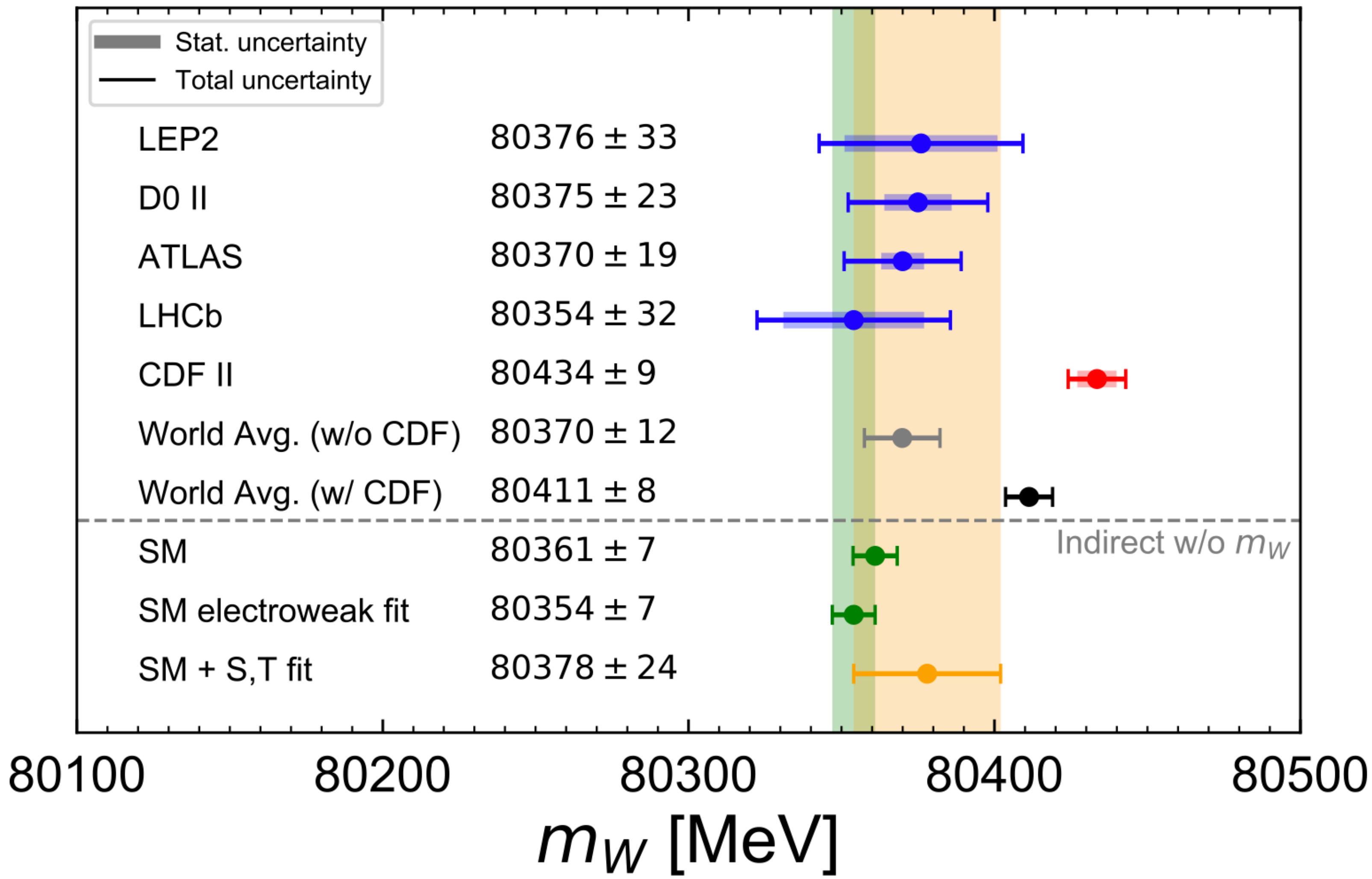
- Top operators in loops: Higgs decays + EWPO
- NLO corrections

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?

Bonus: m_W interpretation

The result



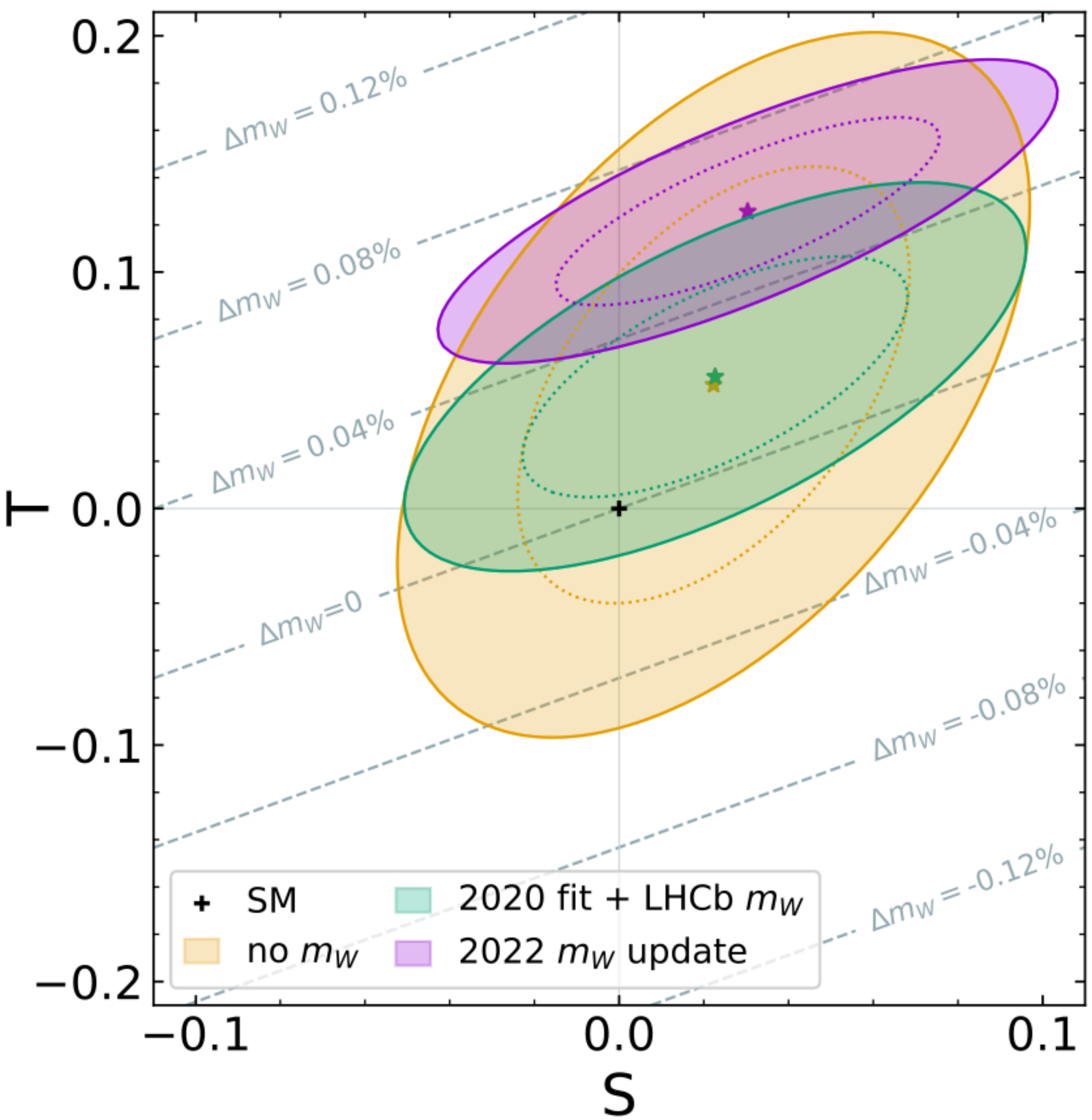
$$\mathcal{O}_{HWB} \equiv H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_{HD} \equiv \left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$$

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

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

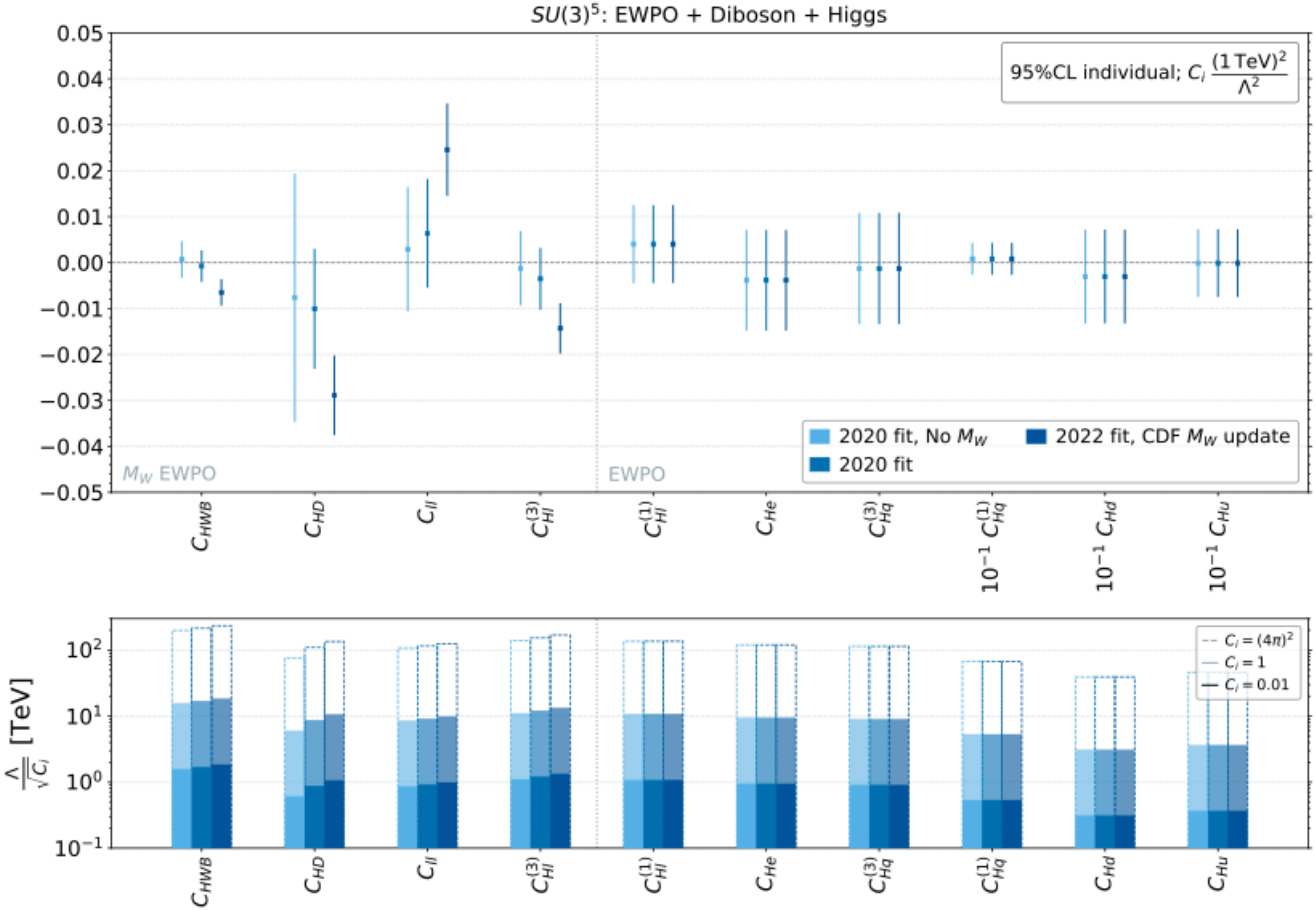
S & T parameters

$\propto C_{HD}$

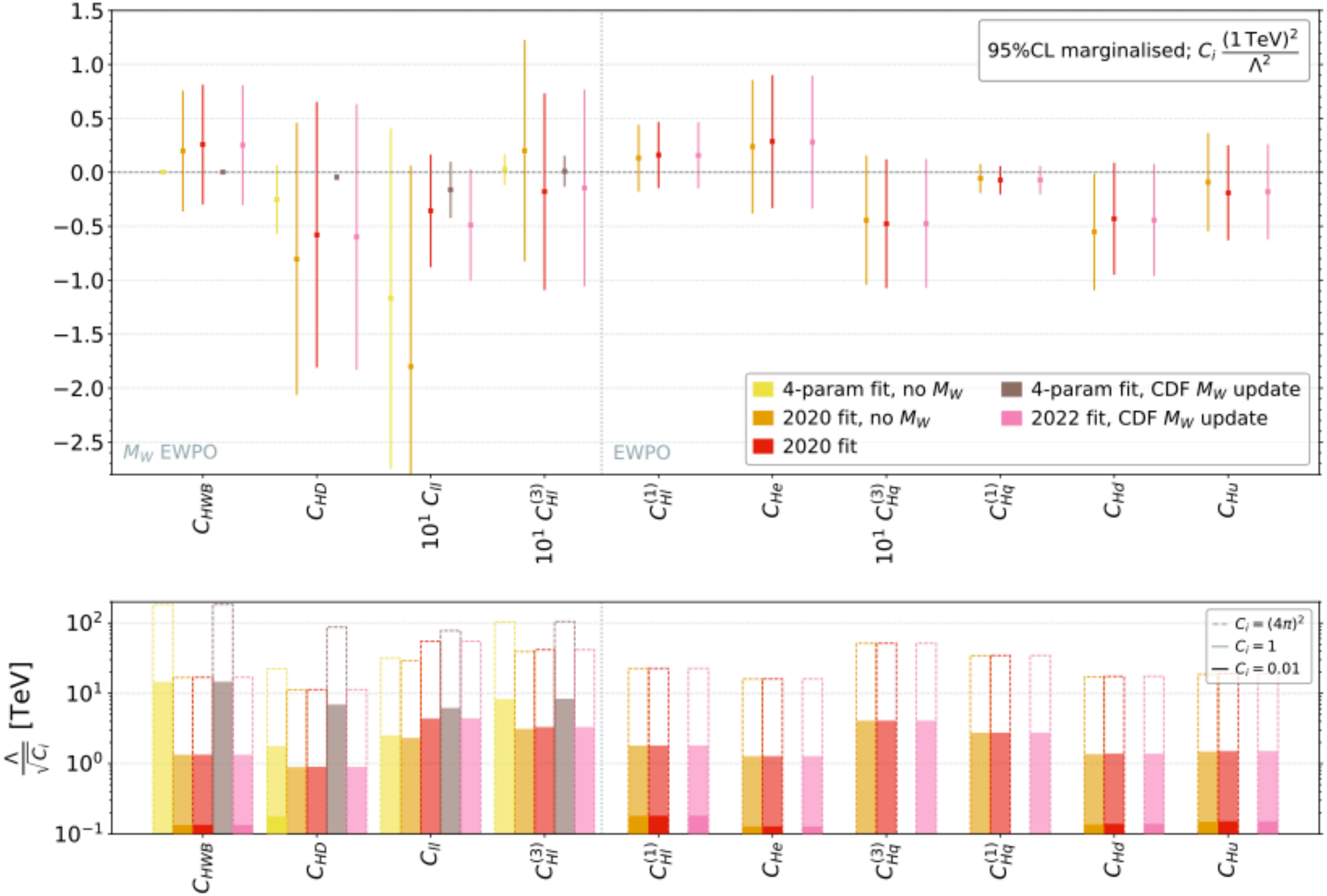


$\propto C_{HWB}$

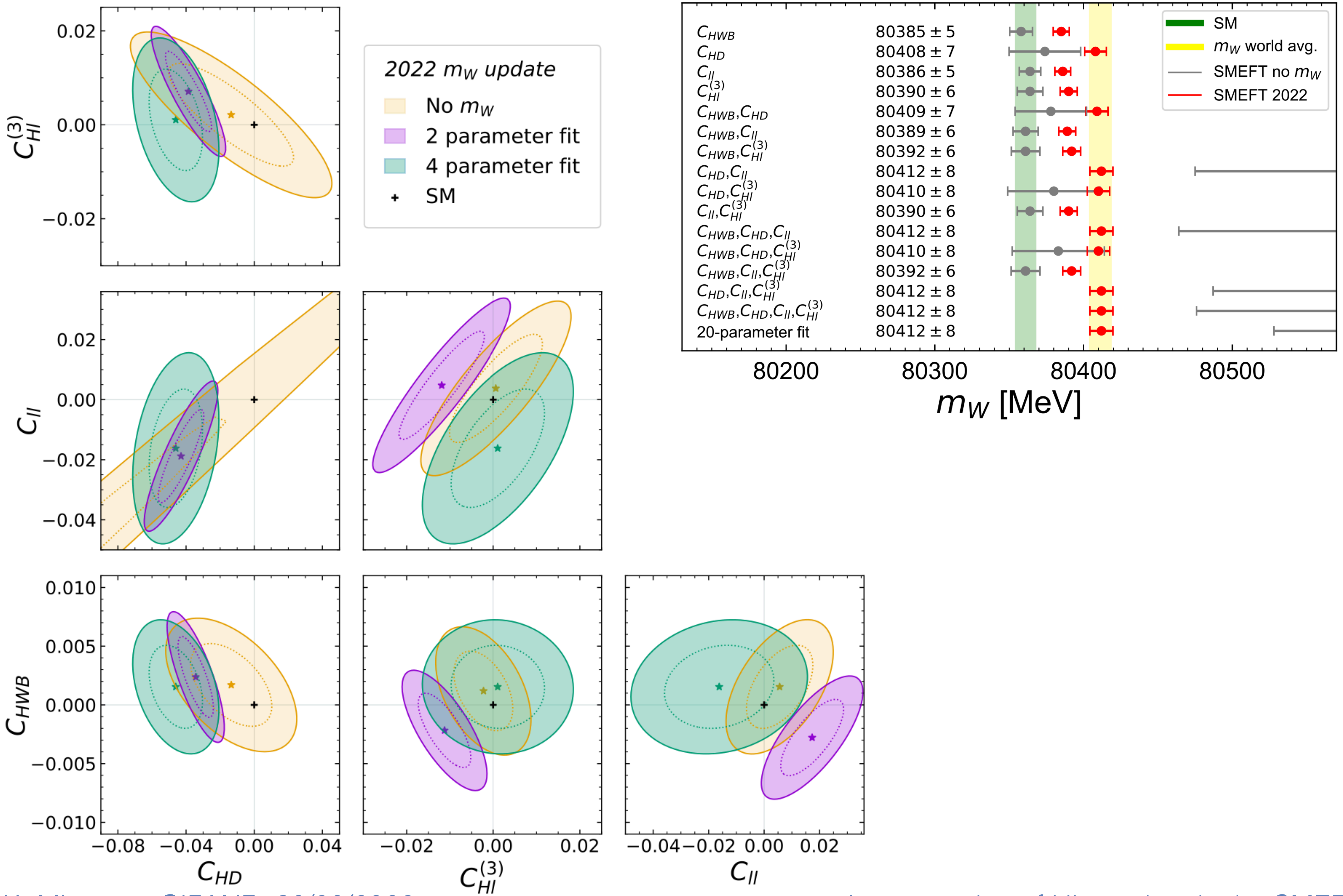
Global fit (20 parameters)



Global fit (20 parameters)

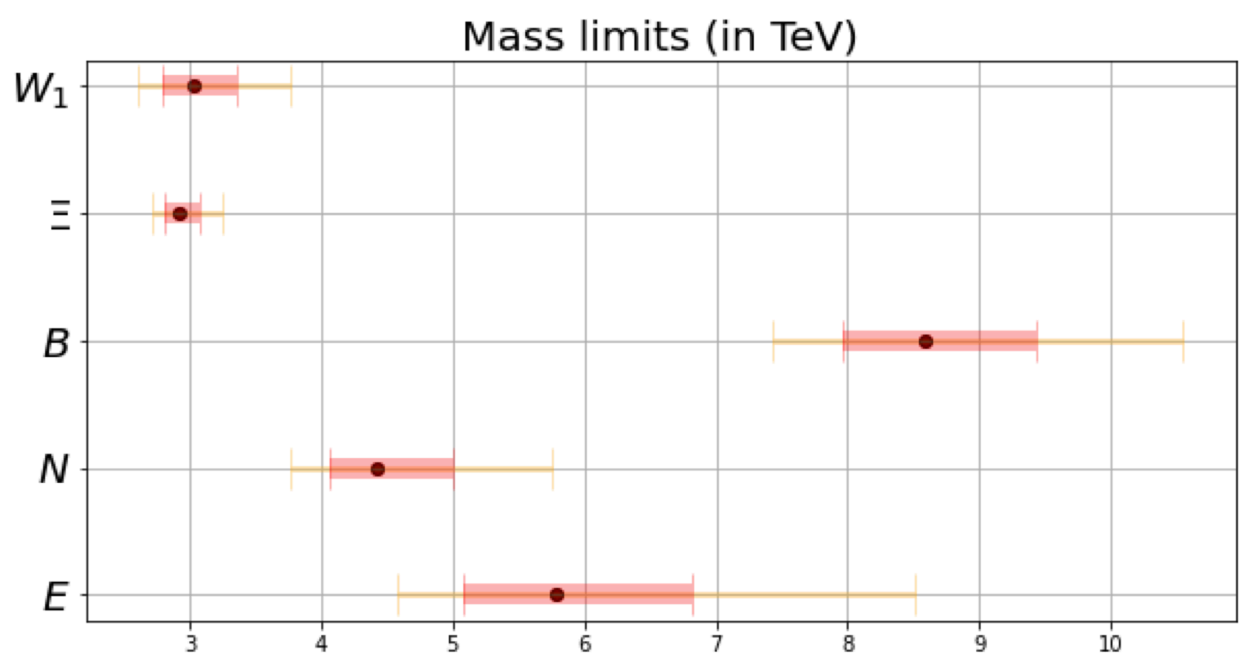


Subsets


2022 m_W update
No m_W
2 parameter fit
4 parameter fit
SM
$C_{HI}^{(3)}$
C_{ll}
C_{HWB}
C_{HD}
C_{HWB} 80385 ± 5
C_{HD} 80408 ± 7
C_{ll} 80386 ± 5
$C_{HI}^{(3)}$ 80390 ± 6
C_{HWB},C_{HD} 80409 ± 7
C_{HWB},C_{ll} 80389 ± 6
C_{HWB},$C_{HI}^{(3)}$ 80392 ± 6
C_{HD},C_{ll} 80412 ± 8
C_{HD},$C_{HI}^{(3)}$ 80410 ± 8
C_{ll},$C_{HI}^{(3)}$ 80390 ± 6
C_{HWB},C_{HD},C_{ll} 80412 ± 8
C_{HWB},C_{HD},$C_{HI}^{(3)}$ 80410 ± 8
C_{HWB},C_{ll},$C_{HI}^{(3)}$ 80392 ± 6
C_{HD},C_{ll},$C_{HI}^{(3)}$ 80412 ± 8
C_{HWB},C_{HD},C_{ll},$C_{HI}^{(3)}$ 80412 ± 8
20-parameter fit 80412 ± 8
SM
m_W world avg.
SMEFT no m_W
SMEFT 2022
m_W [MeV]

Single field extensions

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



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}, $A_\ell(\mathrm{SLD})$, $A_\ell(\mathrm{Pt})$, 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	$n_{\mathbf{obs}}$
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)	$n_{\mathbf{obs}}$
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. $\frac{d\sigma}{dn_{\mathrm{jet}}}$ | $\frac{d\sigma}{dp_H^T}$	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 $t\bar{t}$ 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. $\frac{d\sigma}{dm_{t\bar{t}}}$ | $\frac{d\sigma}{d\|y_{t\bar{t}}\|}$ | $\frac{d\sigma}{dp_T^t}$ | $\frac{d\sigma}{d\|y_t\|}$.	7|5|8|5	[24]
CMS $t\bar{t}$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar{t}}}$ | $\frac{d\sigma}{dy_{t\bar{t}}}$ | $\frac{d\sigma}{dp_T^t}$ | $\frac{d\sigma}{dy_t}$.	7|10|8 |10	[25, 34]
CMS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$ in the dilepton channel.	3	[33]
ATLAS inclusive measurement $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$ in the dilepton channel.	1	[32]
ATLAS & CMS combination of differential $t\bar{t}$ 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. $\frac{d\sigma}{dm_{t\bar{t}}dy_t}$ | $\frac{d\sigma}{dm_{t\bar{t}}dy_{t\bar{t}}}$ | $\frac{d\sigma}{dm_{t\bar{t}}dp_{t\bar{t}}^T}$ | $\frac{d\sigma}{dy_t dp_T^t}$.	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 $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W}\|\sigma_{t\bar{t}Z}$	2	[23]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W}\|\sigma_{t\bar{t}Z}$	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. $\frac{d\sigma}{dp_T^t}$ | $\frac{d\sigma}{dp_T^{\bar{t}}}$ | $\frac{d\sigma}{d\|y_t\|}$ | $\frac{d\sigma}{d\|y_{\bar{t}}\|}$	4|4|4|5	[39]
CMS s-channel single-top cross section measurement.	1	[28]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp_{t+\bar{t}}^T}$ | $\frac{d\sigma}{d\|y_{t+\bar{t}}\|}$	6 |6	[19]
CMS measurement of the t-channel single-top and anti-top cross sections. $\sigma_t\,\|\,\sigma_{\bar{t}}\,\|\,\sigma_{t+\bar{t}}\,\|\,R_t$.	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 $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$.	5	[55]
ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W}\|\sigma_{t\bar{t}Z}$	2	[58]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W}\|\sigma_{t\bar{t}Z}$	1|1	[48]
CMS $t\bar{t}Z$ differential distributions. $\frac{d\sigma}{dp_Z^T}$ | $\frac{d\sigma}{d\cos\theta^*}$	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. $\frac{d\sigma}{dp_{t+\bar{t}}^T}$ | $R_t\,(p_{t+\bar{t}}^T)$	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. $\sigma_t\,\|\,\sigma_{\bar{t}}\,\|\,\sigma_{t+\bar{t}}\,\|\,R_t$.	1|1|1|1	[45]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp_{t+\bar{t}}^T}$ | $\frac{d\sigma}{d\|y_{t+\bar{t}}\|}$	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 $t\bar{t}b\bar{b}$ cross section measurement in the all-jet channel.	1	[57]
CMS $t\bar{t}b\bar{b}$ 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

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
}
```

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

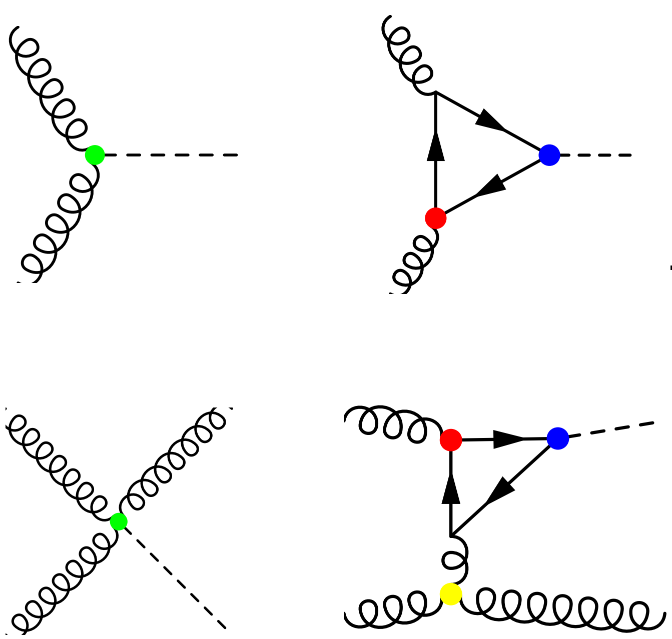
Solution: SMEFT@NLO

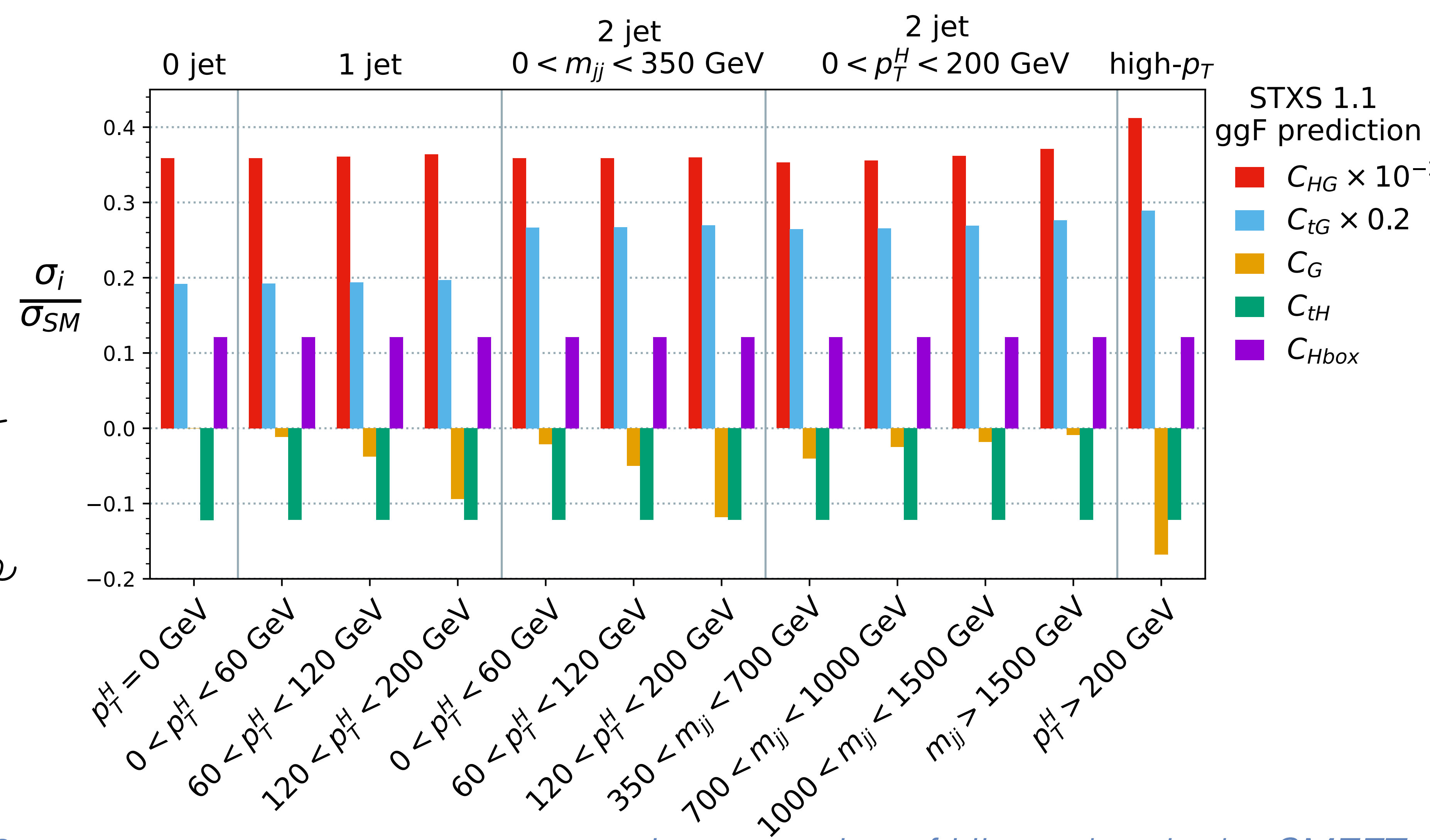
- UFO model for `MadGraph5_aMC@NLO`
- Process-independent implementation: SMEFT in top-specific flavor limit

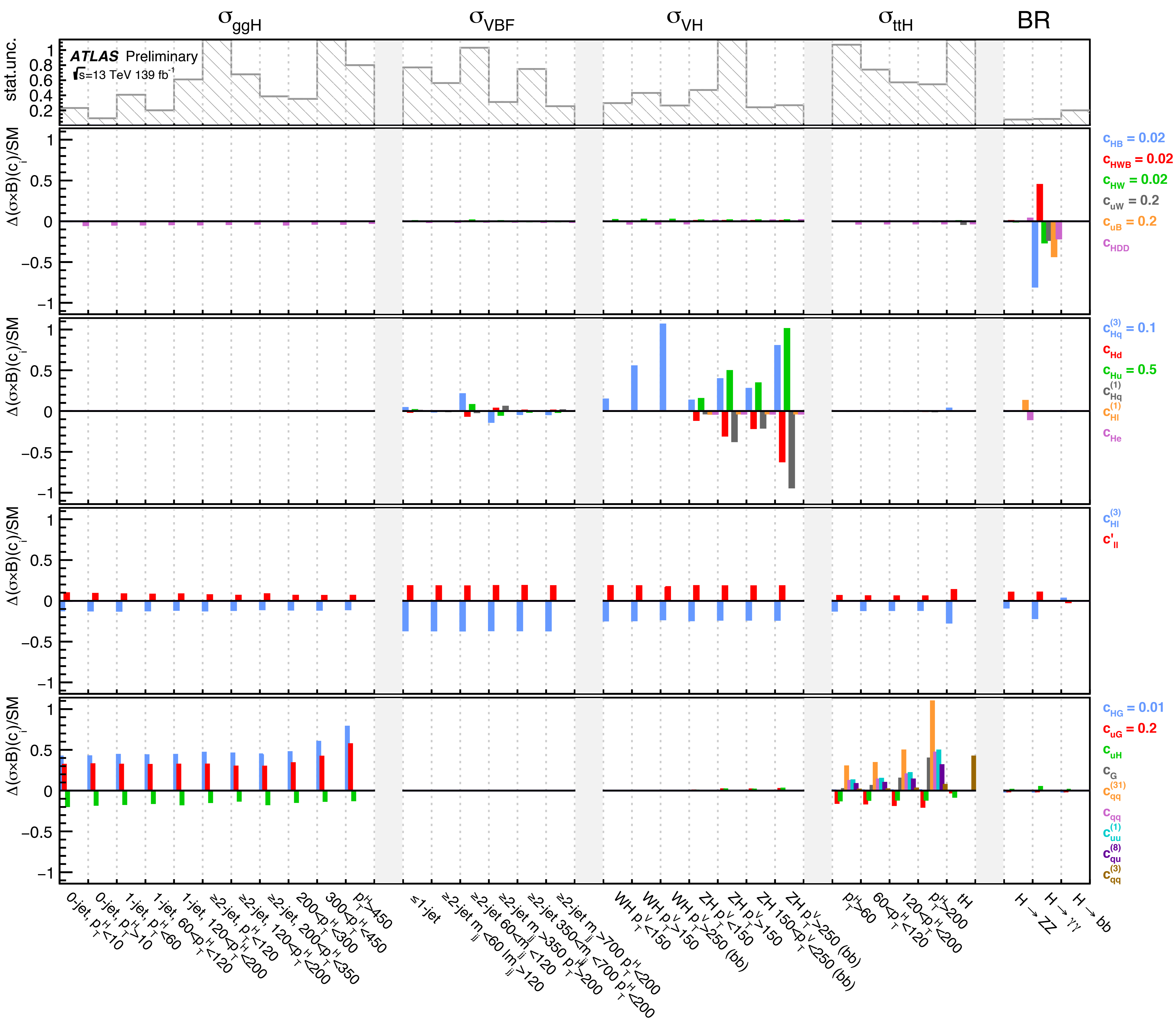
SMEFT@NLO in STXS

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






σggH
σVBF
σVH
σttH
BR
ATLAS Preliminary
√s=13 TeV 139 fb-1
stat.unc.
Δ(σ×B)(ci)/SM
cHB = 0.02
cHWB = 0.02
cHW = 0.02
cuW = 0.2
cuB = 0.2
cHDD
cHq(3) = 0.1
cHd
cHu = 0.5
cHq(1)
cHl(1)
cHe
cHl(3)
c'll
cHG = 0.01
cuG = 0.2
cuH
cG
cqq(31)
cqq
cuu(1)
cqu(8)
cqq(3)
0-jet, pTH<10
0-jet, pTH>10
1-jet, pTH<60
1-jet, 60<pTH<120
1-jet, 120<pTH<200
≥2-jet, pTH<120
≥2-jet, 120<pTH<200
≥2-jet, 200<pTH<300
200<pTH<300
300<pTH<450
pTH>450
≤1-jet
≥2-jet mjj<60 | mjj>120
≥2-jet 60<mjj<120
≥2-jet mjj>350 pTH>200
≥2-jet 350<mjj<700 pTH<200
≥2-jet mjj>700 pTH<200
WH pTV<150
WH pTV>150
WH pTV>250 (bb)
ZH pTV<150
ZH pTV>150
ZH 150<pTV<250 (bb)
ZH pTV>250 (bb)
pTH>60
60<pTH<120
120<pTH<200
pTH>200
tH
H → ZZ
H → γγ
H → bb

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

Standard Model Effective Theory at One-Loop in QCD

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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

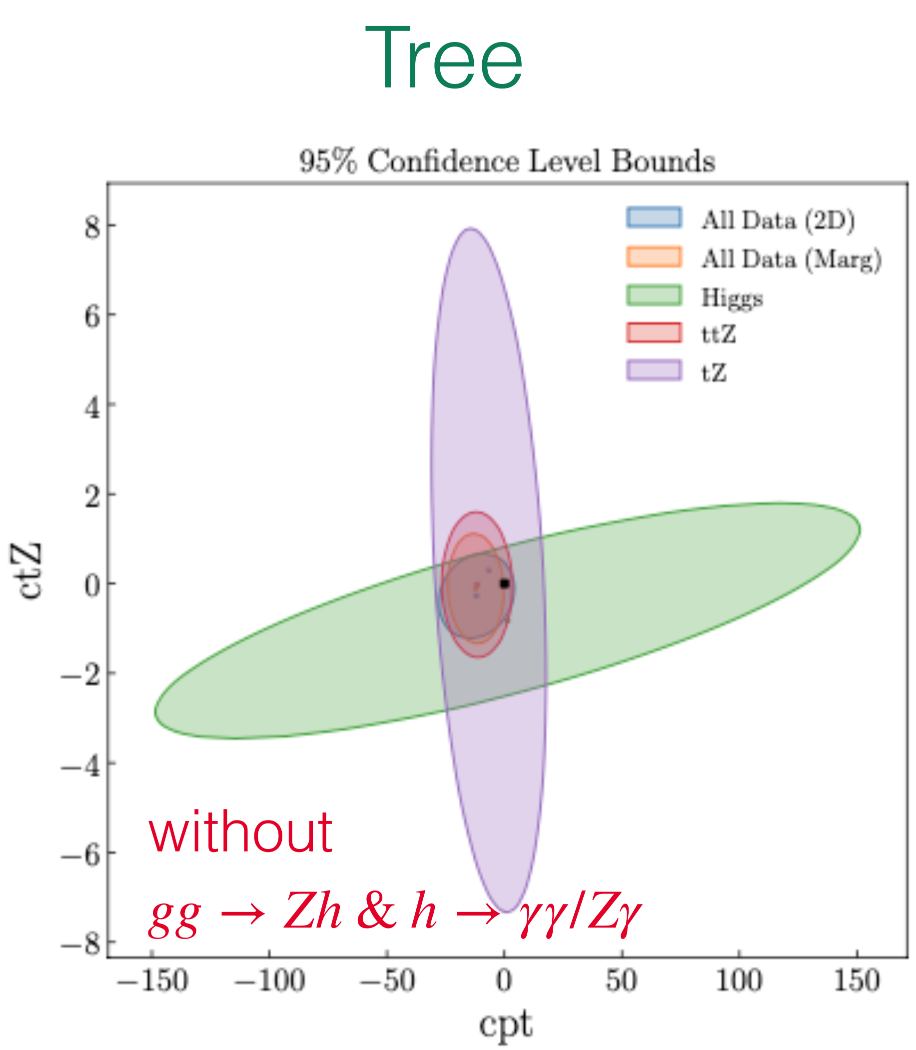
UFO model: SMEFTatNLO_v1.0.tar.gz

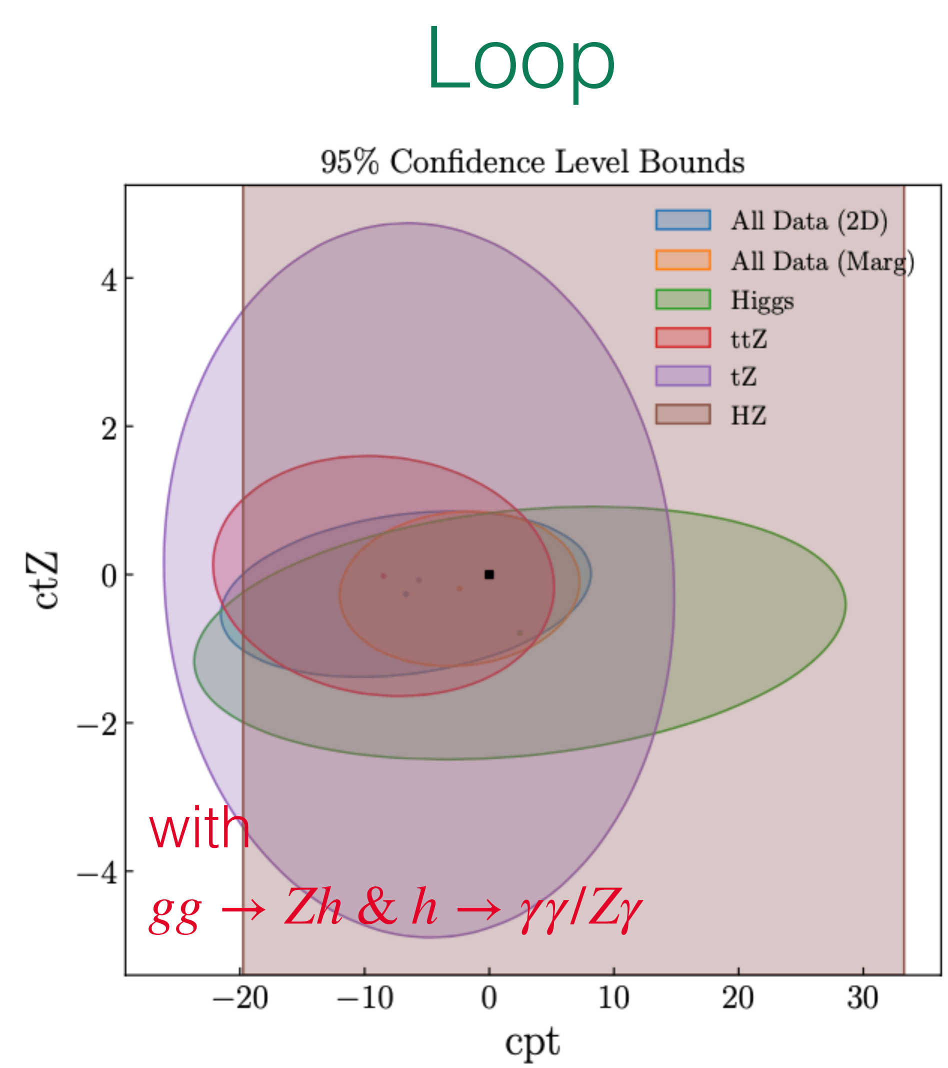
The current implementation imposes CP conservation. In the quark sector, it focuses primarily on top-quark interactions. The light-quark current operator, qqHDH, uuHDH, ddHDH, with coefficients `cpq3i`, `cpqMi`, `cpu`, `cpd` are however included. The triple-gluon operator, with coefficient `cG`, is currently 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).

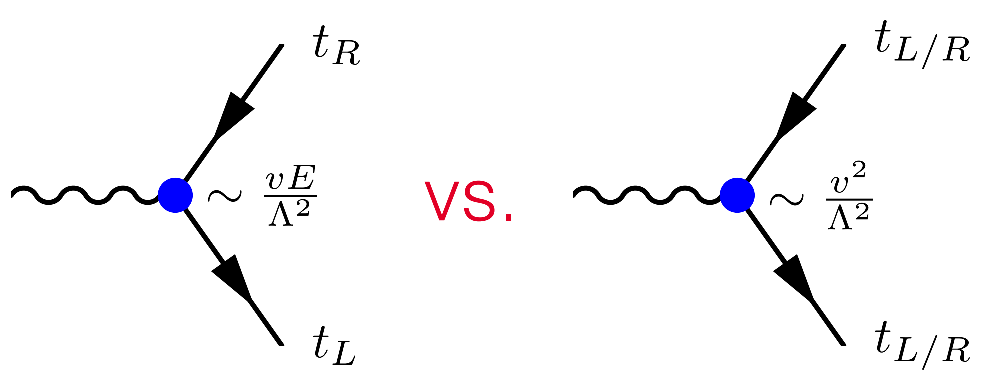
Unlike prescribed by the LHC TOP WG, the top quark chromomagnetic-dipole operator coefficient `ctG` is normalized with a factor of the strong coupling, g_S. This normalization factor temporarily ensures compatibility with the 2.X.X series of MadGraph5_aMC@NLO but may be dropped in the future. As with 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
```

Top couplings via Higgs







- Significant effects on individual observable sensitivities, e.g., tZ
- Loop-induced processes bring new constraints ($h \to \gamma\gamma/\gamma Z$)