SMEFT in the light of recent Higgs measurements

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Outline

* Operator sets and their impact on Higgs observables
* Connection between the Higgs and top sectors in SMEFT
* Impact of Higgs measurements on recent global fit results
* Impact of theory variations in global fits

SMEFT operators

Bosonic

$\mathcal{O}_{\phi G}$	OpG	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right) G_A^{\mu\nu}\, G^A_{\mu\nu}$	$\mathcal{O}_{\phi B}$	OpB	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$
$\mathcal{O}_{\phi W}$	OpW	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}_{\phi WB}$	OpWB	$(\phi^\dagger\tau_I\phi)\, B^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{\phi d}$	Opd	$\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$	$\mathcal{O}_{\phi D}$	OpD	$(\phi^\dagger D^\mu\phi)^\dagger(\phi^\dagger D_\mu\phi)$

2-fermion

$\mathcal{O}_{t\varphi}$	Otp	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, t\, \tilde{\phi} + \text{h.c.}$	$\mathcal{O}_{tG}$	OtG	$igs\,(\bar{Q}\tau^{\mu\nu}\, T_A\, t)\, \tilde{\phi}\, G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{b\varphi}$	Obp	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, b\, \phi + \text{h.c.}$	$\mathcal{O}_{c\varphi}$	Ocp	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, c\, \phi + \text{h.c.}$
$\mathcal{O}_{\tau\varphi}$	Otap	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, \tau\, \tilde{\phi} + \text{h.c.}$	$\mathcal{O}_{tW}$	OtW	$i(\bar{Q}\tau^{\mu\nu}\, \tau_I\, t)\, \tilde{\phi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tB}$	-	$i(\bar{Q}\tau^{\mu\nu}\, t)\, \tilde{\phi}\, B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{tZ}$	OtZ	$-\sin\theta_W \mathcal{O}_{tB} + \cos\theta_W \mathcal{O}_{tW}$
$\mathcal{O}^{(1)}_{\varphi l_1}$	Opl1	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{l}_1\, \gamma^\mu\, l_1)$	$\mathcal{O}^{(3)}_{\varphi l_1}$	O3pl1	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{l}_1\, \gamma^\mu\, \tau^I l_1)$
$\mathcal{O}^{(1)}_{\varphi l_2}$	Opl2	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{l}_2\, \gamma^\mu\, l_2)$	$\mathcal{O}^{(3)}_{\varphi l_2}$	O3pl2	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{l}_2\, \gamma^\mu\, \tau^I l_2)$
$\mathcal{O}^{(1)}_{\varphi l_3}$	Opl3	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{l}_3\, \gamma^\mu\, l_3)$	$\mathcal{O}^{(3)}_{\varphi l_3}$	O3pl3	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{l}_3\, \gamma^\mu\, \tau^I l_3)$
$\mathcal{O}_{\varphi e}$	Ope	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{e}\, \gamma^\mu\, e)$	$\mathcal{O}_{\varphi\mu}$	Opmu	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{\mu}\, \gamma^\mu\, \mu)$
$\mathcal{O}_{\varphi\tau}$	Opta	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{\tau}\, \gamma^\mu\, \tau)$			
$\mathcal{O}^{(1)}_{\varphi q_i}$	-	$\sum_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{q}_i\, \gamma^\mu\, q_i)$	$\mathcal{O}^{(3)}_{\varphi q_i}$	O3pq	$\sum_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{q}_i\, \gamma^\mu\, \tau^I q_i)$
$\mathcal{O}^{(1)}_{\varphi Q}$	-	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{Q}\, \gamma^\mu\, Q)$	$\mathcal{O}^{(3)}_{\varphi Q}$	O3pQ3	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{Q}\, \gamma^\mu\, \tau^I Q)$
$\mathcal{O}^{(-)}_{\varphi q_i}$	OpqMi	$\mathcal{O}^{(1)}_{\varphi q_i} - \mathcal{O}^{(3)}_{\varphi q_i}$	$\mathcal{O}^{(-)}_{\varphi Q}$	OpQM	$\mathcal{O}^{(1)}_{\varphi Q} - \mathcal{O}^{(3)}_{\varphi Q}$
$\mathcal{O}_{\varphi u_i}$	Opui	$\sum_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{u}_i\, \gamma^\mu\, u_i)$	$\mathcal{O}_{\varphi d_i}$	Opdi	$\sum_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{d}_i\, \gamma^\mu\, d_i)$
$\mathcal{O}_{\phi t}$	Opt	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{t}\, \gamma^\mu\, t)$			
$\mathcal{O}_{ll}$	Oll	$(l\gamma_\mu l)(l\gamma^\mu l)$			

4-quark (involving top-quarks)

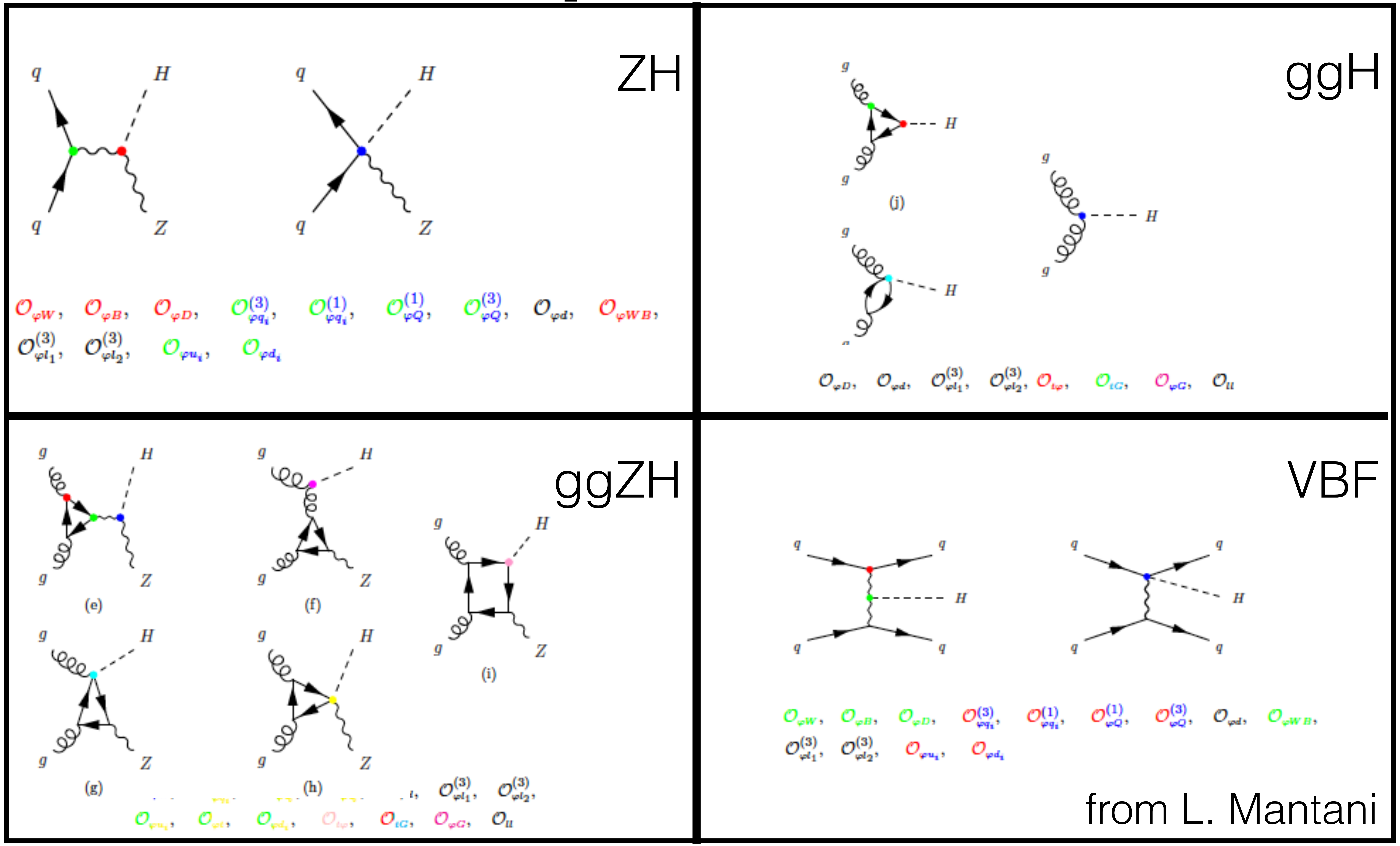
$O^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$	$O^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i)$
$O^{3,8}_{Qq} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i)$	$O^{3,1}_{Qq} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i)$
$O^{8}_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i)$	$O^{1}_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i)$
$O^{8}_{td} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i)$	$O^{1}_{td} = (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)$;
$O^{8}_{Qu} = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i\gamma_\mu T^A u_i)$	$O^{1}_{Qu} = (\bar{Q}\gamma^\mu Q)(\bar{u}_i\gamma_\mu u_i)$
$O^{8}_{Qd} = (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i\gamma_\mu T^A d_i)$	$O^{1}_{Qd} = (\bar{Q}\gamma^\mu Q)(\bar{d}_i\gamma_\mu d_i)$
$O^{8}_{tq} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$	$O^{1}_{tq} = (\bar{q}_i\gamma^\mu q_i)(\bar{t}\gamma_\mu t)$;

4-quark operators entering tt,ttH,ttV

Typical flavour scenarios:

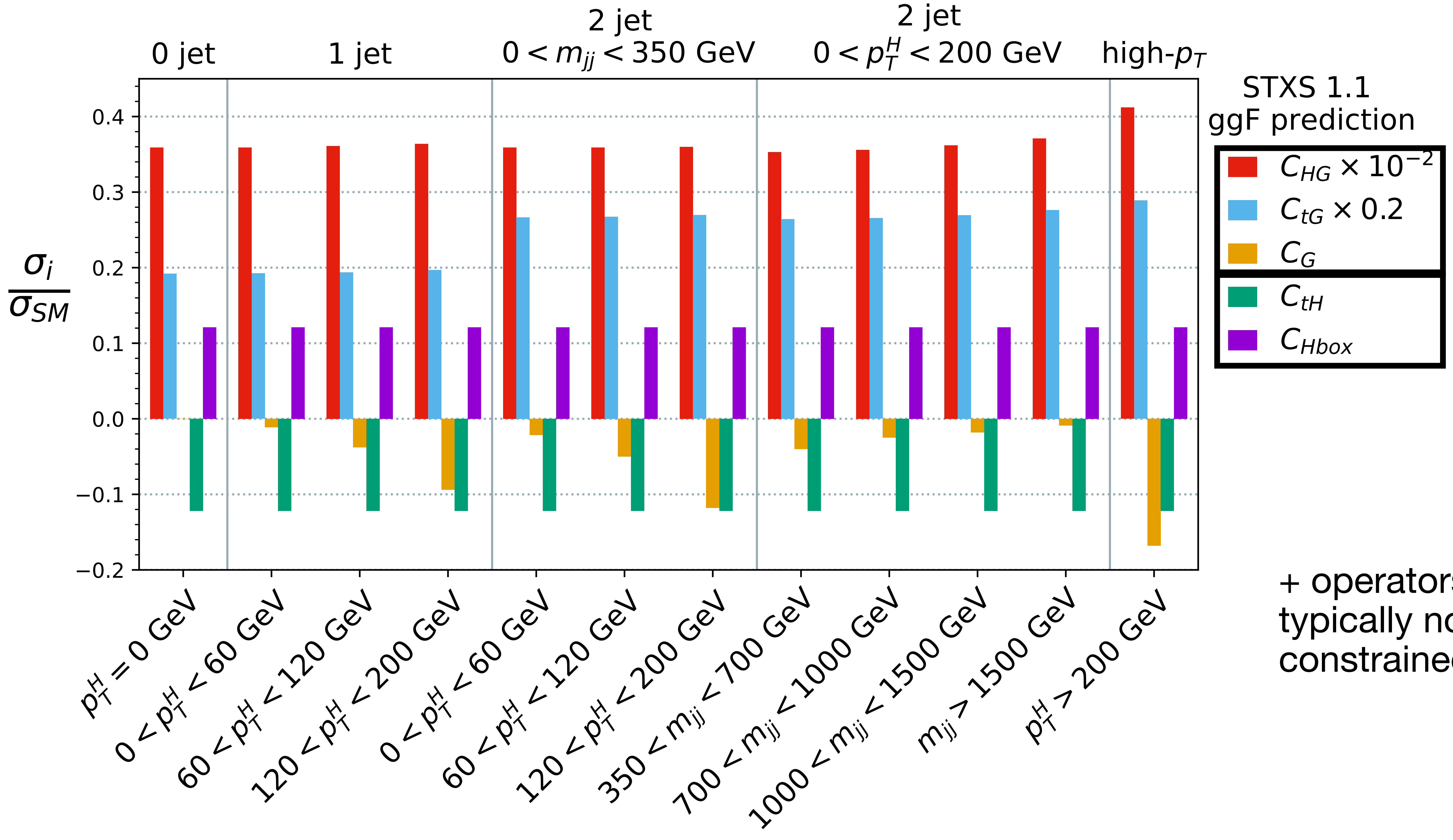
- Flavour Universal
  - $U(3)_L$ x $U(3)_e$ x $U(3)_Q$ x $U(3)_u$ x $U(3)_d$
- Singling out the top (arXiv:1802.07237)
  - $U(3)_L$ x $U(3)_e$ x $U(2)_Q$ x $U(2)_u$ x $U(3)_d$

How do all these operators enter?



Impact of operators on STXS bins

Example: Gluon fusion



Harder tails

Simple rescalings

+ operators which change input parameters, typically not so interesting for Higgs, constrained from EWPO

Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Top-Higgs interplay beyond ggH

Top EW couplings

$$O_{\varphi Q}^{(3)} = \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

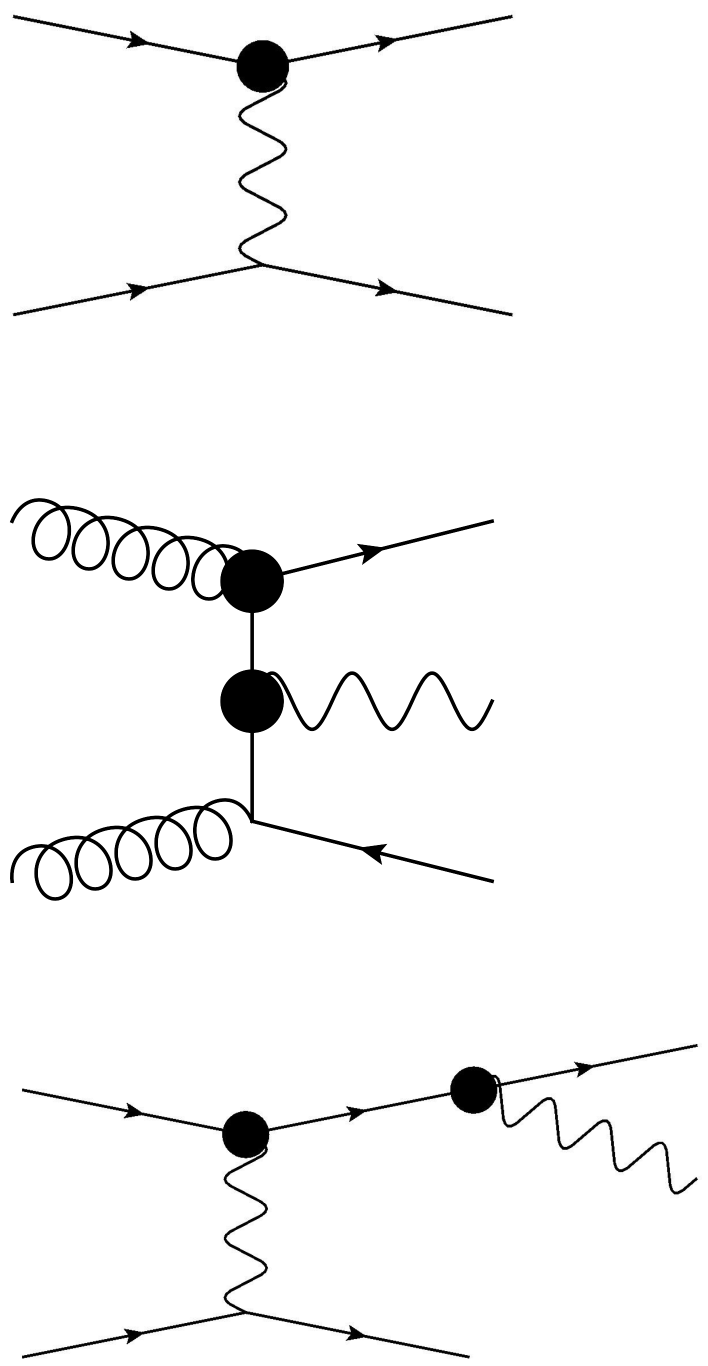
$$O_{\varphi Q}^{(1)} = \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

$$O_{\varphi t} = \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

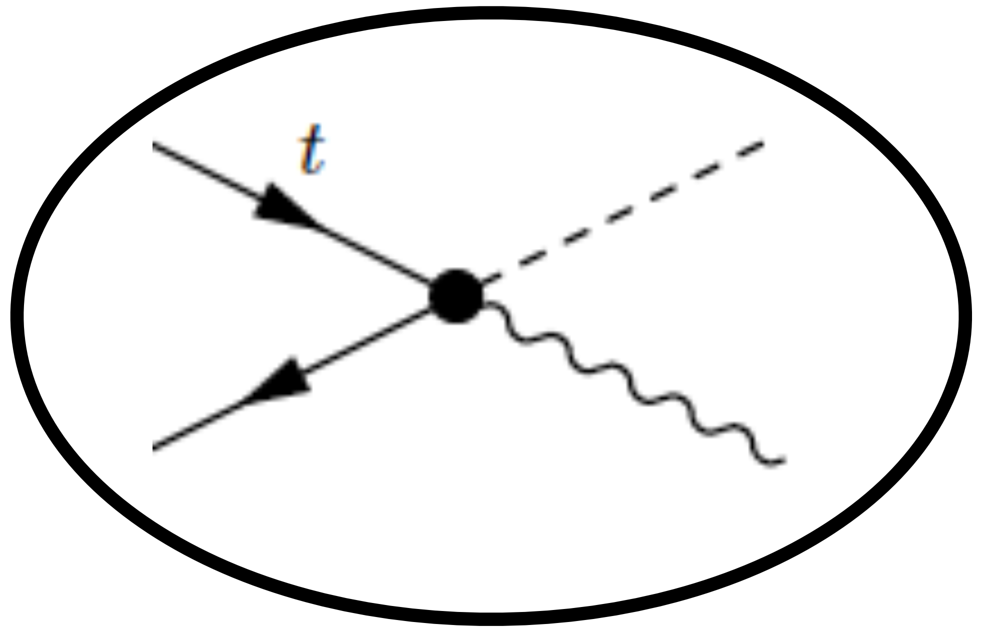
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

Typically searched for in



Also relevant for:



New Higgs interactions

relevant for tHj, gg>HZ
gg>ZZ, H>Zγ

Constraints from top fits are not very stringent

A clear motivation for top+Higgs fits

Extended top-Higgs interplay

Operators

$$O_{\varphi Q}^{(3)} = \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O_{\varphi Q}^{(1)} = \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

$$O_{\varphi t} = \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

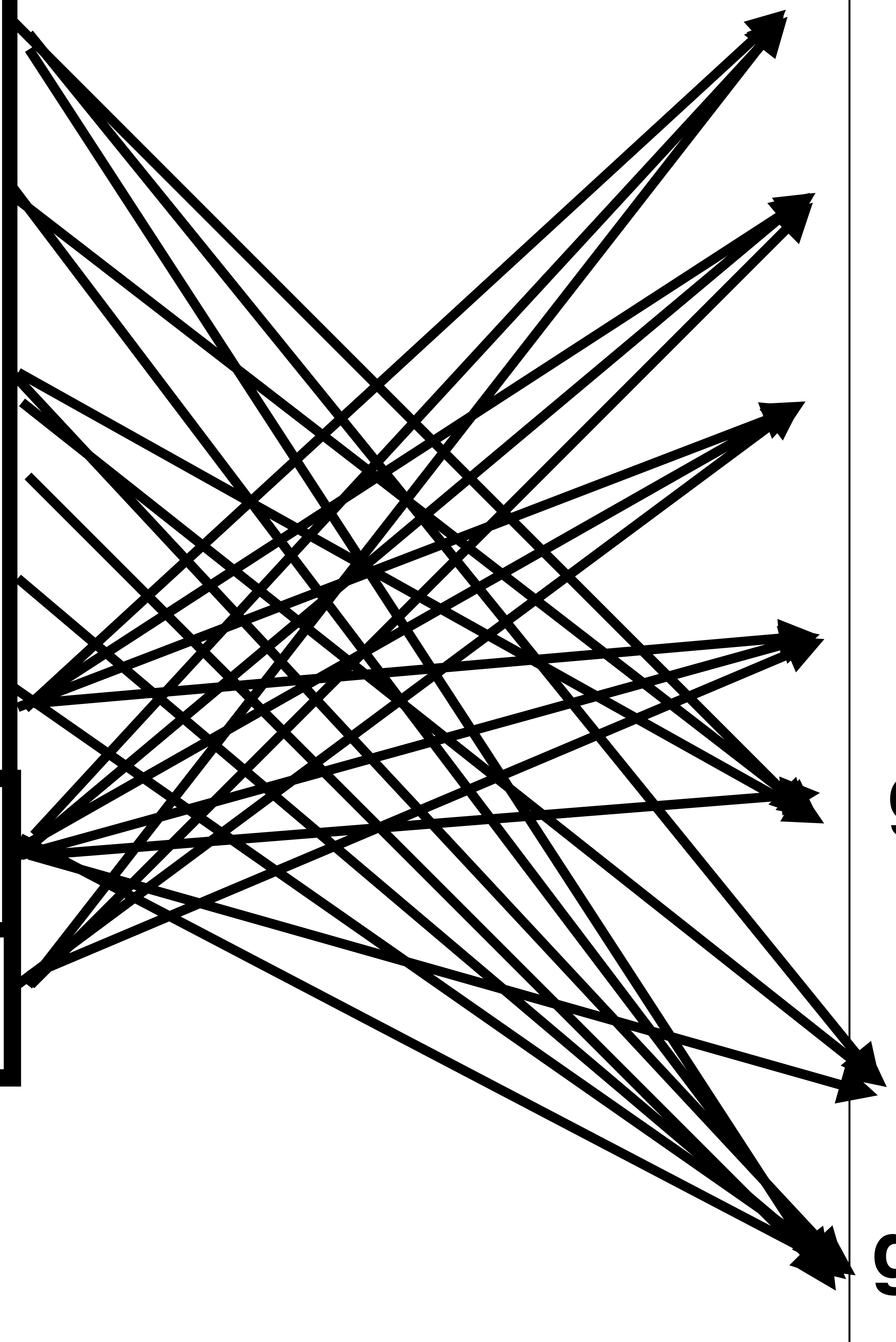
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$O_{t\phi} = \left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}$$

$$O_{\phi G} = \left(\phi^\dagger\phi\right)G^A_{\mu\nu}G^{A\mu\nu}$$



Production process

gg → h

gg → hj

tth

gg → hh

gg → hz

thj

gg → ZZ

Top-Higgs are deeply connected: Global Higgs-top fits needed

SMEFT global fits

What is currently used?

SMEFit

Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_CMS_SSinc_RunI (*)	**7+8 TeV, 20 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, VV, \tau\tau, b\bar{b}$	20	[114]
ATLAS_SSinc_RunI (*)	**8 TeV, 20 fb^{-1}**	Incl. μ_i^f	$h \to Z\gamma, \mu\mu$	2	[115]
ATLAS_SSinc_RunII (*)	**13 TeV, 80 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	16	[116]
CMS_SSinc_RunII (*)	**13 TeV, 36.9 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Wh, Zh $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	24	[117]
CMS_H_13TeV_2015 (*)	**13 TeV, 35.9 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ, \gamma\gamma, b\bar{b}$	$d\sigma/dp_T^h$	9	[121]
ATLAS_ggF_13TeV_2015 (*)	**13 TeV, 36.1 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ(\to 4l)$	$d\sigma/dp_T^h$	9	[122]
ATLAS_Vh_hbb_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	Wh, Zh	$d\sigma^{(\rm fid)}/dp_T^W$ $d\sigma^{(\rm fid)}/dp_T^Z$	2 3	[123]
ATLAS_ggF_ZZ_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	ggF, $h \to ZZ$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[116]
CMS_ggF_aa_13TeV (*)	**13 TeV, 77.4 fb^{-1}**	ggF, $h \to \gamma\gamma$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[124]

Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

FitMaker

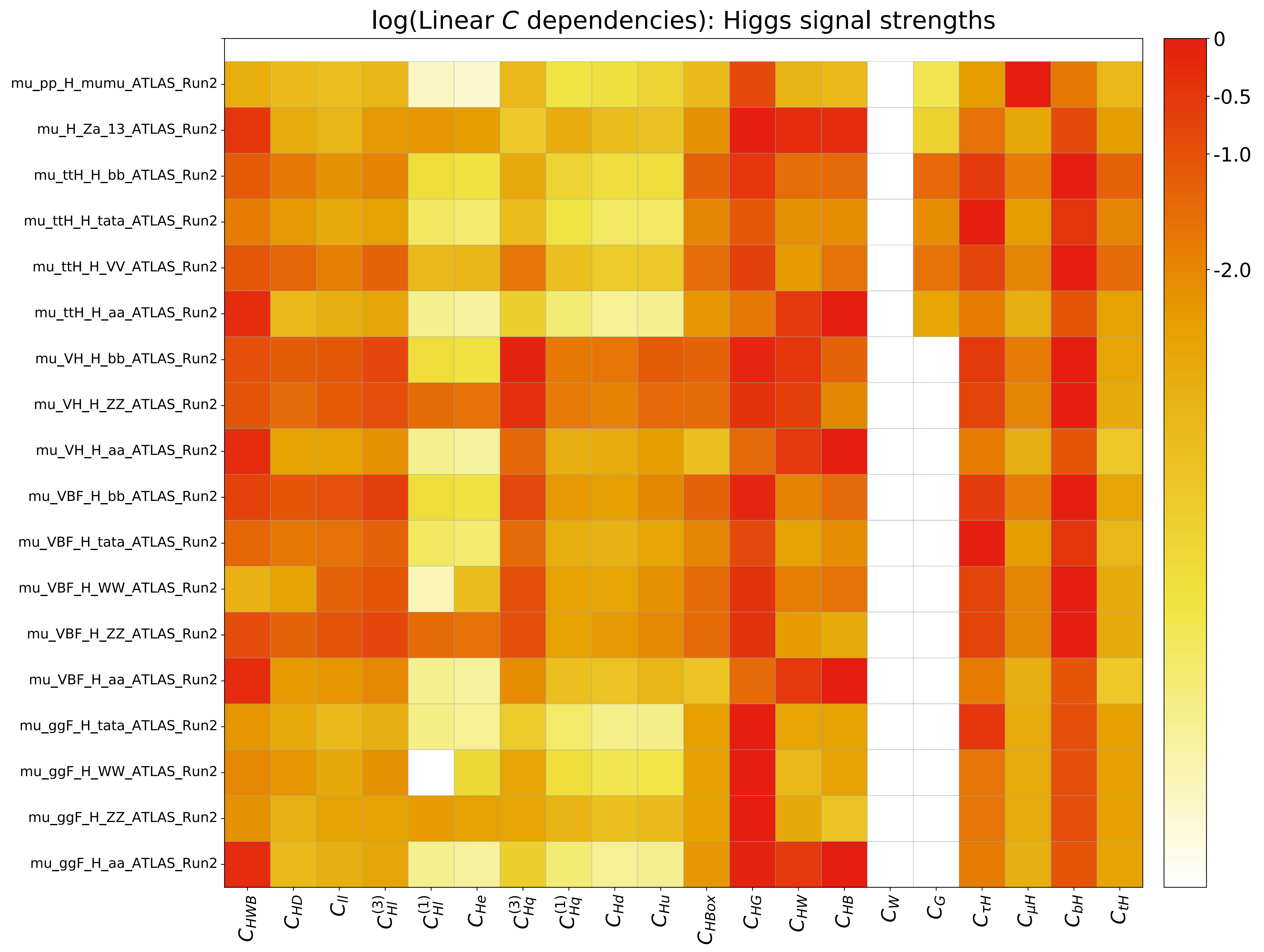
LHC Run 1 Higgs	$n_{\rm obs}$	**Ref.**
ATLAS and CMS LHC Run 1 combination of Higgs signal strengths. Production: ggF, VBF, ZH, WH & ttH Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ & $b\bar{b}$	21	[8]
ATLAS inclusive $Z\gamma$ signal strength measurement	1	[9]

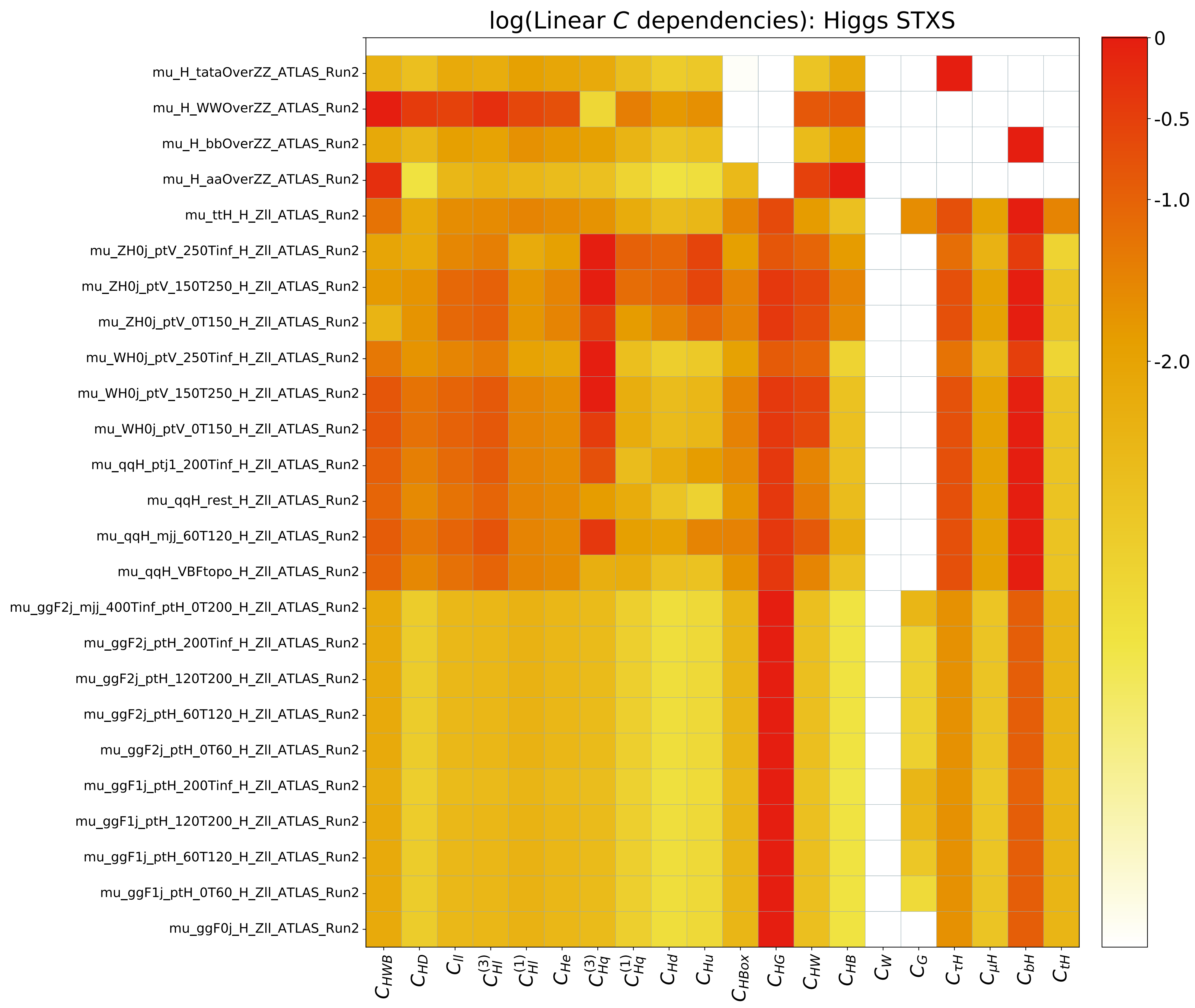
LHC Run 2 Higgs (new)	$n_{\rm obs}$	**Ref.**
ATLAS combination of signal strengths and stage 1.0 STXS in $H \to 4\ell$ including ratios of branching fractions to $\gamma\gamma$, WW^*, $\tau^+\tau^-$ & $b\bar{b}$ Signal strengths|coarse STXS bins| fine STXS bins	16|19|25	[10]
CMS LHC combination of Higgs signal strengths. Production: ggF, VBF, ZH, WH & ttH Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, $b\bar{b}$ & $\mu^+\mu^-$	23	[11]
CMS stage 1.0 STXS measurements for $H \to \gamma\gamma$. 13 parameter fit | 7 parameter fit	13|7	[12]
CMS stage 1.0 STXS measurements for $H \to \tau^+\tau^-$	9	[13]
CMS stage 1.1 STXS measurements for $H \to 4\ell$	19	[14]
CMS differential cross section measurements of inclusive Higgs production in the $WW^* \to \ell\nu\ell\nu$ final state. $\frac{d\sigma}{dn_{\rm jet}}$ | $\frac{d\sigma}{dp_H^T}$	5|6	[15]
ATLAS $H \to Z\gamma$ signal strength.	1	[16]
ATLAS $H \to \mu^+\mu^-$ signal strength.	1	[17]

Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Dependence of predictions on operators

How to quantify the sensitivity to operators?

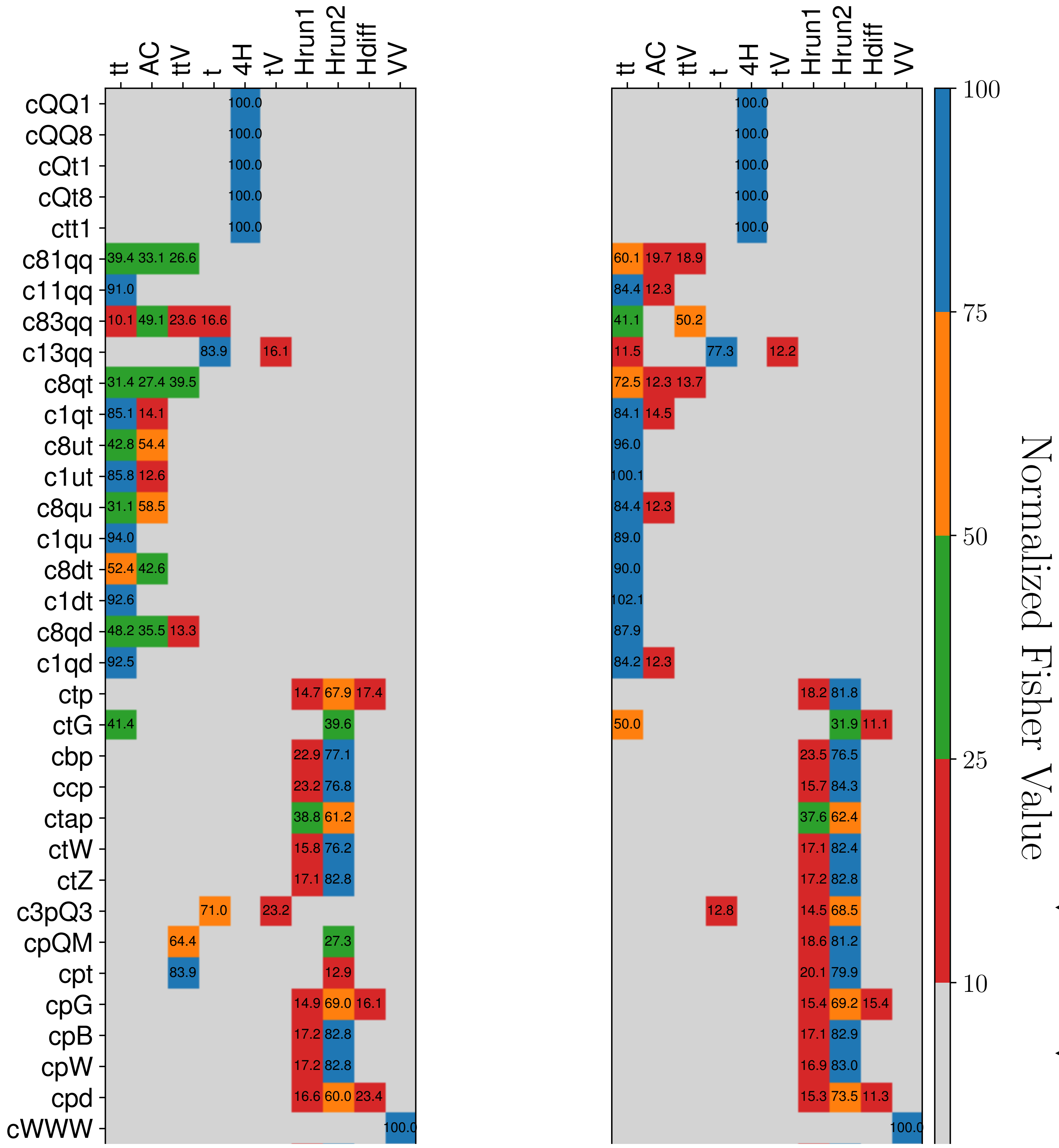




$$\mu_X \equiv \frac{X}{X_{SM}} = 1 + \sum_i a_i^X \frac{C_i}{\Lambda^2}$$

Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Where is most information coming from?

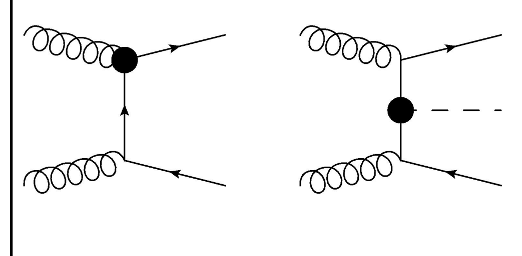
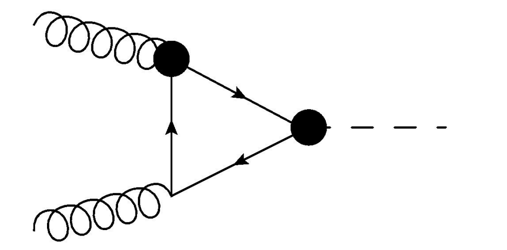
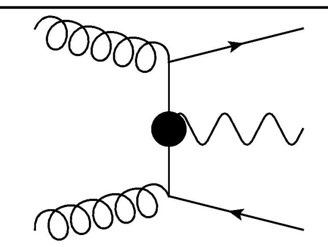
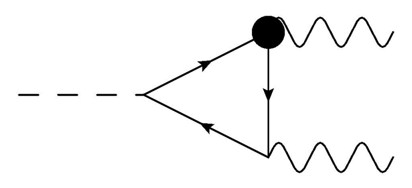


4F mostly top

bottom, charm, tau Yukawa

ggH contact interaction

rescaling of H interactions

	Tree	Loop
Top Yukawa Top Chromomagnetic		
ttV couplings		

HVV: VH, VBF, H->4l

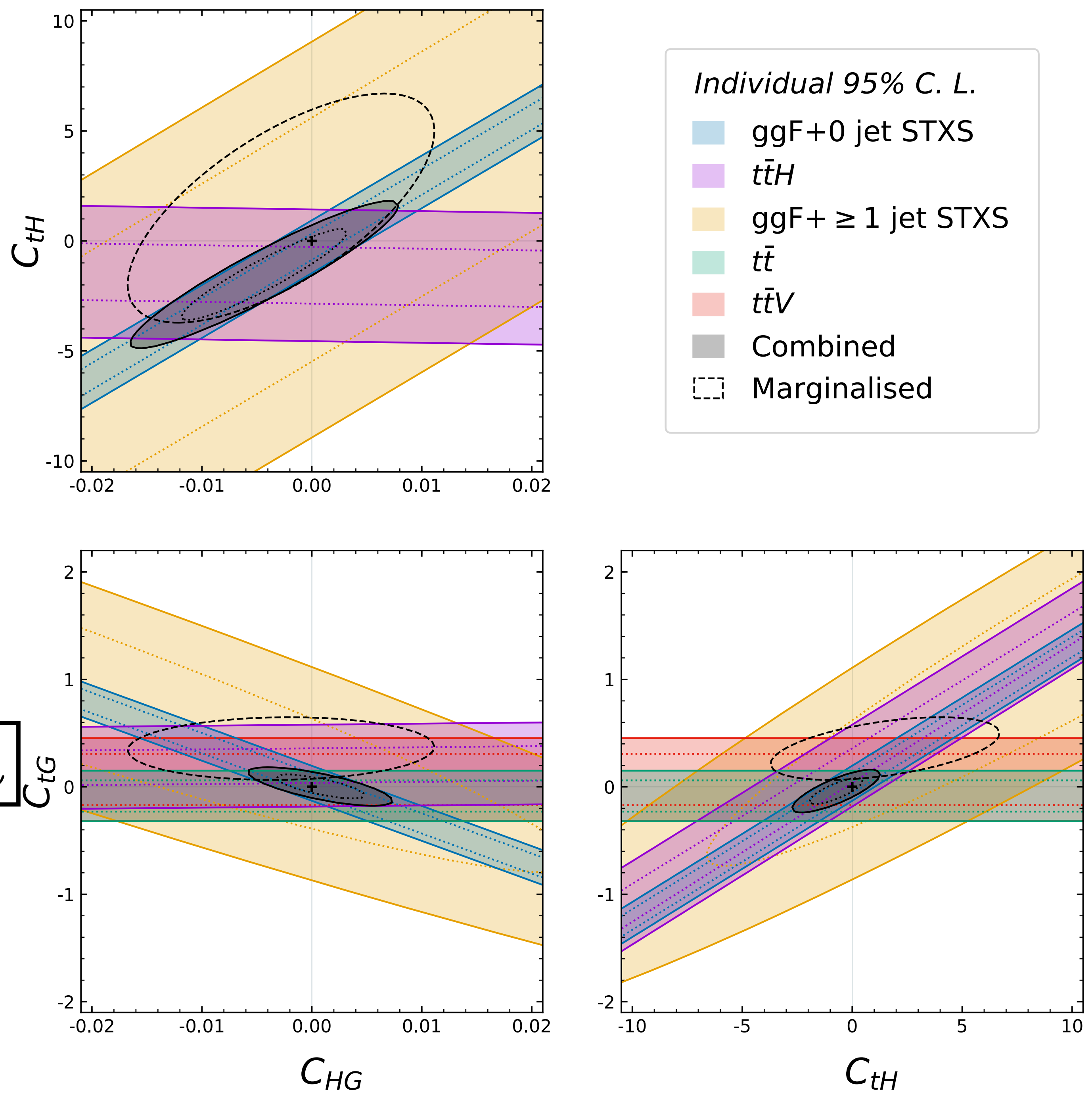
Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Fisher information table: takes into account the experimental precision

Higgs and top interplay

$\left(\varphi^{\dagger}\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$

$(\bar{Q}\tau^{\mu\nu}\,T_{A}\,t)\,\tilde{\varphi}\,G^{A}_{\mu\nu}$



$\left(\varphi^{\dagger}\varphi\right)G^{\mu\nu}_{A}\,G^{A}_{\mu\nu}$ $\left(\varphi^{\dagger}\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$

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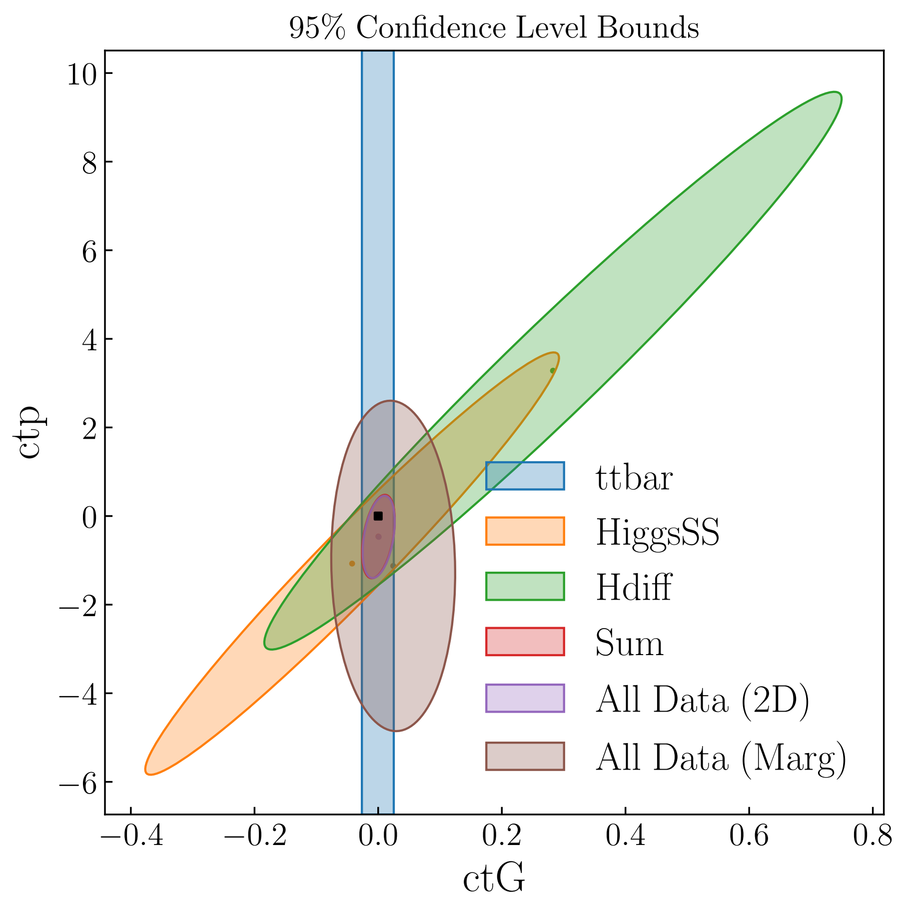
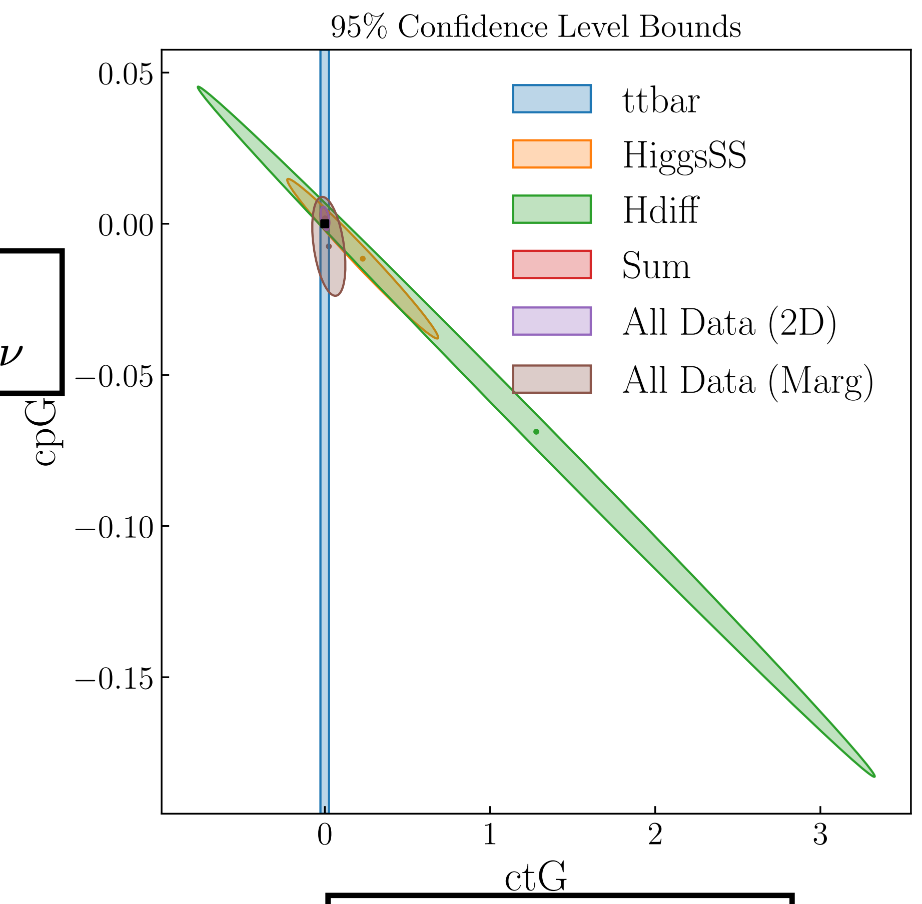
$\left(\varphi^{\dagger}\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$



$\left(\varphi^{\dagger}\varphi\right)G^{\mu\nu}_{A}\,G^{A}_{\mu\nu}$

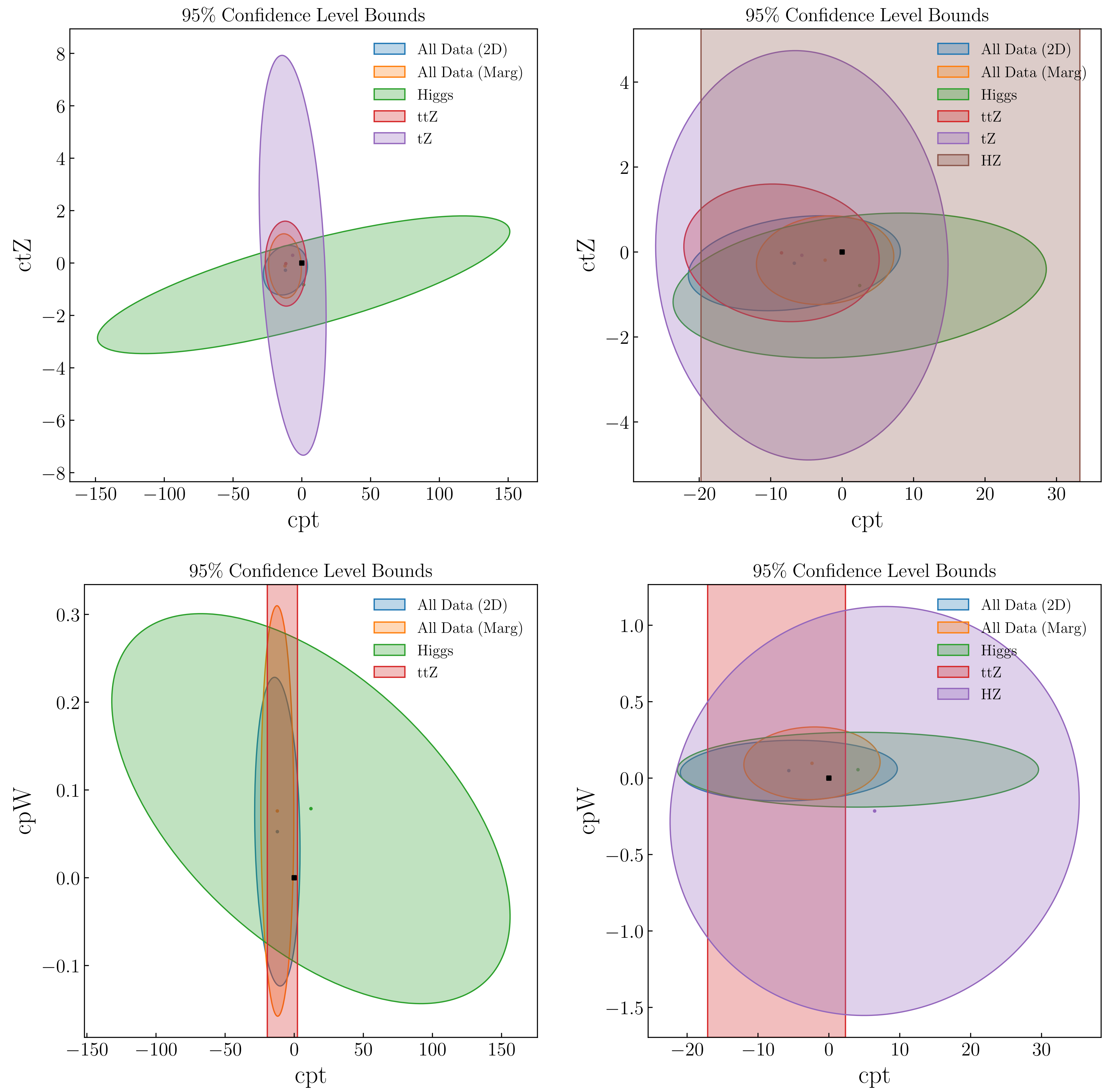


$(\bar{Q}\tau^{\mu\nu}\,T_{A}\,t)\,\tilde{\varphi}\,G^{A}_{\mu\nu}$

Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Top-Higgs measurements break the degeneracy between operators

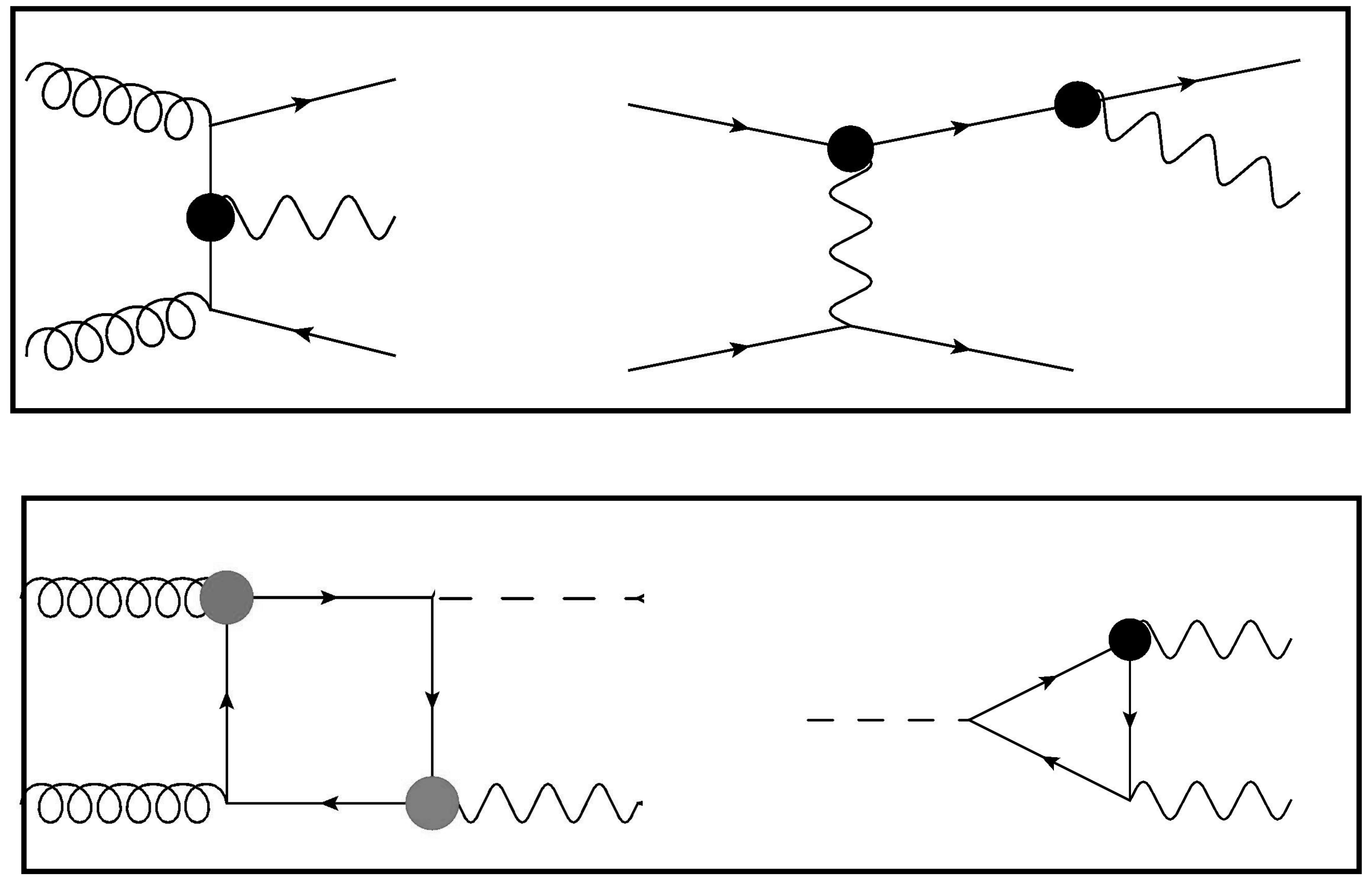
Breaking degeneracies using loops



LO

NLO

(adding HZ and NLO corrections)



$\mathcal{O}_{\varphi t}$	cpt	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, t\big)$
$\mathcal{O}_{\varphi W}$	cpW	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$
$\mathcal{O}_{tW}$	-	$i\big(\bar{Q}\tau^{\mu\nu}\,\tau_I\, t\big)\,\tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tB}$	-	$i\big(\bar{Q}\tau^{\mu\nu}\, t\big)\,\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$

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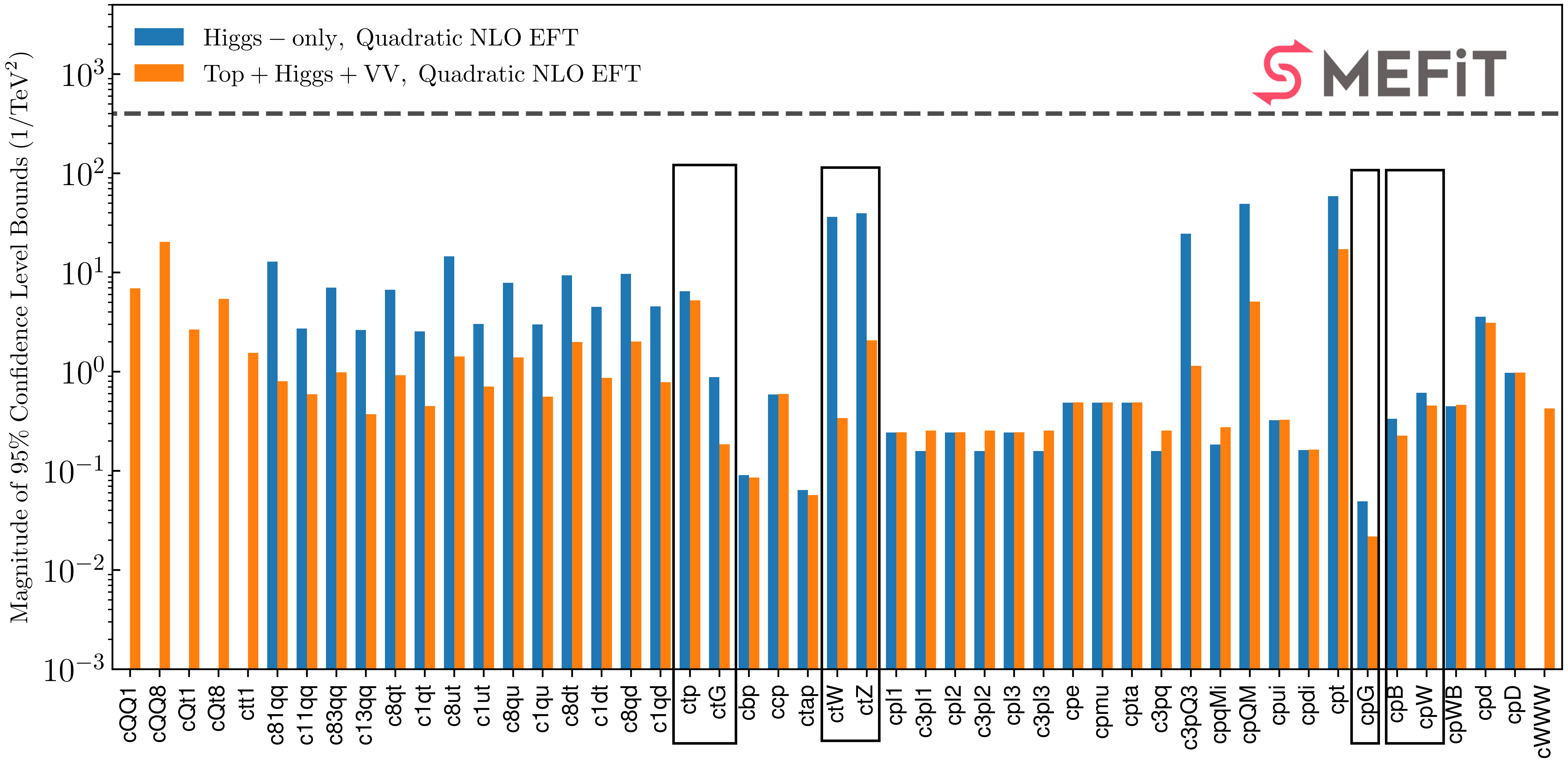
Higgs vs global fit

What happens if we try to fit everything with Higgs?



4F unconstrained

ttV couplings poorly constructed

Chromomagnetic, ggh & Yukawa need input from top

HVV operators not affected

Combination of top and Higgs needed

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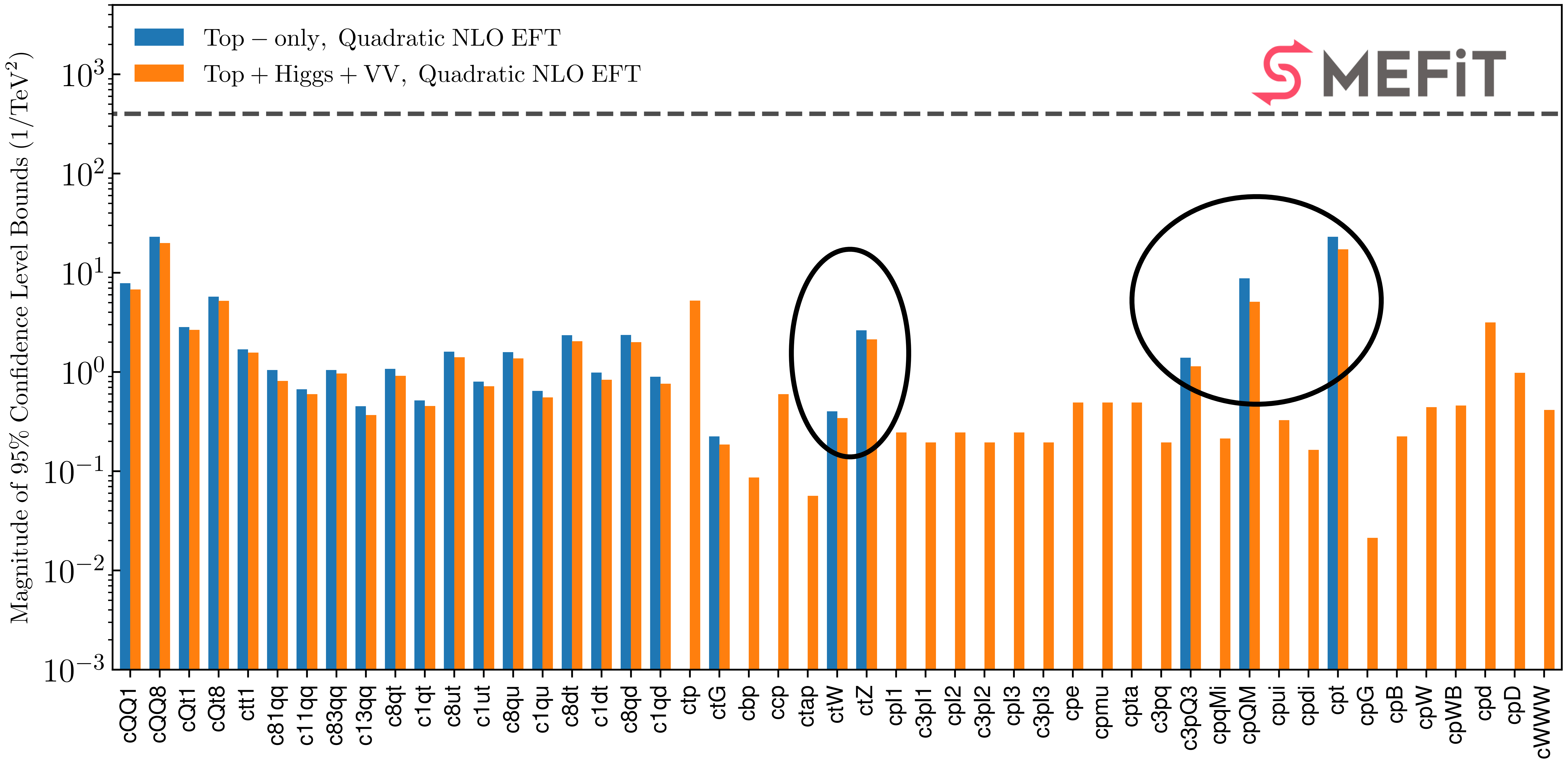
Global fit results

Top vs Global Fit



Higgs data improves certain top operator bounds

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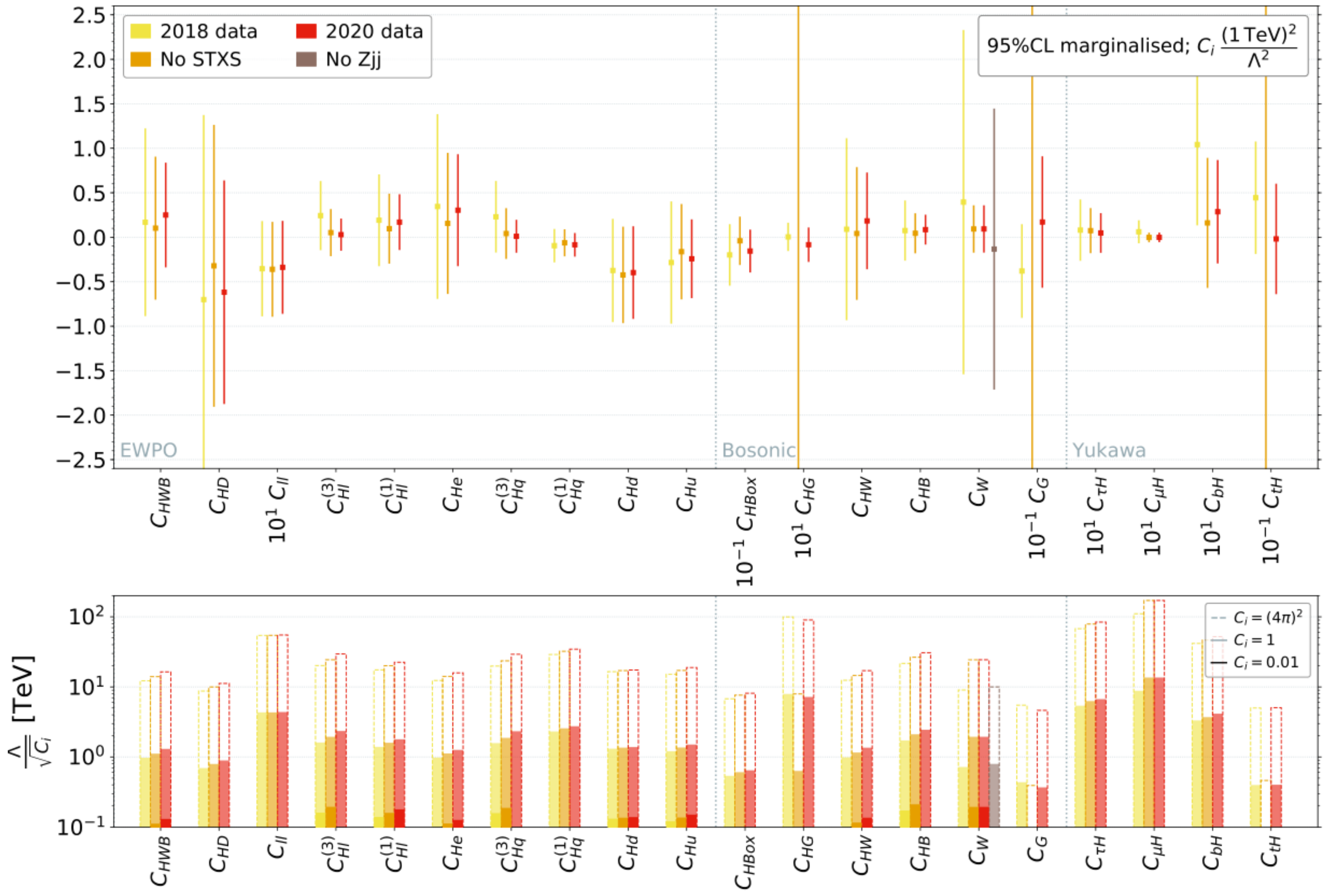
Impact of STXS measurements

Where do Higgs differential measurements help?



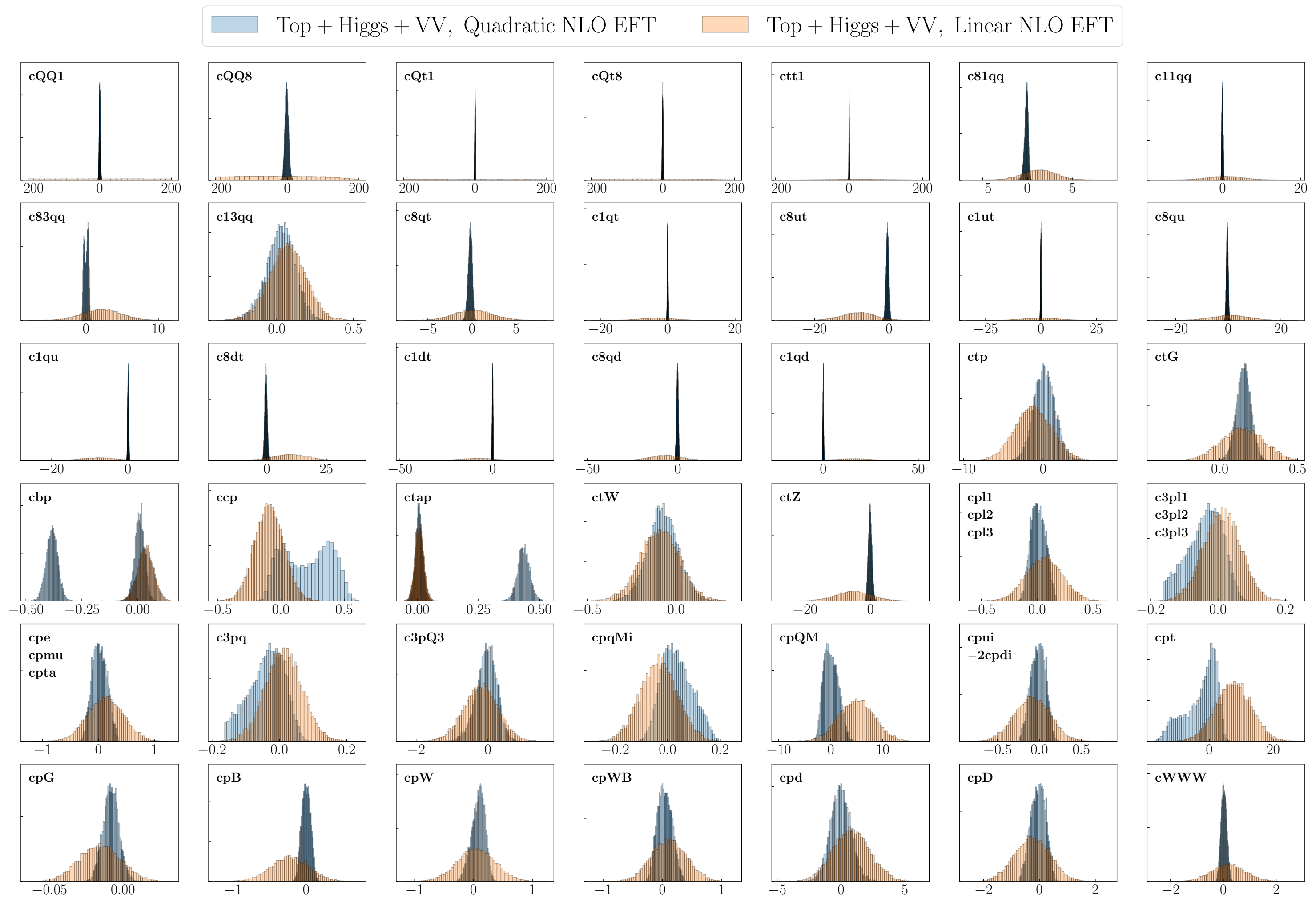
Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

STXS crucial for disentangling:

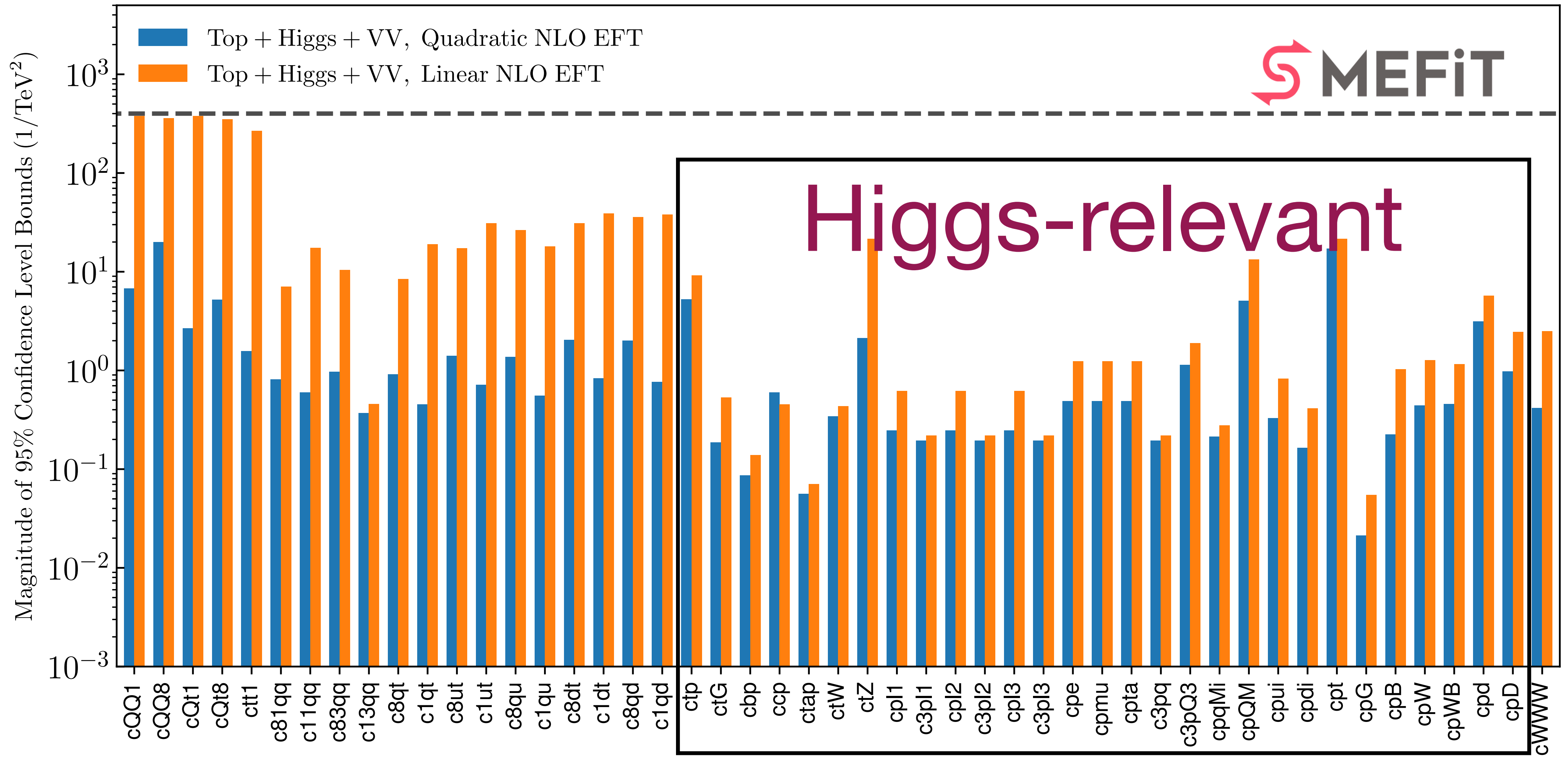
ggH and Yukawa operators

Impact of quadratic terms in global fits

* Higher Orders in $1/\Lambda^4$
    * squared dim-6 contributions



Posterior distributions

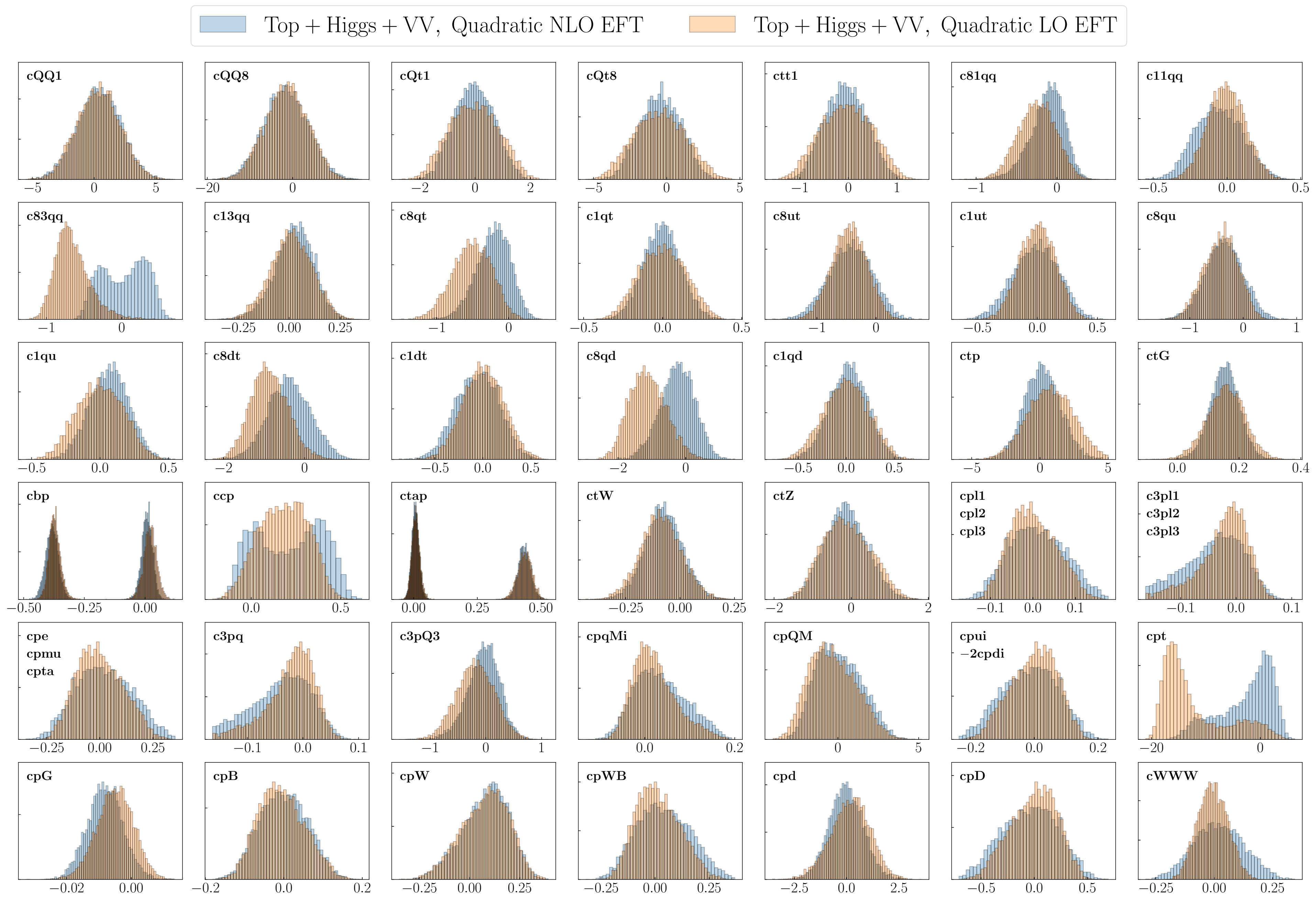


Significant impact for most operators
in particular 4-fermion operators

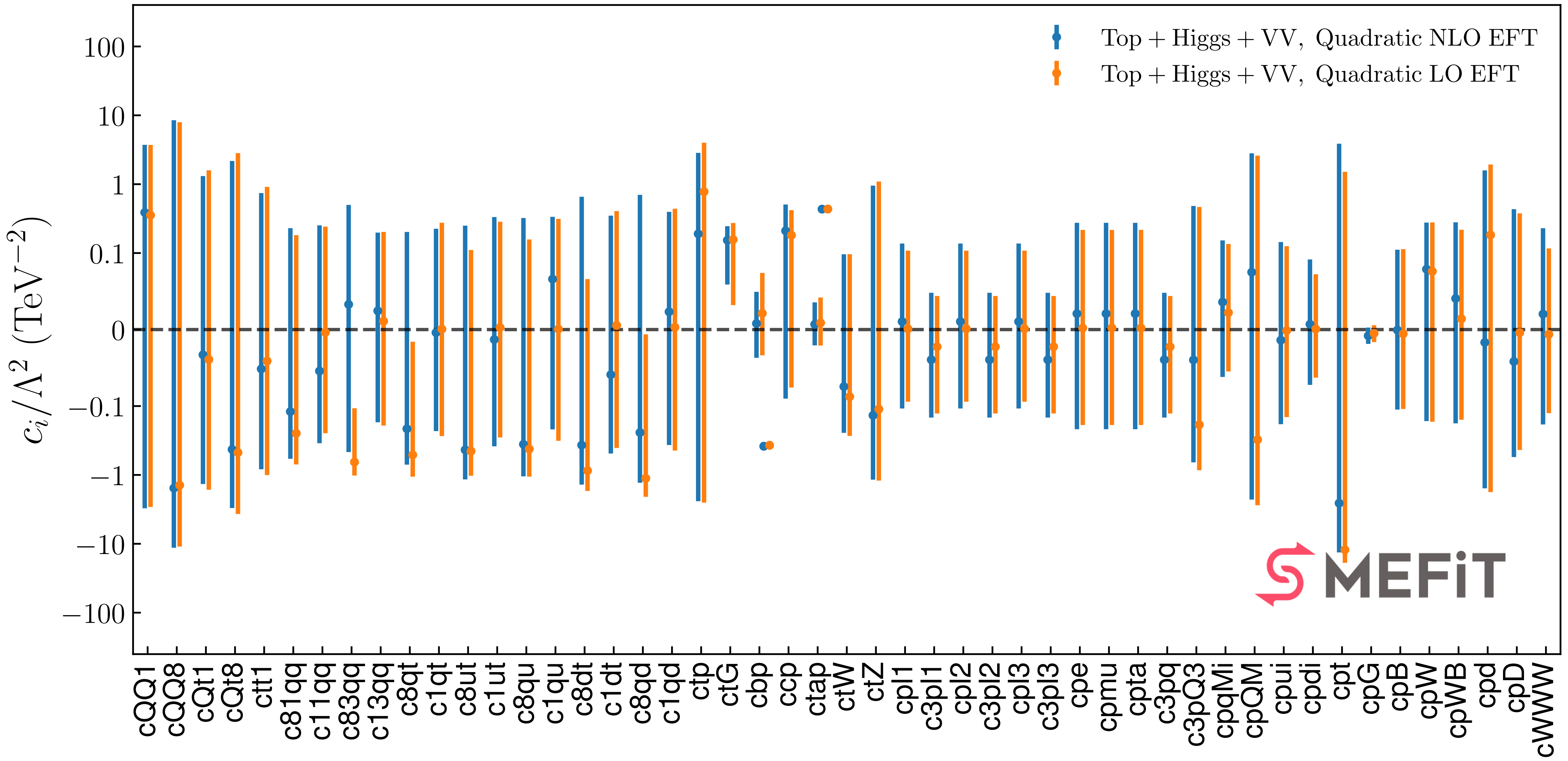
Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Impact of NLO corrections

Quadratic fits:



Posterior distributions



Significant impact of NLO for some operators

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Future prospects

* Use more data: Several full Run II analyses not included in fits yet
    * Other measurements beyond SS and STXS?
* Explore more 1-loop dependences
* Add more processes: e.g. off-shell Higgs, di-Higgs