Four top quark production in SMEFT

[2208.04962]

in collaboration with
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TOP2022, Durham, Sep 6^{th}, 2022

Introduction to $t\bar{t}t\bar{t}$

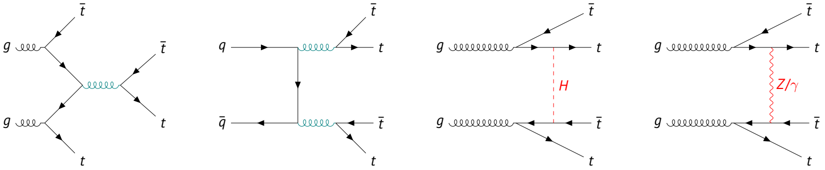
- Rare processes with distinctive signatures
- Firstly computed at **NLO in QCD** in [1206.3064]
- Available in event generators [1405.0301] [1507.05640] [2110.15159]
- **Complete NLO including EW** were computed in [1711.02116] $\rightarrow$ $\sigma^{SM}_{NLO} \sim 12$ fb $\pm 20\%$ at $\sqrt{s} = 13$ TeV
- Experiment; ATLAS: 24^{+7}_{-6} fb, CMS: $12.6^{+5.8}_{-5.2}$ fb, with evidence of 4.7σ by ATLAS

see also talks by Jan van der Linden and Melissa van Beekveld

Introduction to $t\bar{t}t\bar{t}$

[1602.01934][1711.02116][2008.11743][2010.05915]

In the SM, the EW scattering is important, however, there are large cancellations in interfering with purely-QCD ones



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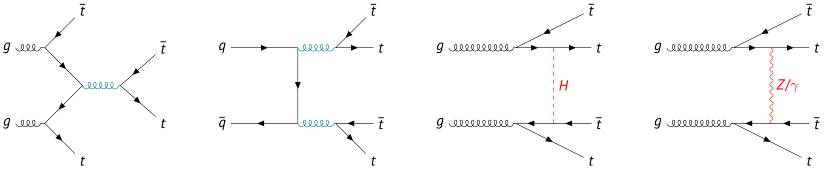
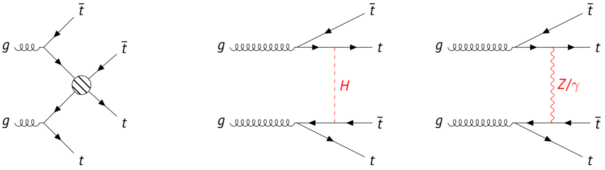


In SMEFT, the EFT interference with the SM EW amplitudes can not be neglected, e.g.



What did we do?

Considered **all** QCD and EW-induced, splitting to α and κ_t, e.g.

$$d\sigma_{\text{int},gg,[4F]} = \alpha_s^3\, d\sigma_{\text{int},gg}^{(3,0,0)} + \alpha_s^2 \left(\alpha\, d\sigma_{\text{int},gg}^{(2,1,0)} + \kappa_t\, d\sigma_{\text{int},gg}^{(2,0,1)} \right)$$

$$d\sigma_{\text{int},qq,[4F]} = \alpha_s^3 \cdots + \alpha_s^2 \cdots + \alpha_s^1 \cdots + \alpha_s^0 \ldots$$

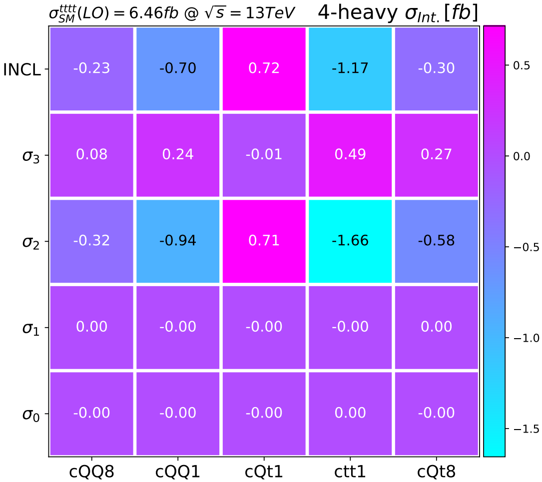
the total interference cross-section reads

$$\sigma_{INCL} = \sigma_3 + \sigma_2 + \sigma_1 + \sigma_0$$

and then systematically ...

- obtain differential and inclusive predictions for all relevant SMEFT operators
- toy fit to illustrate potential bounds on the effective coefficients

An example: 4H LHC inclusive predictions



- σ_2 is dominant in **all 4-heavy** $\rightarrow$ '**non**-naive'
- Sub-leading terms dictate the sign of the interference

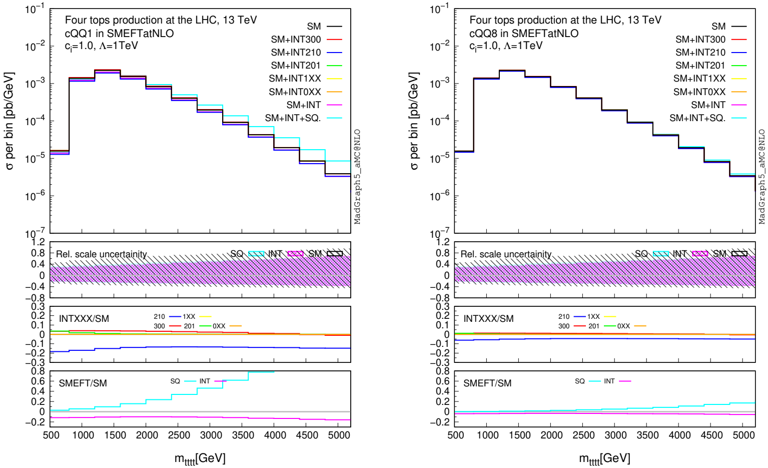
The big picture

	4H	2L2H	2F	0F
$\alpha_s = 4$	$\times$	$\times$	c_{tG}	c_G
$\alpha_s = 3$	-	$c^{83}_{Qq}, c^{8}_{Qu}, c^{8}_{tq}, c^{8}_{Qd}, c^{8}_{tu}, c^{8}_{td}, c^{81}_{Qq}$ $c^{11}_{Qq}, c^{1}_{Qu}, c^{1}_{tq}, c^{1}_{Qd}, c^{1}_{tu}, c^{1}_{td}$	$c_{t\varphi}, c_{tZ}, c_{tW}$	-
$\alpha_s = 2$	$c^{8}_{QQ}, c^{1}_{QQ}, c^{8}_{Qt}, c^{1}_{Qt}, c^{1}_{tt}$	c^{31}_{Qq}	$c_{\varphi t}, c^{(-)}_{\varphi Q}$	-
$\alpha_s = 1$	-	-	-	$c_{\varphi G}$
$\alpha_s = 0$	-	-	-	-

The set of **non-naive** operators are

$$\textit{all } \text{4-heavy} \qquad \text{and} \qquad \{\mathcal{O}^{3,1}_{Qq}, \mathcal{O}_{t\varphi}, \mathcal{O}_{tG}, \mathcal{O}^{(-)}_{\varphi Q}, \mathcal{O}_{\varphi t}, \mathcal{O}_{\varphi G}\}$$

4H LHC differential predictions



- **Z/γ contributions** are dominant → expected from the inclusive study
- Mild interference growth with $m_{tttt} \sim \sqrt{s}$

Toy fit

Goal $\rightarrow$ provide illustrative constraints on WCs

All fit results are shown in **two cases:** when including **only QCD contributions**, and when **including all terms**

- **LHC**
  - Available measurements are ATLAS: 24^{+7}_{-6} fb, CMS: $12.6^{+5.8}_{-5.2}$ fb
  - Theory prediction of 12 $\pm$20% fb [1711.02116]
- **HL-LHC**
  - We assume the measurement sits on the SM rate, within an expected total experimental uncertainty of 28% [1902.04070]
  - Assume 20% total theoretical uncertainty
- **FCC-hh**
  - Same as HL-LHC but we keep 5% total experimental uncertainty

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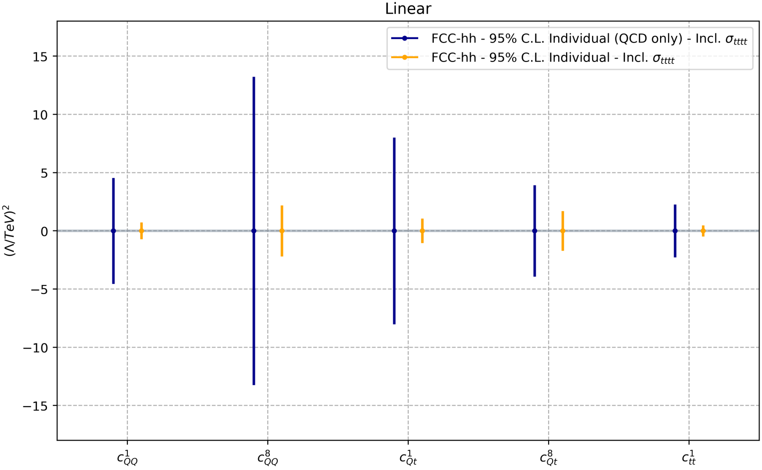
We show three different fit results assessing different aspects of four-top production ...

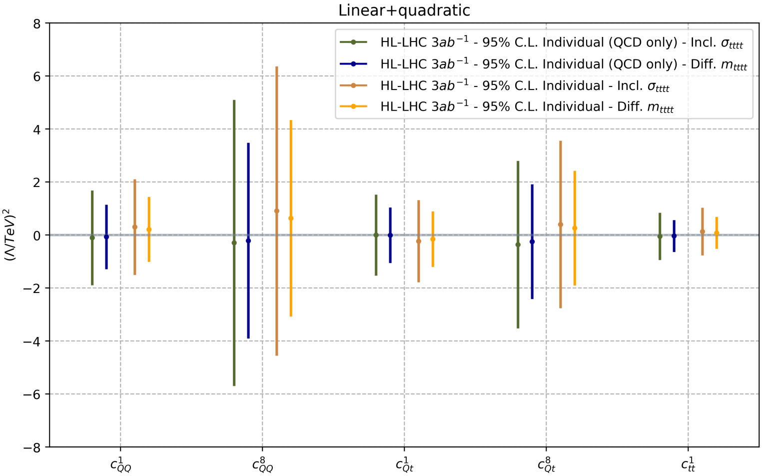
Toy fit: impact of subleading terms



At the linear interference level, the inclusion of subleading terms in 4H predictions is crucial

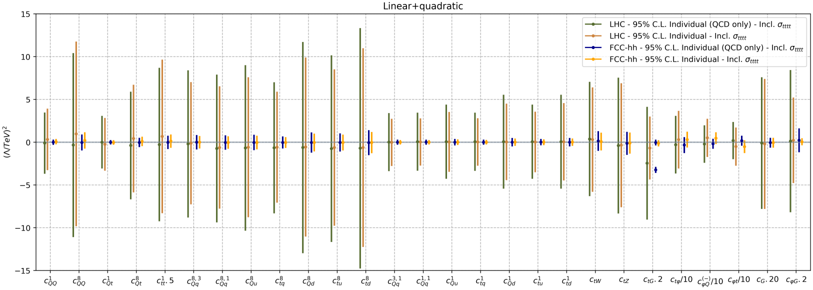
Toy fit: impact of differential information

We add information from m_{tttt} in three bins ...



differential information improves sensitivity

Toy fit: the big picture



- The effect of subleading terms in 4H is diluted by including the quadratic contributions $\rightarrow$ 4H amplitudes are QCD-induced
- $\sqrt{s} = 100$ TeV will have a strong handle on all of the operators

$t\bar{t}t\bar{t}$ summary

- The EW scattering in four-top amplitudes is crucial element of its predictions
- Computed four-top SMEFT predictions considering all QCD and EW-induced amplitudes
- We defined a set of '**non**-naive' operators for which formal subleading terms can not be neglected

$$\textit{all}\ \text{4-heavy} \qquad \text{and} \qquad \{\mathcal{O}_{Qq}^{3,1}, \mathcal{O}_{t\varphi}, \mathcal{O}_{tG}, \mathcal{O}_{\varphi Q}^{(-)}, \mathcal{O}_{\varphi t}, \mathcal{O}_{\varphi G}\}$$

- Performed a toy fit to assess the impact of subleading terms and differential information in constraining relevant effective coefficients

Backup

Operators' definitions: 4F in Warsaw basis

$$\mathcal{Q}_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$\mathcal{Q}_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$\mathcal{Q}_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$\mathcal{Q}_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$^\dagger\mathcal{Q}_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\epsilon(\bar{q}_k d_l),$$

$$\mathcal{Q}_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu \tau^I q_j)(\bar{q}_k\gamma_\mu \tau^I q_l),$$
$$\mathcal{Q}_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$\mathcal{Q}_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$\mathcal{Q}_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$^\dagger\mathcal{Q}_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\epsilon(\bar{q}_k T^A d_l),$$
$$\mathcal{Q}_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l)$$

Operators' definitions: 2F and 0F in top-basis

$$\mathcal{Q}_{tB} = i\big(\bar{Q}\tau^{\mu\nu}\, t\big)\,\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.},$$

$$\mathcal{O}_{tW} = i\big(\bar{Q}\tau^{\mu\nu}\,\tau_I\, t\big)\,\tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.},$$

$$\mathcal{O}_{tZ} = -\mathcal{Q}_{tB}/\sin\theta_{\rm w},$$

$$\mathcal{O}_{tG} = ig_S\,\big(\bar{Q}\tau^{\mu\nu}\, T_A\, t\big)\,\tilde{\varphi}\, G^A_{\mu\nu} + \text{h.c.},$$

$$\mathcal{O}_{t\varphi} = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}t\tilde{\varphi} + \text{h.c.},$$

$$\mathcal{O}_{\varphi t} = i\big(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, t\big),$$

$$\mathcal{O}^{(3)}_{\varphi Q} = i\big(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu\, \tau_I\varphi\big)\big(\bar{Q}\,\gamma^\mu\, \tau^I Q\big),$$

$$\mathcal{O}^{(-)}_{\varphi Q} = i\big(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu\, \varphi\big)\big(\bar{Q}\,\gamma^\mu\, Q\big)$$

$\mathcal{Q}_{tB}$ introduced in the Warsaw basis to show the `SMEFTatNLO` rotation of the $\mathcal{O}_{tZ}$ operator; the coefficients of $\mathcal{O}_{tW}$ and $\mathcal{O}_{tZ}$ reads

$$c_{tW} = C_{tW},\; c_{tZ} = -\sin\theta_{\rm w} C_{tB} + \cos\theta_{\rm w} C_{tW}$$

$c_i \rightarrow$, $C_i \rightarrow$ Warsaw basis.

Purely bosonic operators are defined as follows:

$$\mathcal{O}_{\varphi G} = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)G^{\mu\nu}_A G^A_{\mu\nu}, \qquad \mathcal{O}_G = g_S f_{ABC} G^A_{\mu\nu} G^{B,\nu\rho} G^{C,\mu}_\rho$$

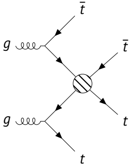
Decomposition of the SM cross-section

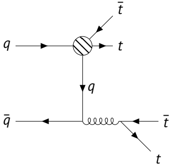
$\sqrt{s}$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^3\alpha)$	$\mathcal{O}(\alpha_s^3\alpha_t)$	$\sum_n \mathcal{O}(\alpha_s^2\alpha_{\rm w}^n)$	$\sum_n \mathcal{O}(\alpha_s\alpha_{\rm w}^n)$	$\sum_n \mathcal{O}(\alpha_{\rm w}^n)$	Inclusive
13 TeV	6.15	-1.44	-0.58	2.33	$\times$	$\times$	6.46
100 TeV	2570	-313	-197	753	$\times$	$\times$	2812

In orders of α_s and $\alpha_{\rm w} \equiv \alpha + \alpha_t$

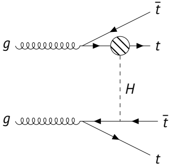
- EW contributions, i.e. $\mathcal{O}(\alpha_s^2\alpha_w^2)$, are significant, yet the interference of the corresponding amplitudes with QCD ones, i.e. $\mathcal{O}(\alpha_s^3\alpha_w)$, dilutes their effect
- Same cancellations, yet even larger, are observed at NLO in [1711.02116]

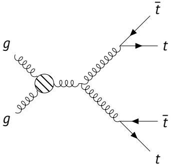
$t\bar{t}t\bar{t}$ in SMEFT: operators's insertions





Four-fermion (4F); 4-heavy (4H) and 2-heavy 2-light (2H2L)





Relevant two-fermion (2F) and purely-bosonic (0F);

$$\{\mathcal{O}_{t\varphi}, \mathcal{O}_{tZ}, \mathcal{O}_{tW}, \mathcal{O}_{tG}, \mathcal{O}_{\varphi Q}^{(-)}, \mathcal{O}_{\varphi t}, \mathcal{O}_{G}, \mathcal{O}_{\varphi G}\}$$

LO expansion

In the presence of dim-6 SMEFT operators, the scattering amplitude reads

$$\mathcal{A} = \mathcal{A}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\mathcal{A}_{(\mathrm{d6})} + \frac{1}{\Lambda^4}\left(\mathcal{A}_{(\mathrm{d6})^2} + \mathcal{A}_{(\mathrm{d8})}\right),$$

leading to the partonic differential cross-section

$$d\sigma = d\sigma_{\mathrm{SM}} + \frac{1}{\Lambda^2} d\sigma_{\mathrm{int}} + \frac{1}{\Lambda^4}\left(d\sigma_{\mathrm{quad}} + d\sigma_{\mathrm{dbl}} + d\sigma_{\mathrm{d8}}\right).$$

Lets just focus on the linear interference,

$$\begin{aligned} d\sigma_{\mathrm{int}} &= d\sigma_{\mathrm{int},gg} + d\sigma_{\mathrm{int},qq} \\ &\sim 2\Re\left(\mathcal{A}_{\mathrm{SM},gg}\,\mathcal{A}^{\dagger}_{\mathrm{EFT},gg}\right) + 2\Re\left(\mathcal{A}_{\mathrm{SM},qq}\,\mathcal{A}^{\dagger}_{\mathrm{EFT},qq}\right). \end{aligned}$$

LO expansion

Write down the SM amplitudes (skipping $q\bar{q}$-mode for simplicity),

$$\mathcal{A}^{(i,j,k)}_{\mathrm{SM},gg} = \alpha_s^2\,\mathcal{A}^{(2,0,0)}_{\mathrm{SM},gg} + \alpha_s\left(\alpha\,\mathcal{A}^{(1,1,0)}_{\mathrm{SM},gg} + \alpha_t\,\mathcal{A}^{(1,0,1)}_{\mathrm{SM},gg}\right),$$

and the EFT ones,

$$\mathcal{A}^{(i,j,k)}_{\mathrm{EFT},gg,[4F]} = \alpha_s \mathcal{A}^{(1,0,0)}_{\mathrm{EFT},gg\,[4F]}.$$

Do some work and then write the cross-section,

$$d\sigma_{\mathrm{int},gg,[4F]} = \alpha_s^3\,d\sigma^{(3,0,0)}_{\mathrm{int},gg} + \alpha_s^2\left(\alpha\,d\sigma^{(2,1,0)}_{\mathrm{int},gg} + \kappa_t\,d\sigma^{(2,0,1)}_{\mathrm{int},gg}\right),$$

The total interference (including $q\bar{q}-$mode) cross-section reads

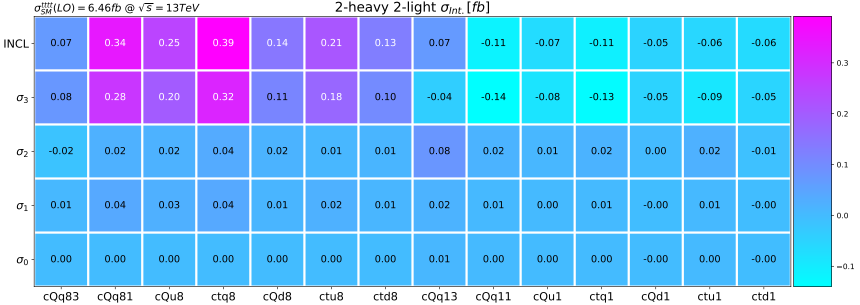
$$\sigma_{INCL} = \sigma_3 + \sigma_2 + \sigma_1 + \sigma_0,$$

where σ_3 is the cross-section induced from all terms with α_s^3, etc.

$q\bar{q}$-initiated σ_{int} in 4F

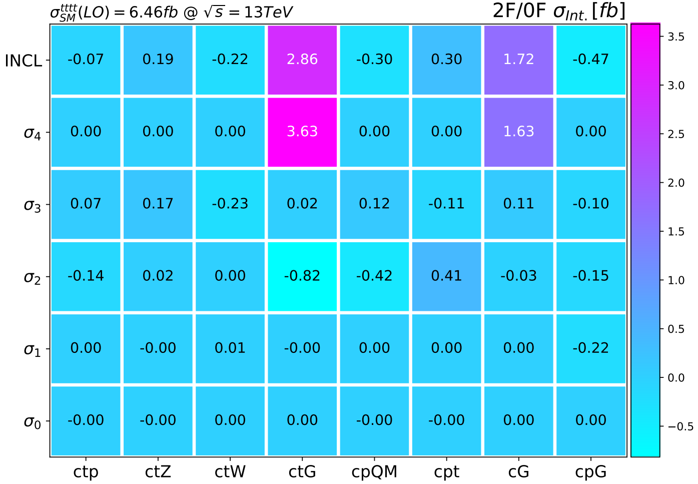
$$
\begin{aligned}
d\sigma_{\mathrm{int},qq,[4F]} &= \alpha_s^3\, d\sigma_{\mathrm{int},qq}^{(3,0,0)} \\
&+ \alpha_s^2 \left(\alpha\, d\sigma_{\mathrm{int},qq}^{(2,1,0)} + \alpha_t\, d\sigma_{\mathrm{int},qq}^{(2,0,1)}\right) \\
&+ \alpha_s \left(\alpha^2\, d\sigma_{\mathrm{int},qq}^{(1,2,0)} + \alpha^{3/2}\, \alpha_t^{1/2}\, d\sigma_{\mathrm{int},qq}^{(1,3/2,1/2)} + \alpha\alpha_t\, d\sigma_{\mathrm{int},qq}^{(1,1,1)} + \alpha_t^2\, d\sigma_{\mathrm{int},qq}^{(1,0,2)}\right) \\
&+ (\alpha^3)\, d\sigma_{\mathrm{int},qq}^{(0,3,0)} + (\alpha^{5/2}\, \alpha_t^{1/2})\, d\sigma_{\mathrm{int},qq}^{(0,5/2,1/2)} \\
&+ (\alpha^2\, \alpha_t)\, d\sigma_{\mathrm{int},qq}^{(0,2,1)} + (\alpha^{3/2}\, \alpha_t^{3/2})\, d\sigma_{\mathrm{int},qq}^{(0,3/2,3/2)} + (\alpha\, \alpha_t^2)\, d\sigma_{\mathrm{int},qq}^{(0,1,2)}
\end{aligned}
$$

2H2L at $\sqrt{s} = 13$ TeV



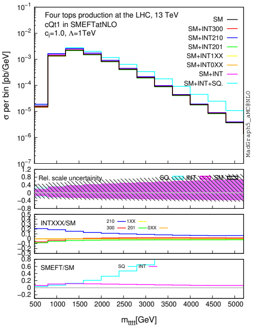
- dominant $\boldsymbol{\sigma_3}$ $\longrightarrow$ almost all 2H2L are 'naive' operators
- All enter in ***qq***-induced production $\longrightarrow$ EW scattering effects are **less critical** in interference with ***qq***-initiated amplitudes?

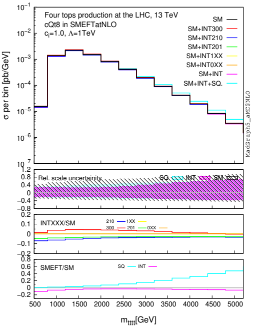
Relevant 2F and 0F at $\sqrt{s} = 13$ TeV

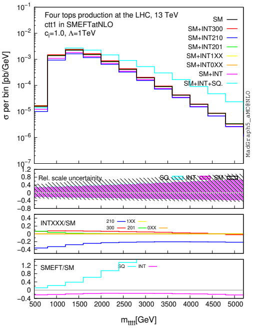


Non-four-fermion operators can also be ‘**non**-naive’

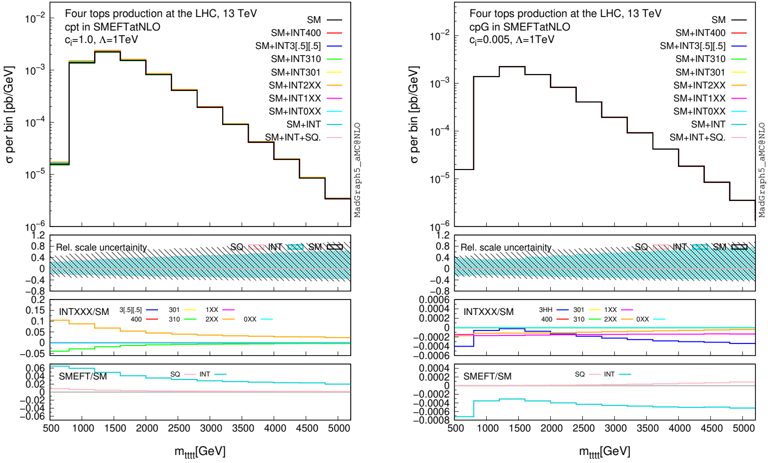
Rest of 4-heavy at $\sqrt{s} = 13$ TeV







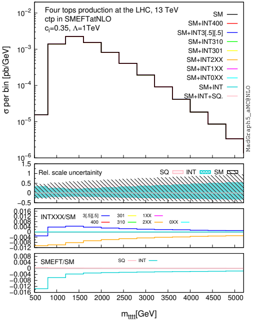
2F and 0F differential predictions $\sqrt{s} = 13$ TeV

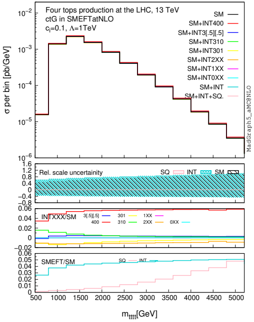


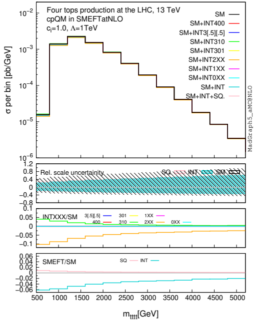
Different EFT structure than contact-term insertions (4F) $\rightarrow$ can be inferred from the amplitudes scaling with $\sim E$

2F and 0F differential predictions $\sqrt{s} = 13$ TeV

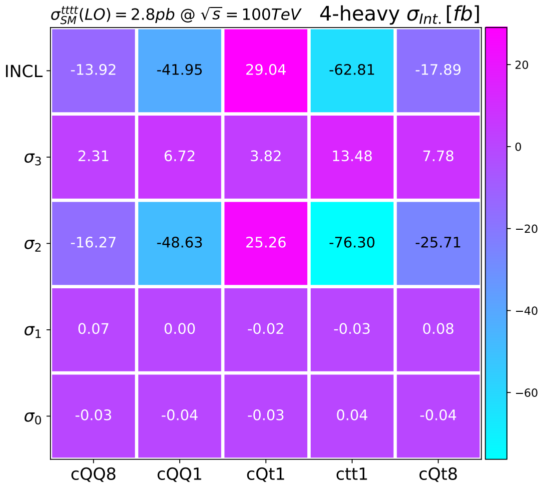
coefficients approximate values extracted from [2105.00006]





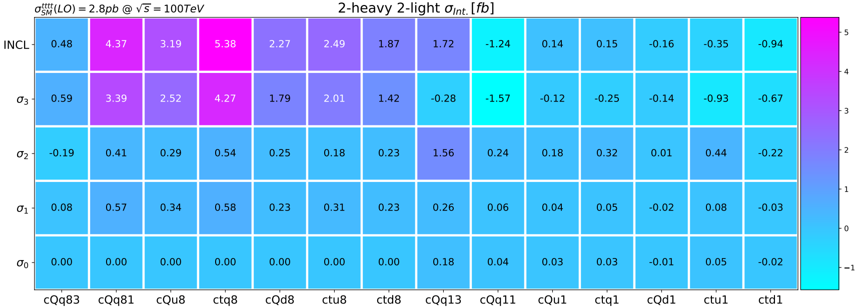


FCC-hh 4H



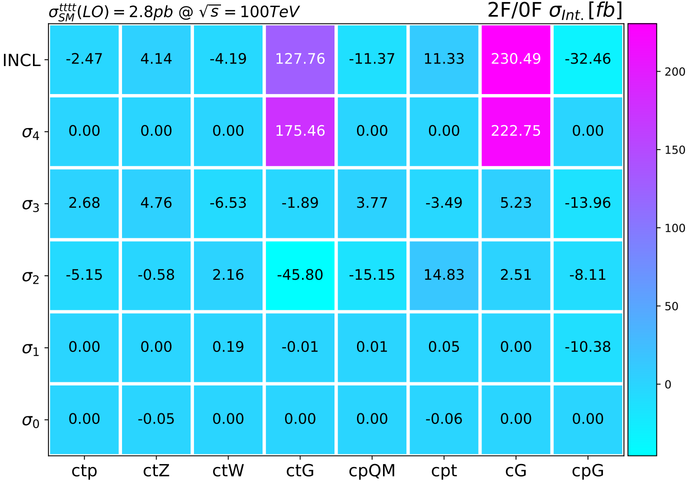
$\sigma_{SM}^{tttt}(LO) = 2.8pb$ @ $\sqrt{s} = 100TeV$
4-heavy $\sigma_{Int.}[fb]$
INCL
σ_3
σ_2
σ_1
σ_0
cQQ8
cQQ1
cQt1
ctt1
cQt8
-13.92
-41.95
29.04
-62.81
-17.89
2.31
6.72
3.82
13.48
7.78
-16.27
-48.63
25.26
-76.30
-25.71
0.07
0.00
-0.02
-0.03
0.08
-0.03
-0.04
-0.03
0.04
-0.04
20
0
−20
−40
−60

FCC-hh 2H2L

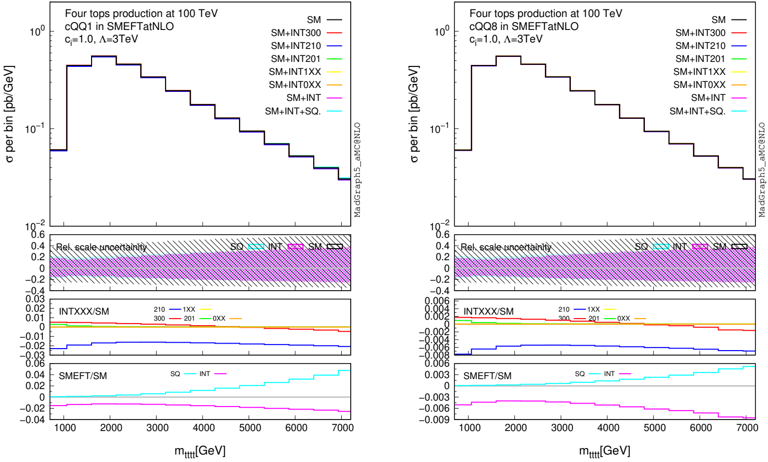


	cQq83	cQq81	cQu8	ctq8	cQd8	ctu8	ctd8	cQq13	cQq11	cQu1	ctq1	cQd1	ctu1	ctd1
INCL	0.48	4.37	3.19	5.38	2.27	2.49	1.87	1.72	-1.24	0.14	0.15	-0.16	-0.35	-0.94
σ_3	0.59	3.39	2.52	4.27	1.79	2.01	1.42	-0.28	-1.57	-0.12	-0.25	-0.14	-0.93	-0.67
σ_2	-0.19	0.41	0.29	0.54	0.25	0.18	0.23	1.56	0.24	0.18	0.32	0.01	0.44	-0.22
σ_1	0.08	0.57	0.34	0.58	0.23	0.31	0.23	0.26	0.06	0.04	0.05	-0.02	0.08	-0.03
σ_0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.04	0.03	0.03	-0.01	0.05	-0.02

FCC-hh relevant 2F and 0F



FCC 4H differential predictions



FCC 2F and 0F differential predictions