Four top quarks in SMEFT

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

Hesham El Faham
University of Manchester

“I would like to live in Manchester, England. The transition between Manchester and death would be unnoticeable.”

goodreads

— Mark Twain

"I would like to live in Manchester, England. The transition between Manchester and death would be unnoticeable."

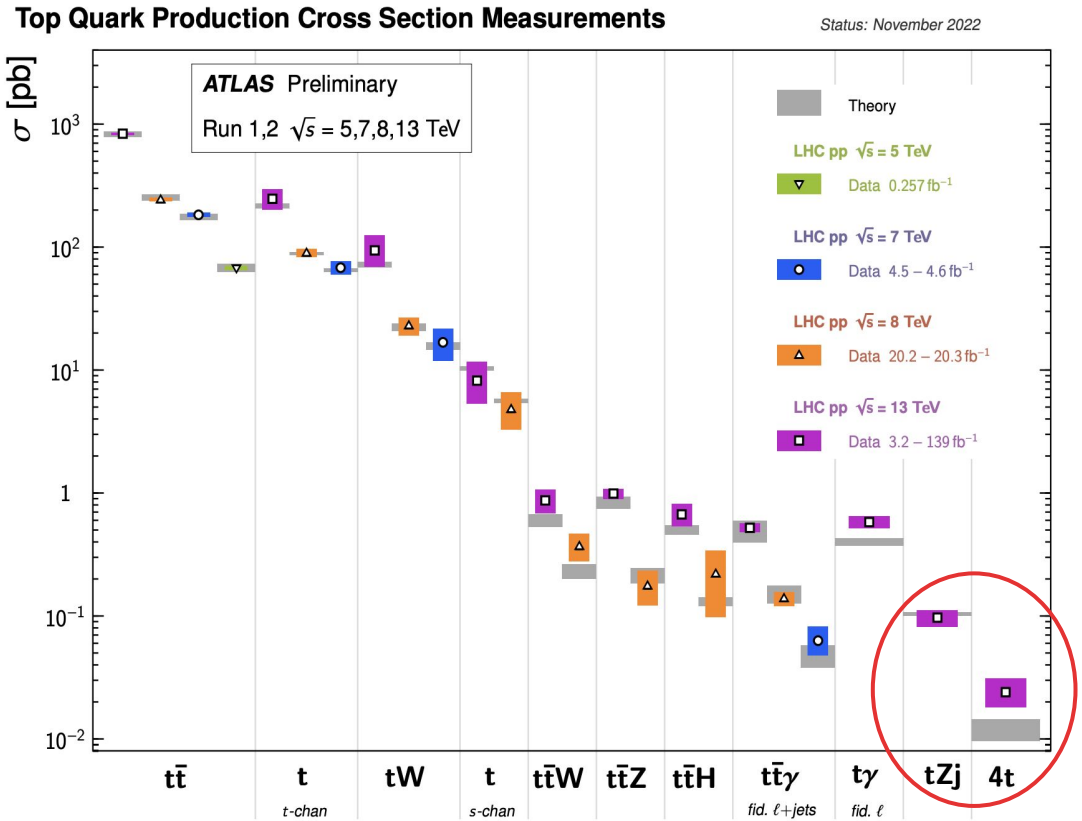
goodreads

— Mark Twain

NOT TRUE!

Status

- Top quark plays a special role in SM and beyond
- So far, no direct signs of beyond the SM physics → **effective theories?**
- Keep measuring rare processes

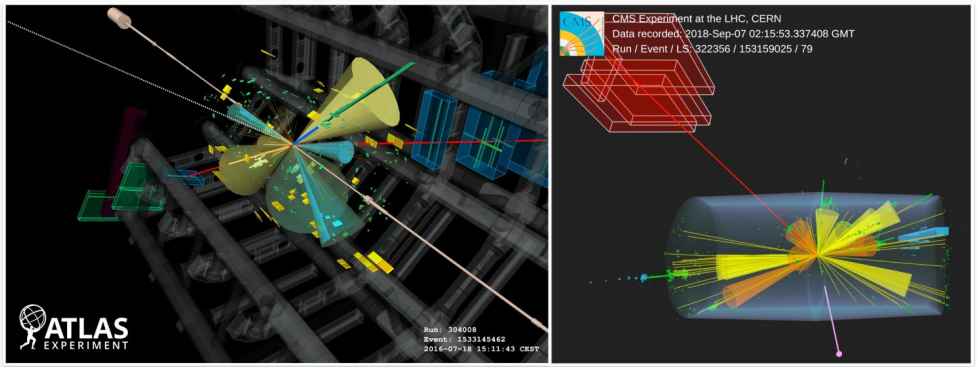


Four tops observed

ATLAS and CMS observe simultaneous production of four top quarks

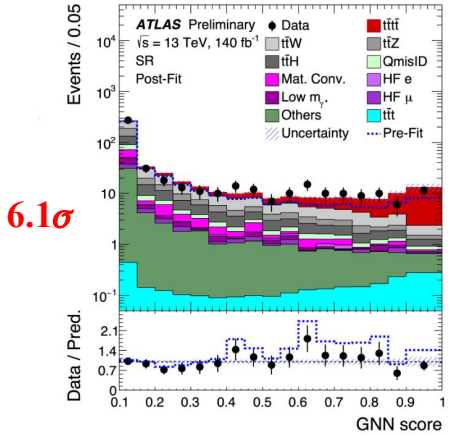
The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore

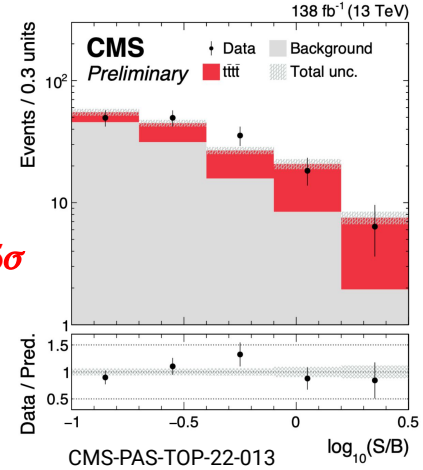


Event displays of four-top-quark production from ATLAS (left) and CMS (right).

arXiv:2303.15061



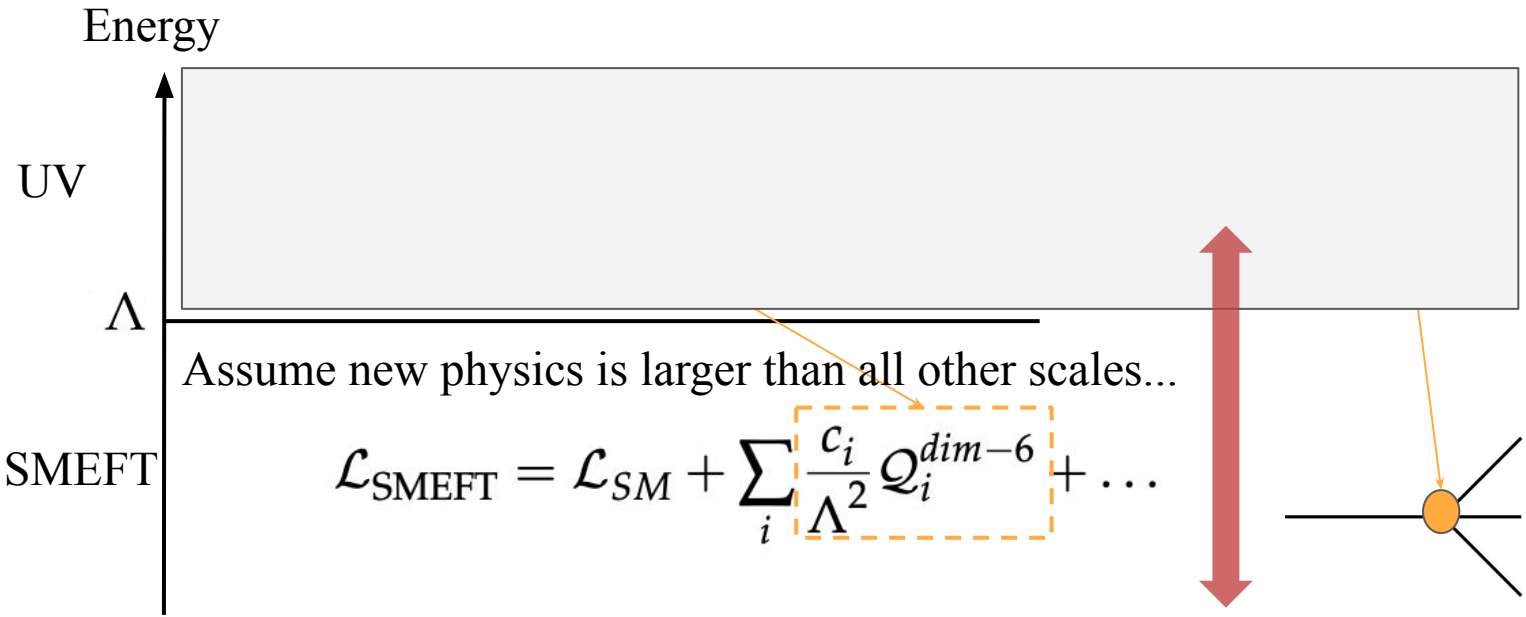
6.1σ



5.5σ

CMS-PAS-TOP-22-013

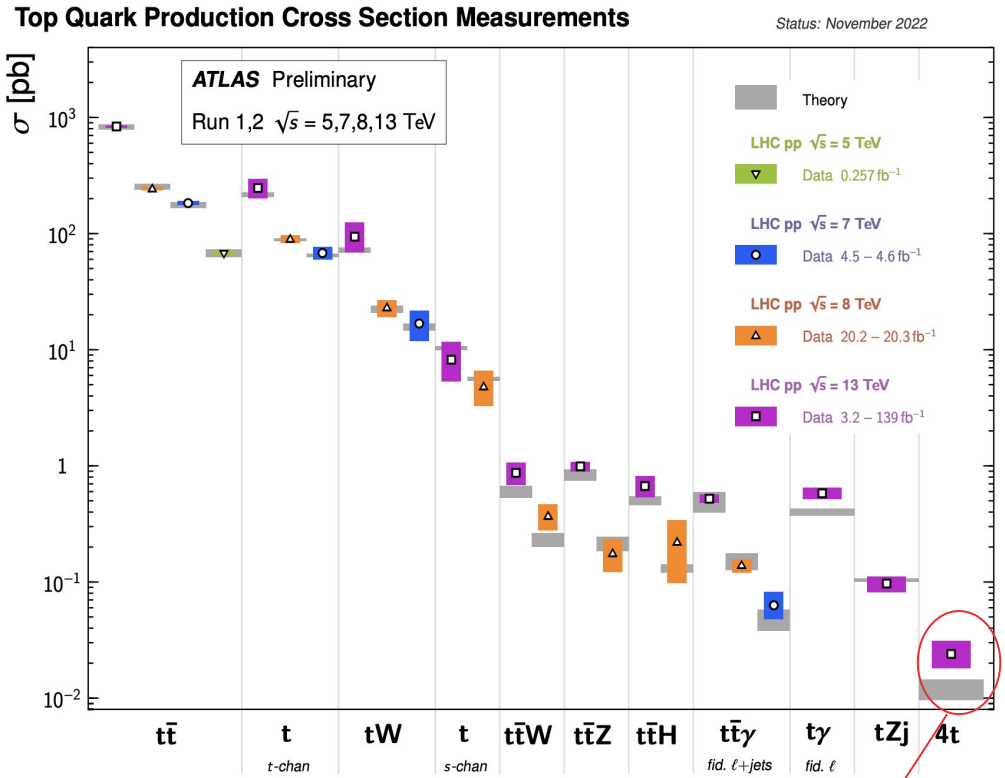
SMEFT in a nutshell



UV physics projected onto the low-energy dynamics

https://en.wikipedia.org/wiki/Four_Tops

Four tops in SMEFT



tttt in SM ~ 0.012 pb

Frederix, Pagani, Zaro, arXiv: 1711.02116

What did we need?

Courtesy of Ramon Winterhalder

Automated one-loop computations in the SMEFT

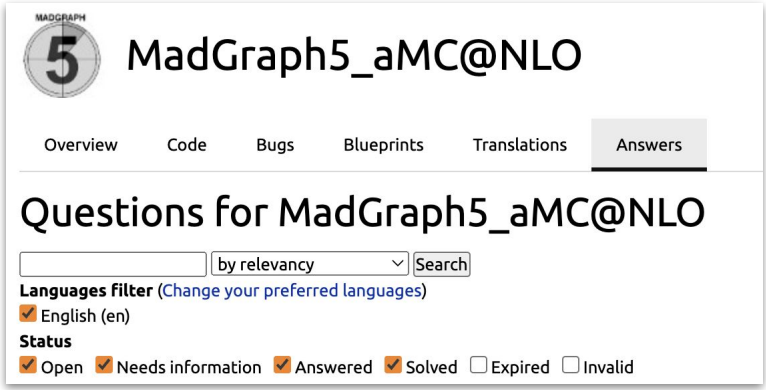
Céline Degrande,[1,*] Gauthier Durieux,[2,†] Fabio Maltoni,[1,3,‡]
Ken Mimasu,[1,§] Eleni Vryonidou,[4,¶] and Cen Zhang[5,6,**]

What did we need?

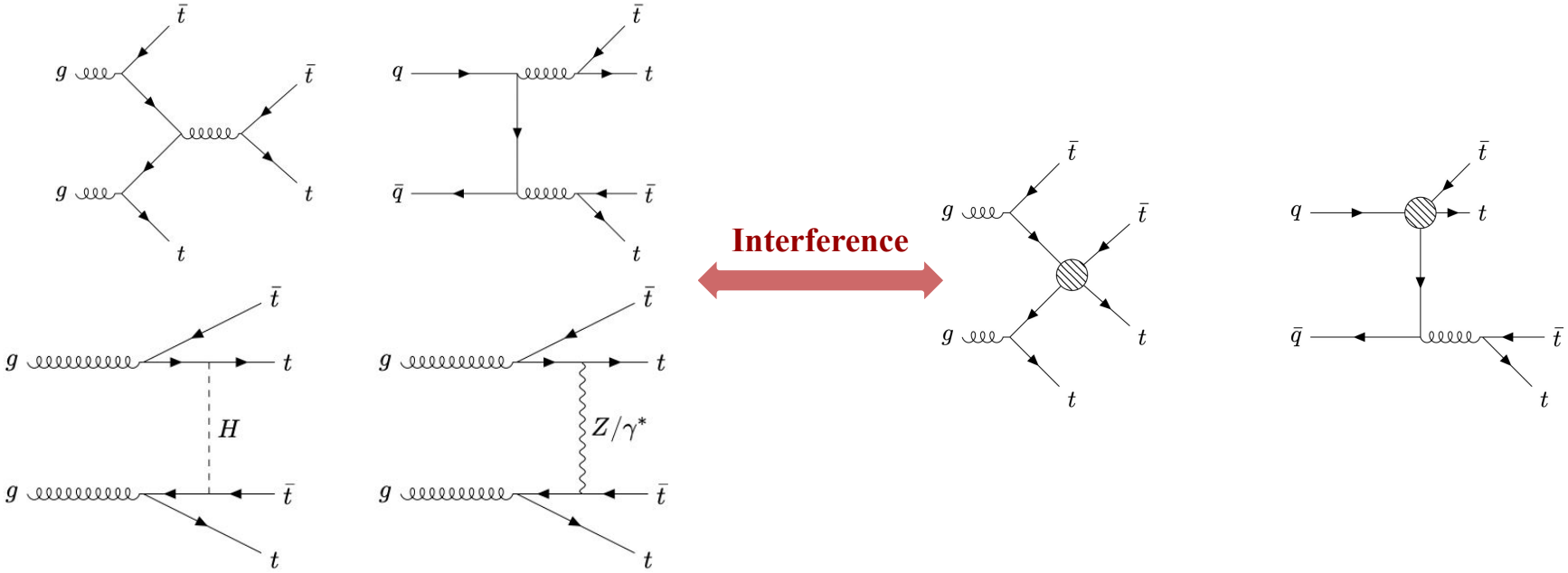
Courtesy of Ramon Winterhalder

Automated one-loop computations in the SMEFT

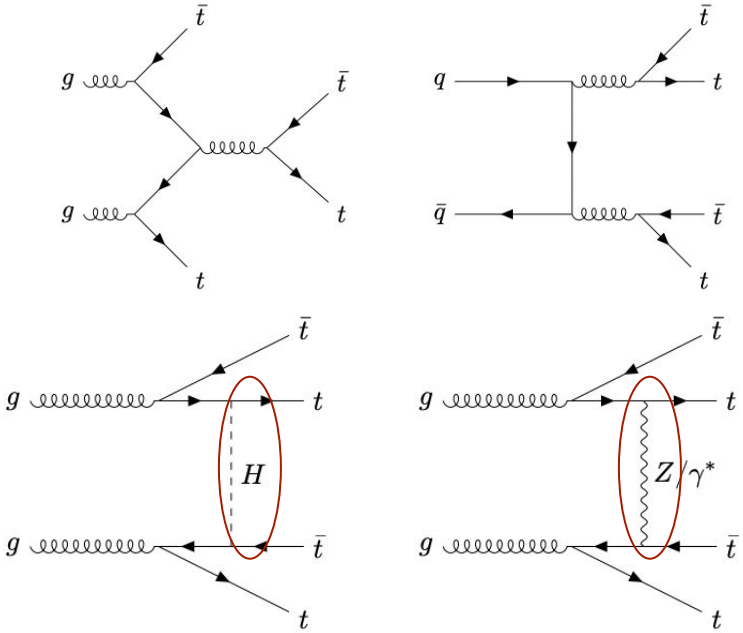
Céline Degrande,[1,*] Gauthier Durieux,[2,†] Fabio Maltoni,[1,3,‡]
Ken Mimasu,[1,§] Eleni Vryonidou,[4,¶] and Cen Zhang[5,6,**]



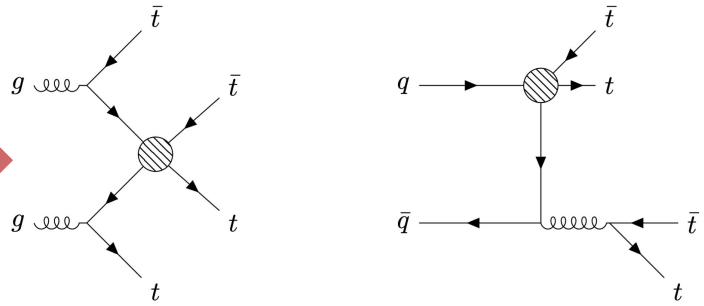
Four tops in SMEFT: interference



Four tops in SMEFT: interference



Interference

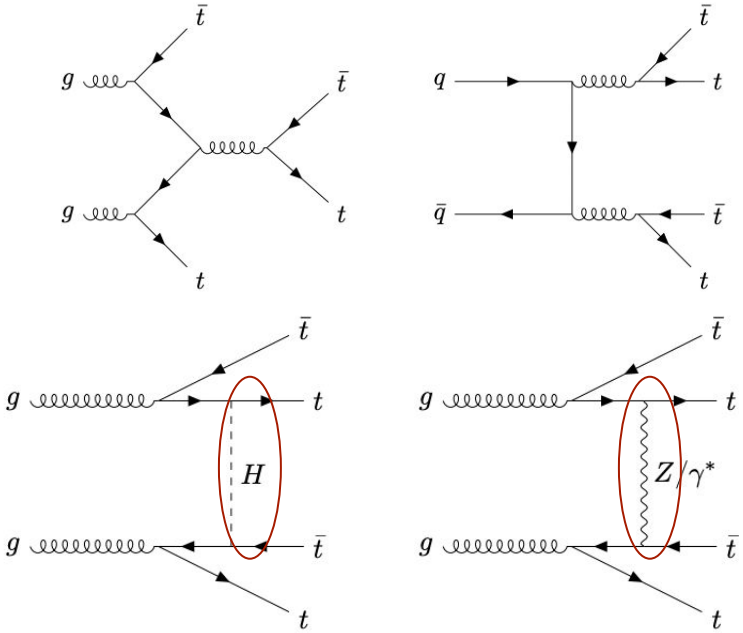


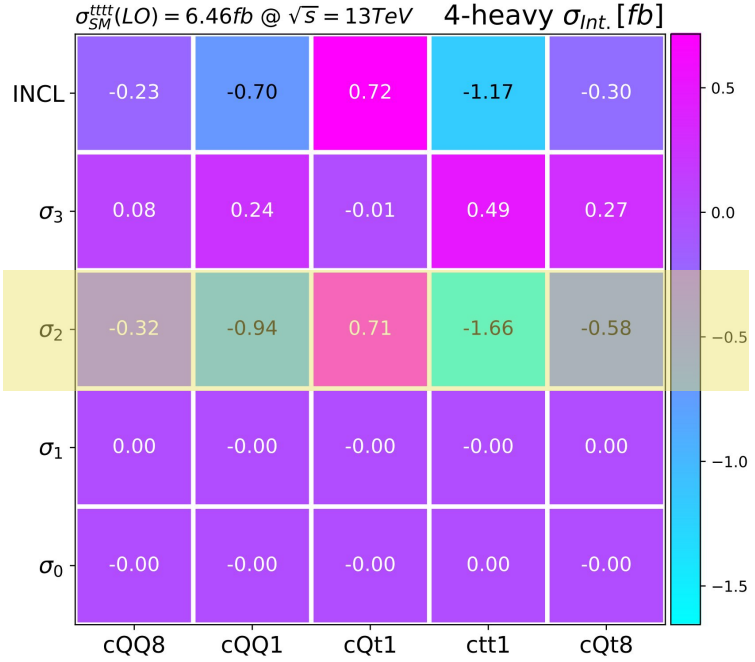
$t\bar{t}$ production, noted above. Table II also provides the LO interferences with subleading SM amplitudes of order $\alpha_S\alpha_{\rm EW}$ and $\alpha_S y_t^2$ which are actually larger than with the leading QCD ones. Note they also have opposite signs. At the quadratic level, the NLO enhance-

Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, arXiv: 2008.11743

Four tops in SMEFT

4-heavy					
$\mathcal{O}^1_{QQ}$	cQQ1	$2[C^{(1)}_{qq}]^{3333} - \frac{2}{3}[C^{(3)}_{qq}]^{3333}$	$\mathcal{O}^8_{QQ}$	cQQ8	$8[C^{(3)}_{qq}]^{3333}$
$\mathcal{O}^1_{Qt}$	cQt1	$[C^{(1)}_{qu}]^{3333}$	$\mathcal{O}^8_{Qt}$	cQt8	$[C^{(8)}_{qu}]^{3333}$
$\mathcal{O}^1_{tt}$	ctt1	$[C^{(1)}_{uu}]^{3333}$			





Electroweak contributions are important

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

Who said what?

- Cao, Chen, Liu, arXiv: 1602.01934
  ".. be careful at LO SM"

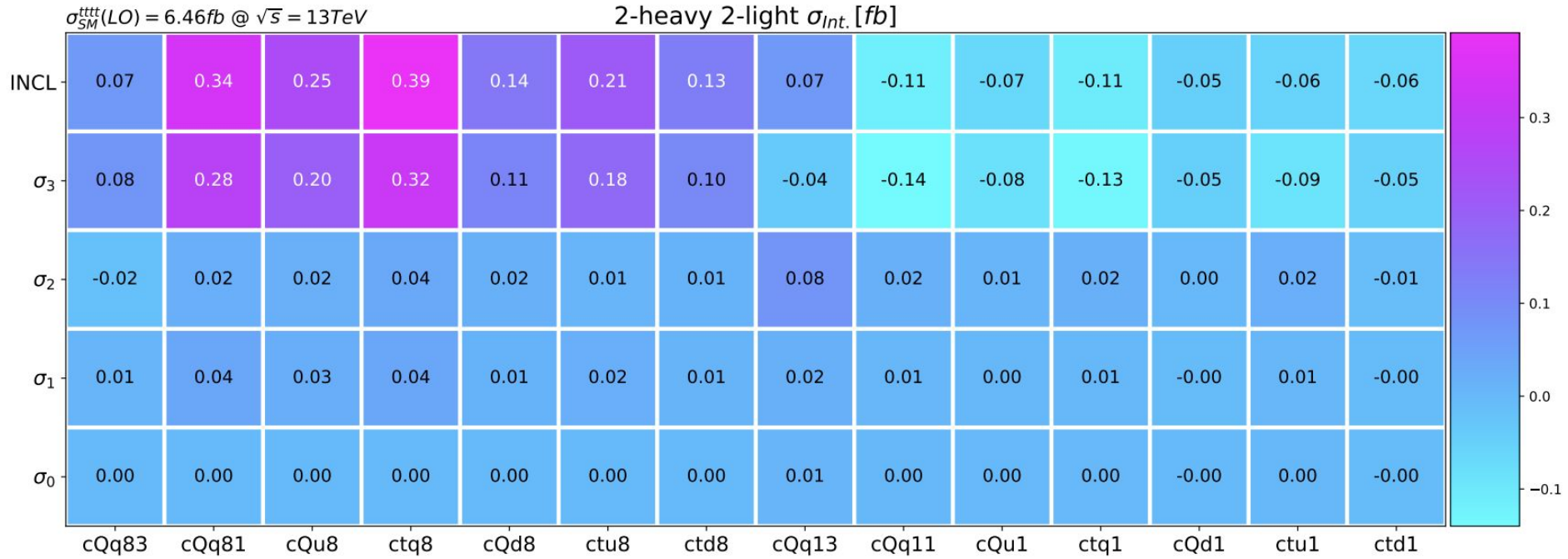
- Frederix, Pagani, Zaro, arXiv: 1711.02116
  ".. be careful at NLO SM"

- Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, arXiv: 2008.11743
  ".. be careful at SMEFT for some operators"

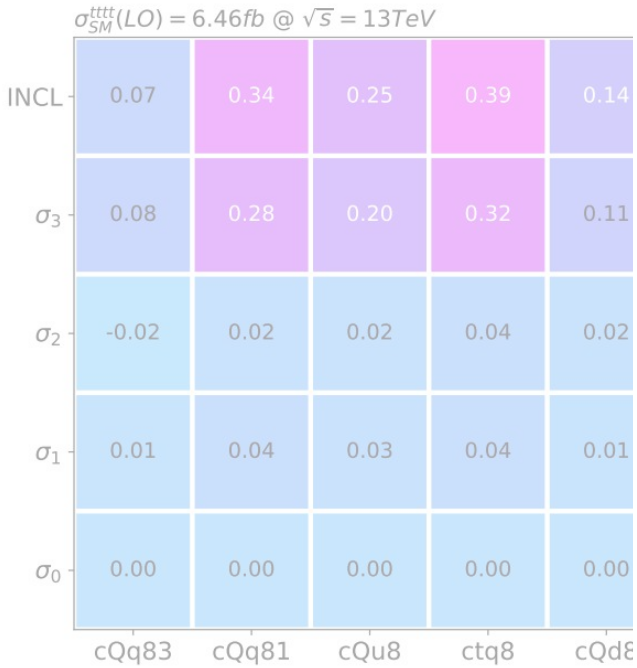
- Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962
  "..we are being careful at SMEFT for all operators"

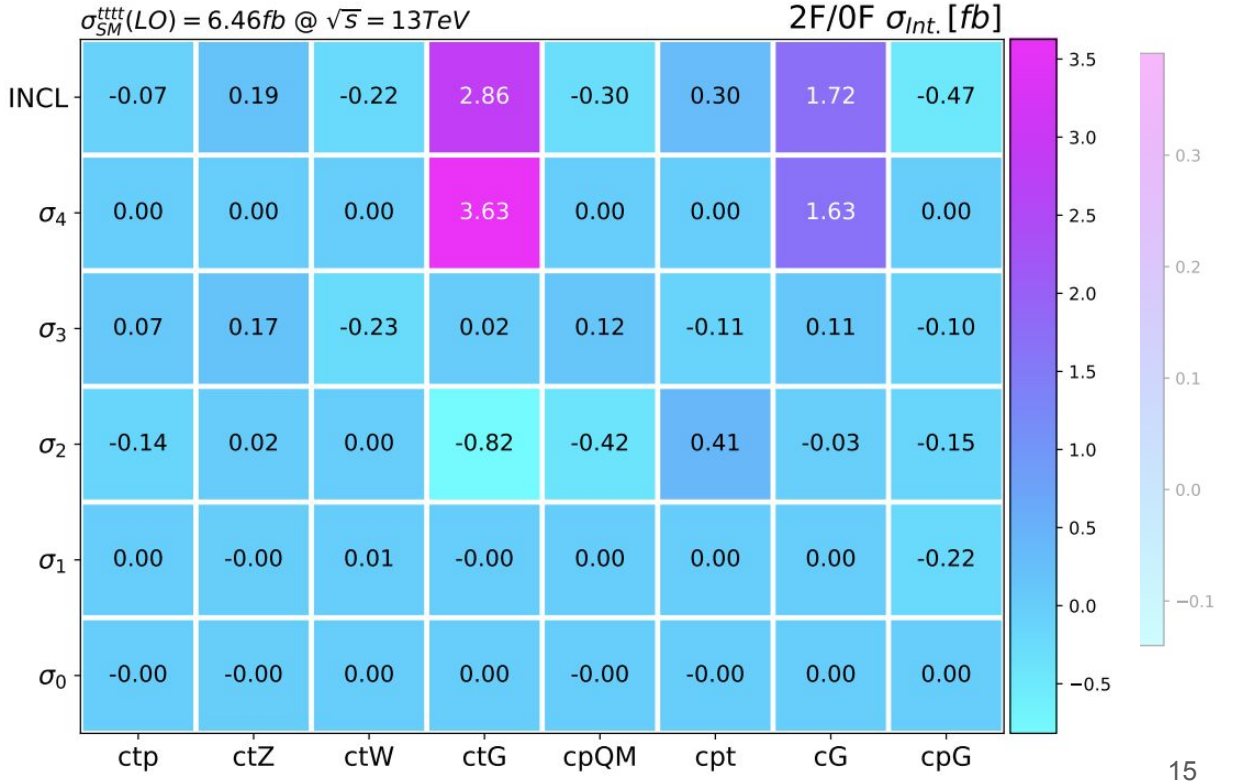
.. and a lot of other work considering four-fermion operators/ four tops in SMEFT [arXiv:1010.6304, 1708.05928, 1903.07725, 2010.05915, 2104.09512, ..]

And for all dimension-six operators..



And for all dimension-six operators..





And for all dimension-six operators: summary

	4H	2L2H	2F	0F
σ_4	×	×	c_{tG}	c_G
σ_3	-	$c_{Qq}^{83}, c_{Qu}^{8}, c_{tq}^{8}, c_{Qd}^{8}, c_{tu}^{8}, c_{td}^{8}, c_{Qq}^{81}$ $c_{Qq}^{11}, c_{Qu}^{1}, c_{tq}^{1}, c_{Qd}^{1}, c_{tu}^{1}, c_{td}^{1}$	$c_{t\varphi}, c_{tZ}, c_{tW}$	-
σ_2	$c_{QQ}^{8}, c_{QQ}^{1}, c_{Qt}^{8}, c_{Qt}^{1}, c_{tt}^{1}$	c_{Qq}^{31}	$c_{\varphi t}, c_{\varphi Q}^{(-)}$	-
σ_1	-	-	-	$c_{\varphi G}$
σ_0	-	-	-	-

sub-leading

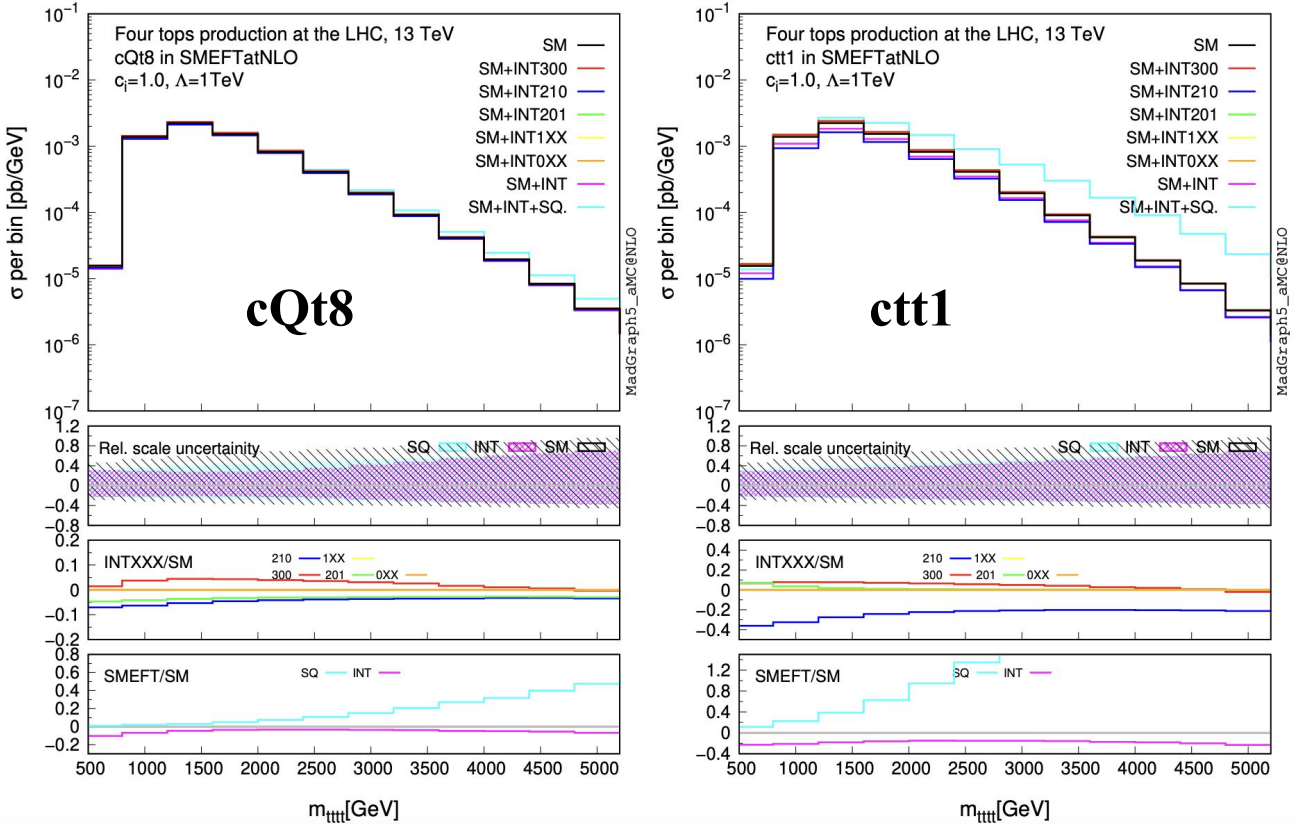
..where sub-leading interference is important

	4H	2L2H	2F	0F
σ_2	$c_{QQ}^8, c_{QQ}^1, c_{Qt}^8, c_{Qt}^1, c_{tt}^1$	c_{Qq}^{31}	$c_{\varphi t}, c_{\varphi Q}^{(-)}$	-
σ_1	-	-	-	$c_{\varphi G}$
σ_0	-	-	-	-

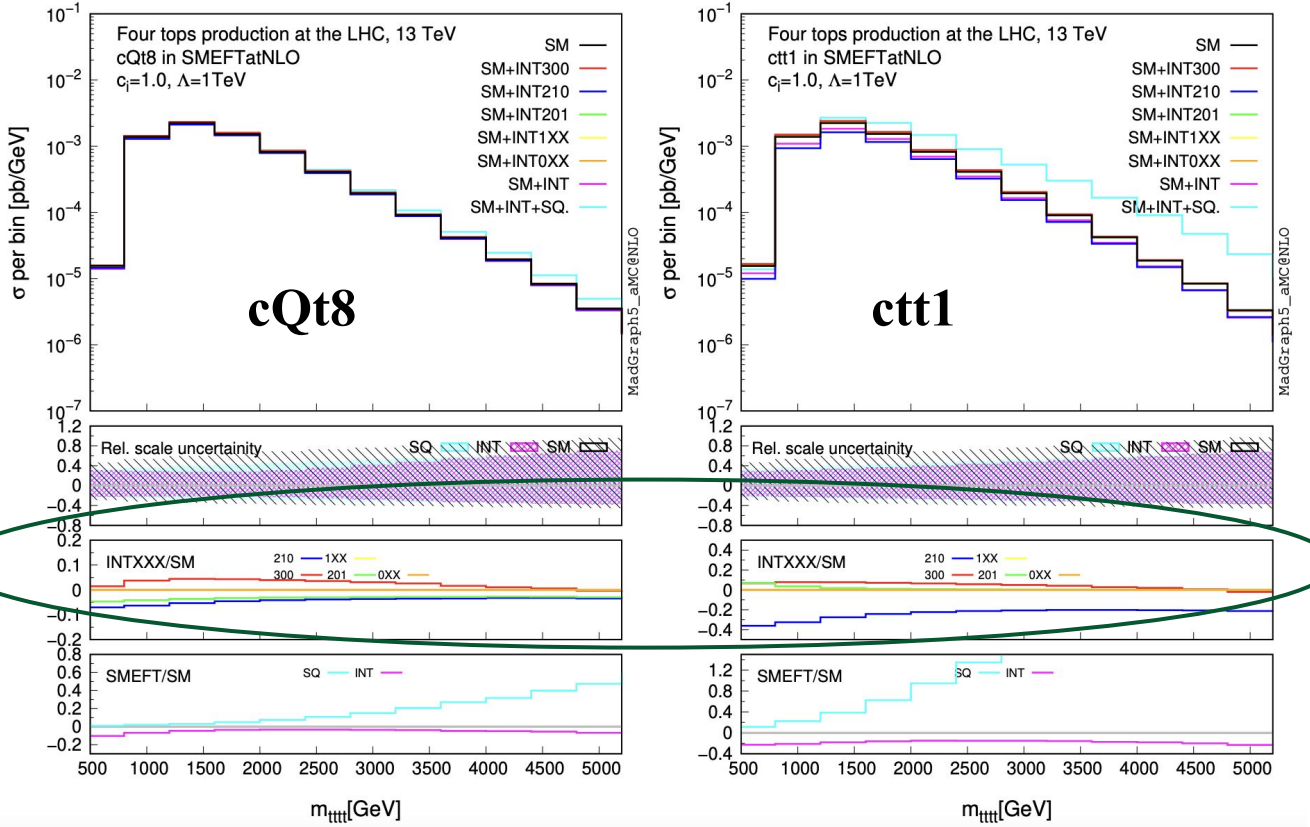
sub-leading

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

On the interference structure



On the interference structure

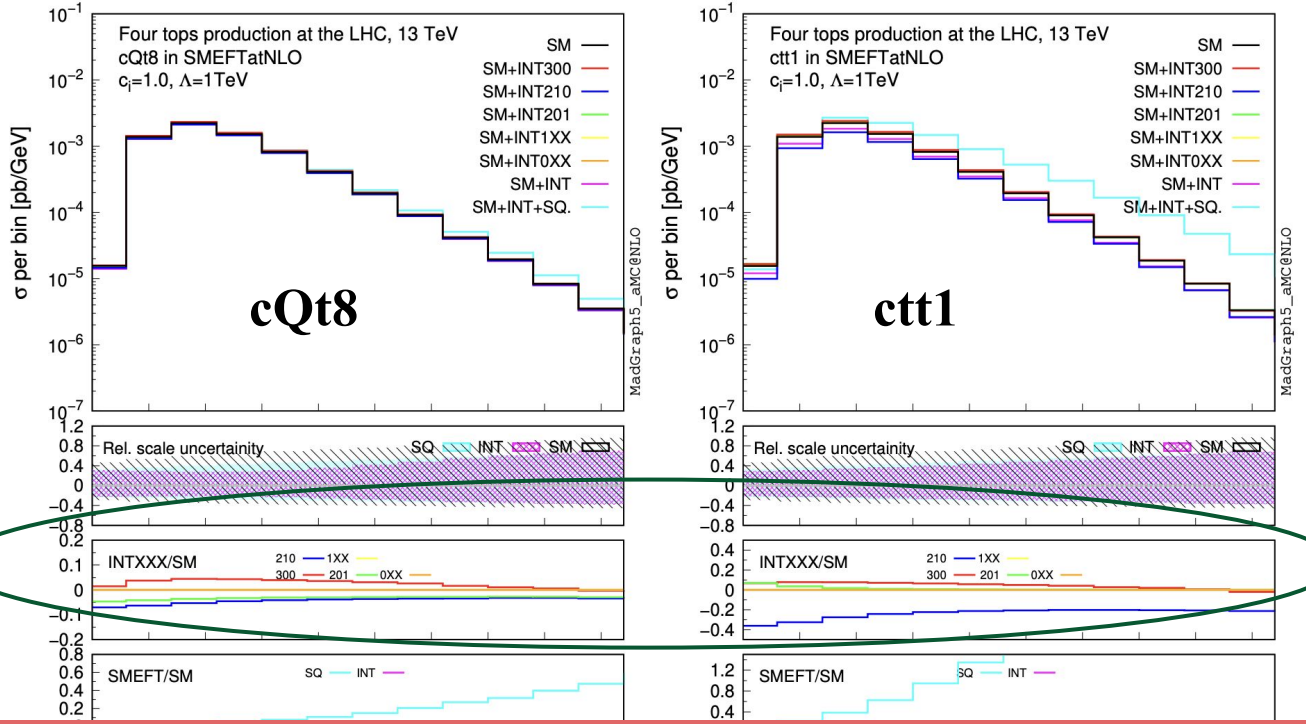


Interference ratio

red: leading

blue: subleading

On the interference structure



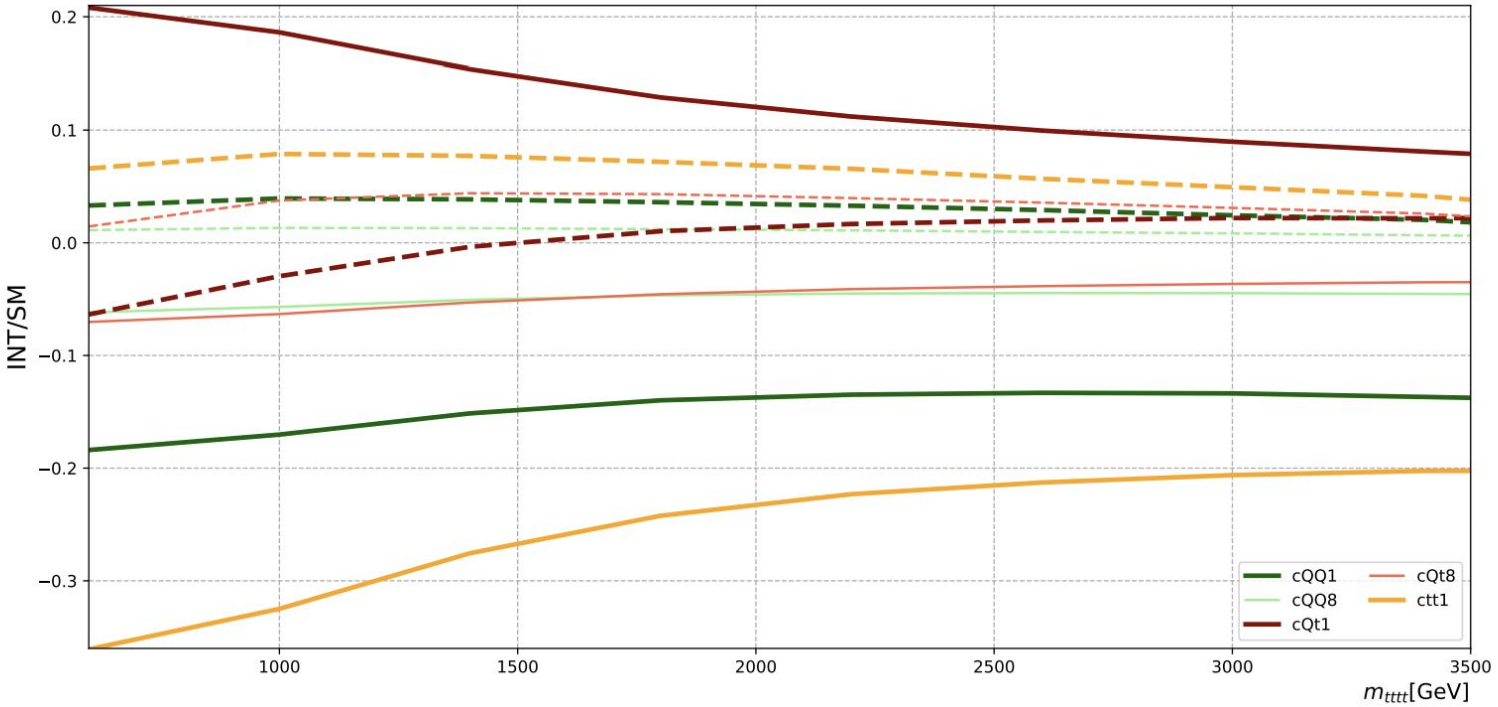
Interference ratio

red: leading

blue: subleading

Color-singlets feature ‘stronger’ subleading interference structure

On the interference structure: summary



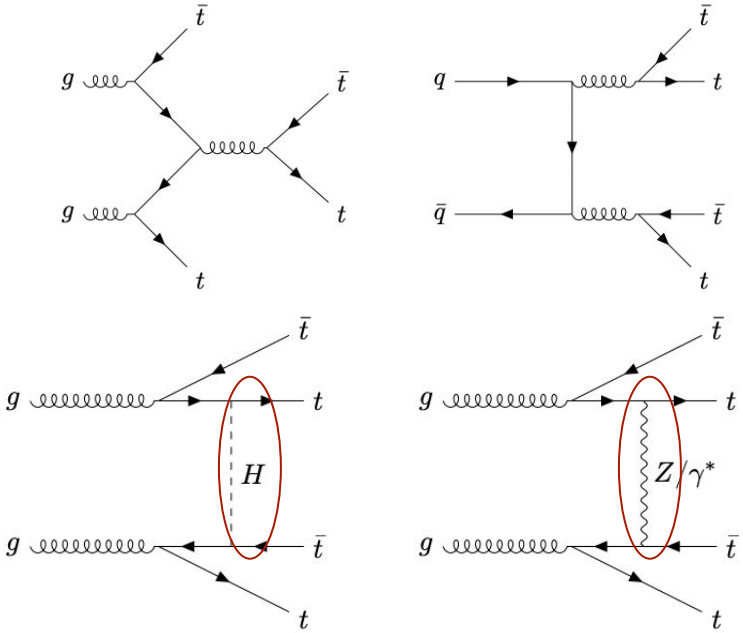
solid: subleading interference, **dashed**: leading one

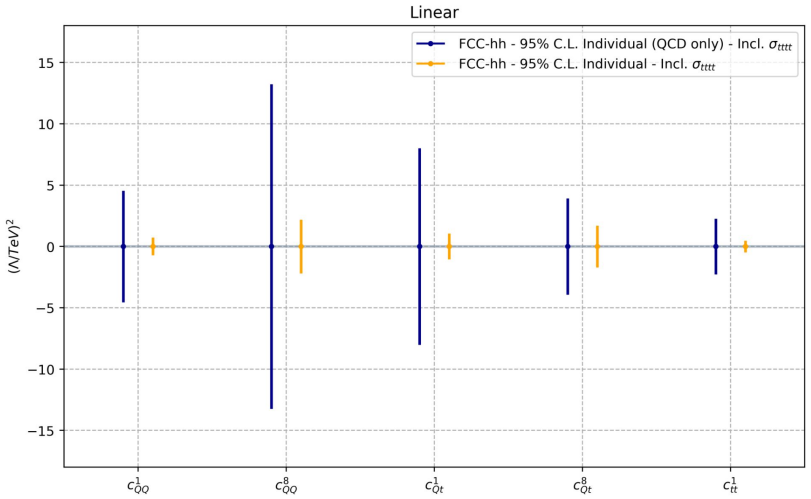
Toy fits and bounds

Four tops in SMEFT

4-heavy

$\mathcal{O}^1_{QQ}$	cQQ1	$2[C^{(1)}_{qq}]^{3333} - \frac{2}{3}[C^{(3)}_{qq}]^{3333}$	$\mathcal{O}^8_{QQ}$	cQQ8	$8[C^{(3)}_{qq}]^{3333}$
$\mathcal{O}^1_{Qt}$	cQt1	$[C^{(1)}_{qu}]^{3333}$	$\mathcal{O}^8_{Qt}$	cQt8	$[C^{(8)}_{qu}]^{3333}$
$\mathcal{O}^1_{tt}$	ctt1	$[C^{(1)}_{uu}]^{3333}$			



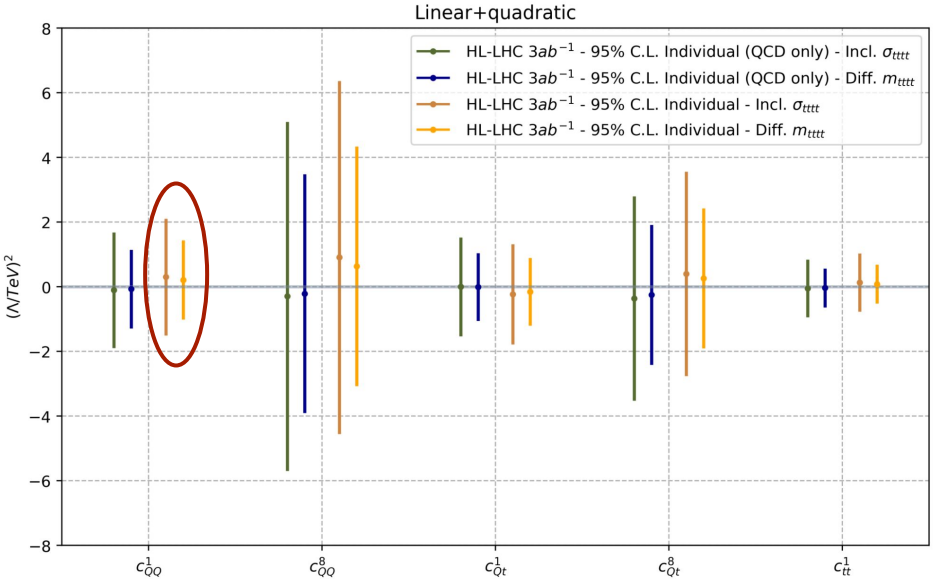


Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

Electroweak contributions are important

Four tops in SMEFT

4-heavy					
$\mathcal{O}^1_{QQ}$	cQQ1	$2[C^{(1)}_{qq}]^{3333} - \frac{2}{3}[C^{(3)}_{qq}]^{3333}$	$\mathcal{O}^8_{QQ}$	cQQ8	$8[C^{(3)}_{qq}]^{3333}$
$\mathcal{O}^1_{Qt}$	cQt1	$[C^{(1)}_{qu}]^{3333}$	$\mathcal{O}^8_{Qt}$	cQt8	$[C^{(8)}_{qu}]^{3333}$
$\mathcal{O}^1_{tt}$	ctt1	$[C^{(1)}_{uu}]^{3333}$			

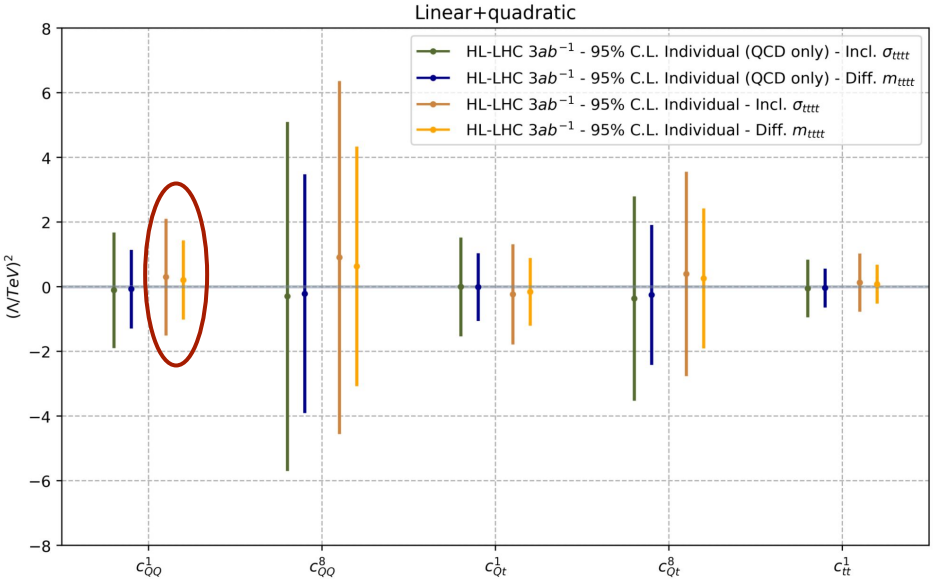


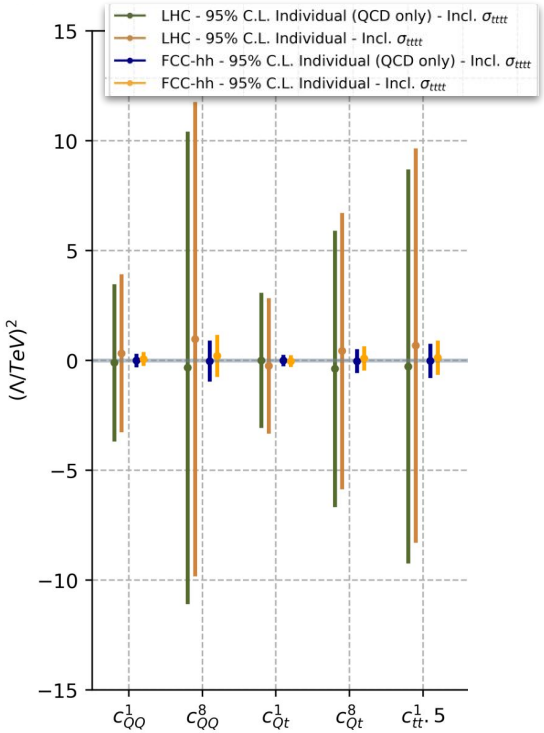
Differential information is important

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

Four tops in SMEFT

4-heavy					
$\mathcal{O}^1_{QQ}$	cQQ1	$2[C^{(1)}_{qq}]^{3333} - \frac{2}{3}[C^{(3)}_{qq}]^{3333}$	$\mathcal{O}^8_{QQ}$	cQQ8	$8[C^{(3)}_{qq}]^{3333}$
$\mathcal{O}^1_{Qt}$	cQt1	$[C^{(1)}_{qu}]^{3333}$	$\mathcal{O}^8_{Qt}$	cQt8	$[C^{(8)}_{qu}]^{3333}$
$\mathcal{O}^1_{tt}$	ctt1	$[C^{(1)}_{uu}]^{3333}$			

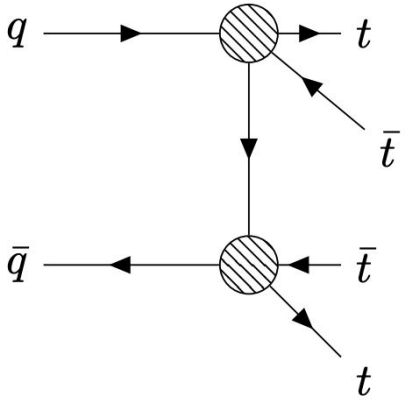


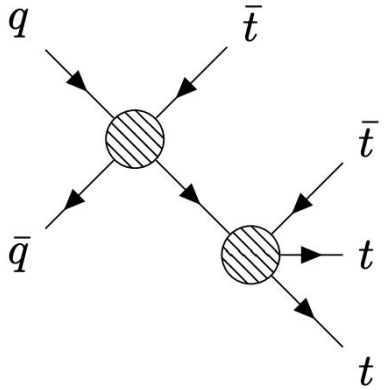


Differential information is important
FCC-hh provides a good handle

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

Double insertions





Double insertions of dimension-six

Constraining *qqtt* operators from four-top production: a case for enhanced EFT sensitivity *

Cen Zhang(张岑)[1]

[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Abstract: Recently, experimental collaborations have reported $\mathcal{O}(10)$ upper limits on the signal strength of four-top production at the LHC. Surprisingly, we find that the constraining power of four-top production on the *qqtt* type of operators is already competitive with the measurements of top-pair production, even though the precision level of the latter is more than two orders of magnitude better. This is explained by the enhanced sensitivity of the four-top cross section to *qqtt* operators, due to multiple insertion of operators in the squared amplitude, and to the large threshold energy of four-top production. We point out that even though the dominant contribution beyond

Reminder and a question

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

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

$$d\sigma_{\mathrm{quad}} \sim |\mathcal{A}_{(\mathrm{d6})}|^2, \qquad d\sigma_{\mathrm{dbl}} \sim |\mathcal{A}_{\mathrm{SM}}\,\mathcal{A}_{(\mathrm{d6})^2}|, \qquad d\sigma_{\mathrm{d8}} \sim |\mathcal{A}_{\mathrm{SM}}\,\mathcal{A}_{(\mathrm{d8})}|$$

Reminder and a question

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

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

$$d\sigma_{\mathrm{quad}} \sim |\mathcal{A}_{(\mathrm{d6})}|^2, \qquad d\sigma_{\mathrm{dbl}} \sim |\mathcal{A}_{\mathrm{SM}}\,\mathcal{A}_{(\mathrm{d6})^2}|, \qquad d\sigma_{\mathrm{d8}} \sim |\mathcal{A}_{\mathrm{SM}}\,\mathcal{A}_{(\mathrm{d8})}|$$

Are those competitive in four tops?

Double insertions of dimension-six

2-heavy 2-light at c_i=1						
	$\sqrt{s} = 13$ TeV			$\sqrt{s} = 100$ TeV		
$\mathcal{O}_i$	$\lvert\mathcal{A}_1\rvert^2$ [fb]	$\sum_k \mathcal{O}(\mathcal{A}_2)_k$ [fb]	ratio	$\lvert\mathcal{A}_1\rvert^2$ [fb]	$\sum_k \mathcal{O}(\mathcal{A}_2)_k$ [fb]	ratio
$\mathcal{O}_{Qq}^{3,8}$	0.27	0.01	0.04	6.40	0.40	0.06
$\mathcal{O}_{Qq}^{1,8}$	0.28	0.05	0.18	6.36	0.63	0.10
$\mathcal{O}_{Qu}^{8}$	0.21	0.03	0.14	5.34	0.50	0.09
$\mathcal{O}_{tq}^{8}$	0.34	0.06	0.18	8.44	0.76	0.09
$\mathcal{O}_{Qd}^{8}$	0.13	0.03	0.23	3.13	0.35	0.11
$\mathcal{O}_{tu}^{8}$	0.17	0.03	0.18	3.97	0.41	0.10
$\mathcal{O}_{td}^{8}$	0.10	0.02	0.20	2.18	0.27	0.12
$\mathcal{O}_{Qq}^{3,1}$	1.84	0.15	0.08	46.98	5.49	0.12
$\mathcal{O}_{Qq}^{1,1}$	1.84	0.08	0.04	47.35	0.81	0.02
$\mathcal{O}_{Qu}^{1}$	1.14	0.06	0.05	29.94	2.83	0.09
$\mathcal{O}_{tq}^{1}$	1.80	0.14	0.08	46.54	6.33	0.14
$\mathcal{O}_{Qd}^{1}$	0.70	0.08	0.11	17.55	2.15	0.12
$\mathcal{O}_{tu}^{1}$	1.11	0.04	0.04	29.10	2.48	0.09
$\mathcal{O}_{td}^{1}$	0.68	0.05	0.07	17.44	1.79	0.10

Ratios of double insertions to quadratic contributions

Given the bounds by SMEFiT [2105.00006]

Double insertions of dimension-six

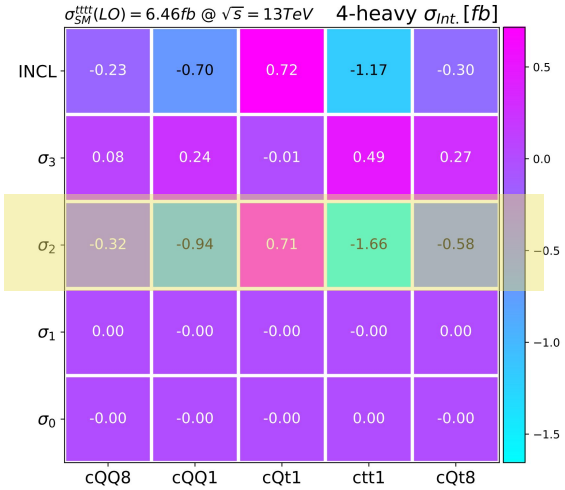
2-heavy 2-light at c_i=1						
	$\sqrt{s} = 13$ TeV			$\sqrt{s} = 100$ TeV		
$\mathcal{O}_i$	$\lvert\mathcal{A}_1\rvert^2$ [fb]	$\sum_k \mathscr{O}(\mathcal{A}_2)_k$ [fb]	ratio	$\lvert\mathcal{A}_1\rvert^2$ [fb]	$\sum_k \mathscr{O}(\mathcal{A}_2)_k$ [fb]	ratio
$\mathcal{O}_{Qq}^{3,8}$	0.27	0.01	0.04	6.40	0.40	0.06
$\mathcal{O}_{Qq}^{1,8}$	0.28	0.05	0.18	6.36	0.63	0.10
$\mathcal{O}_{Qu}^{8}$	0.21	0.03	0.14	5.34	0.50	0.09
$\mathcal{O}_{tq}^{8}$	0.34	0.06	0.18	8.44	0.76	0.09
$\mathcal{O}_{Qd}^{8}$	0.13	0.03	0.23	3.13	0.35	0.11
$\mathcal{O}_{tu}^{8}$	0.17	0.03	0.18	3.97	0.41	0.10
$\mathcal{O}_{td}^{8}$	0.10	0.02	0.20	2.18	0.27	0.12
$\mathcal{O}_{Qq}^{3,1}$	1.84	0.15	0.08	46.98	5.49	0.12
$\mathcal{O}_{Qq}^{1,1}$	1.84	0.08	0.04	47.35	0.81	0.02
$\mathcal{O}_{Qu}^{1}$	1.14	0.06	0.05	29.94	2.83	0.09
$\mathcal{O}_{tq}^{1}$	1.80	0.14	0.08	46.54	6.33	0.14
$\mathcal{O}_{Qd}^{1}$	0.70	0.08	0.11	17.55	2.15	0.12
$\mathcal{O}_{tu}^{1}$	1.11	0.04	0.04	29.10	2.48	0.09
$\mathcal{O}_{td}^{1}$	0.68	0.05	0.07	17.44	1.79	0.10

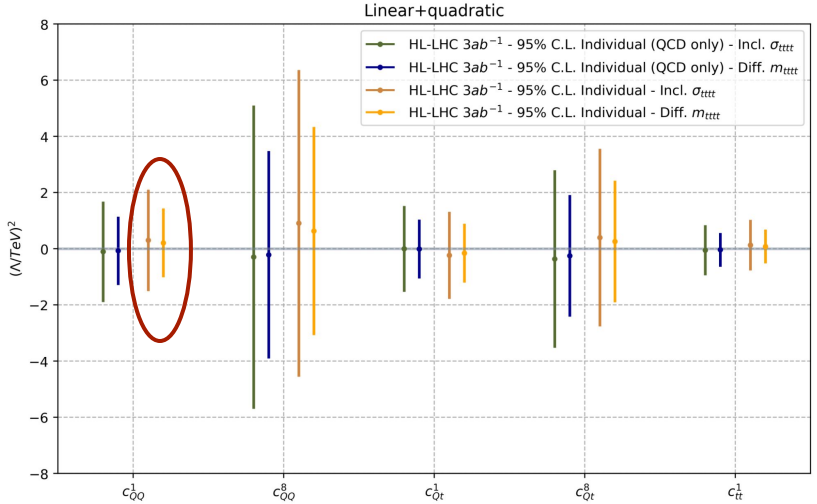
Ratios of double insertions to quadratic contributions

Given the bounds by SMEFiT [2105.00006]

qq-initiated remain constrained somewhere else

Summary





- subleading interference in SMEFT is key for four tops
- differential information are important for four-fermion operators
- 2H2L are better constrained somewhere else