

# Four top quarks in SMEFT

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

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University of Manchester

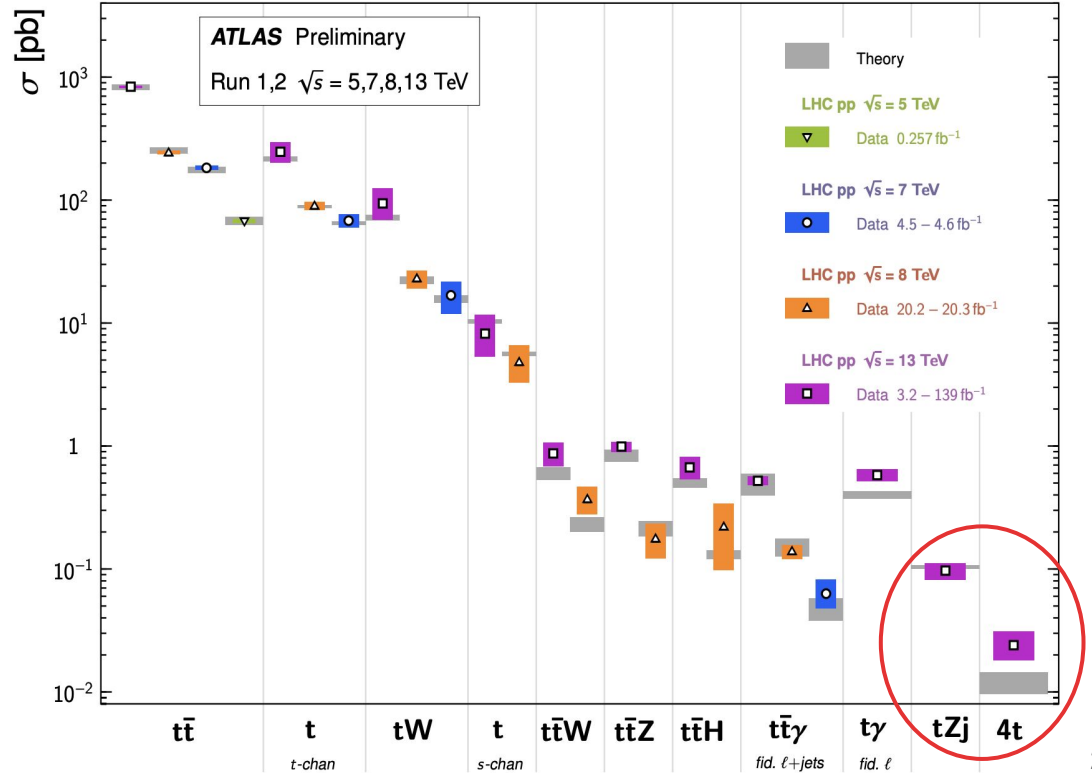


# Status

- 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**

Top Quark Production Cross Section Measurements

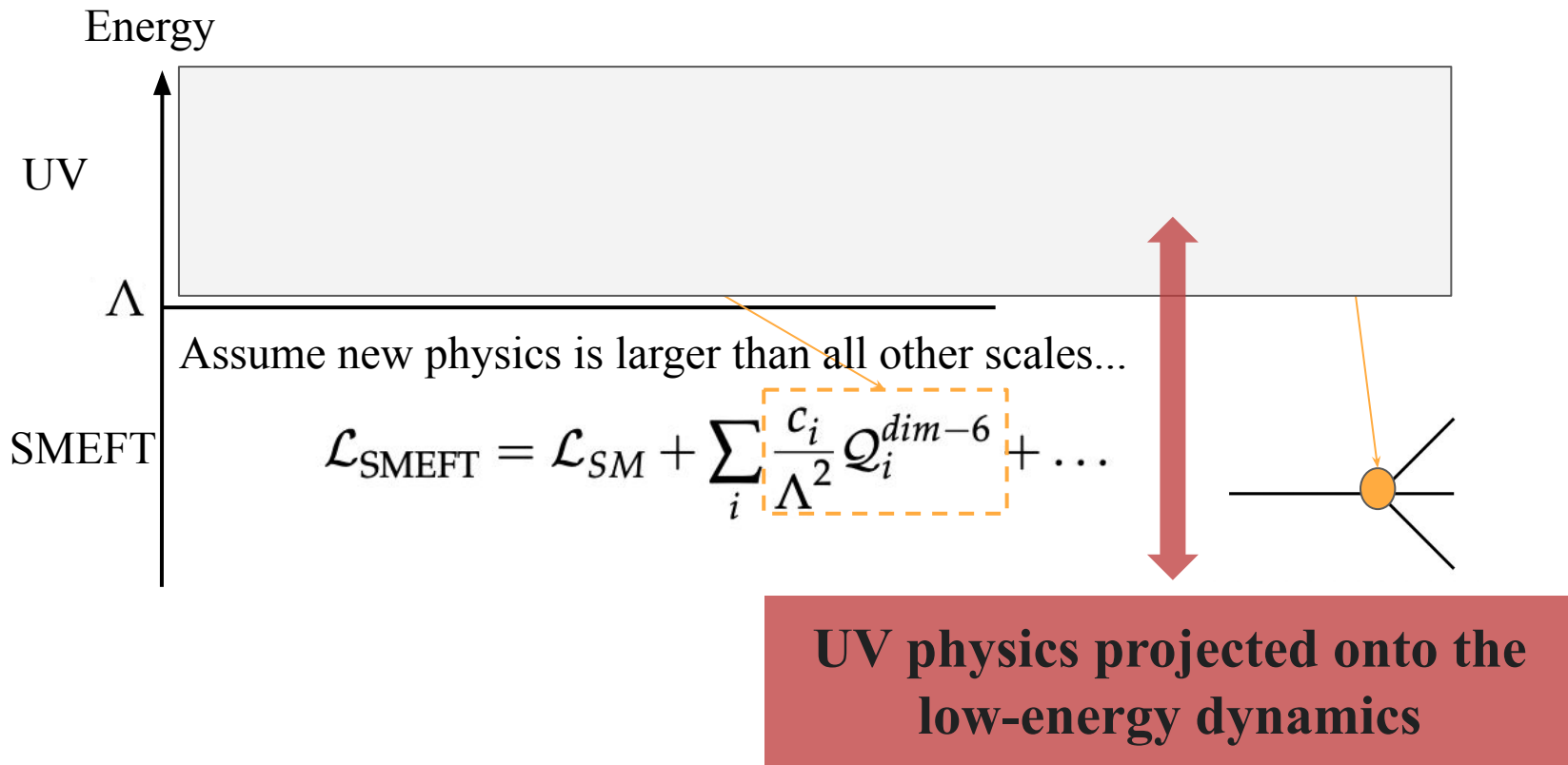
Status: November 2022



# Into effective field theories and SMEFT

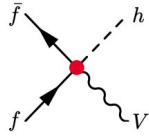
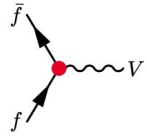


# SMEFT in a nutshell



# Top quark operators in SMEFT

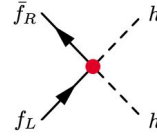
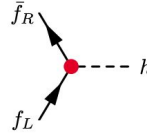
currents  $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$



$C_{\phi f}$

- Shift SM  $f\bar{f}V$  couplings
- $f\bar{f}Vh$  contact interactions

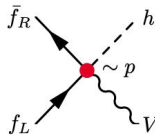
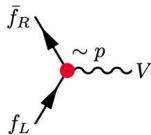
Yukawa  $(\bar{q}t\tilde{\varphi})(\varphi^\dagger\varphi)$



$C_{t\phi}$

- Decouple  $m_t$  &  $y_t$
- $t\bar{t}hh(h)$  contact interactions

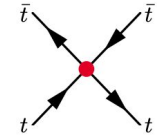
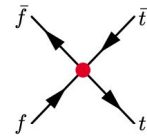
dipole  $(\bar{q}\sigma_{\mu\nu}t\tilde{\varphi})V^{\mu\nu}$



$C_{tV}$

- Chirality flipping  $f\bar{f}V$  couplings
- $f\bar{f}V(V)h$  contact interactions
- $W, B$  &  $G$  fields

4 fermion  $(\bar{q}\gamma_\mu q)(\bar{Q}\gamma^\mu Q)$   $(\bar{Q}\gamma^\mu Q)(\bar{\ell}\gamma_\mu \ell)$



$C_{ft}$

- Contact interactions
- 2-heavy-2-light or 4-heavy
- Numerous ( $\sim O(20)$  w/ top)

# Pragmatic SMEFT

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2} \sum_i c_i^6(\mu) a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Precise experimental measurements

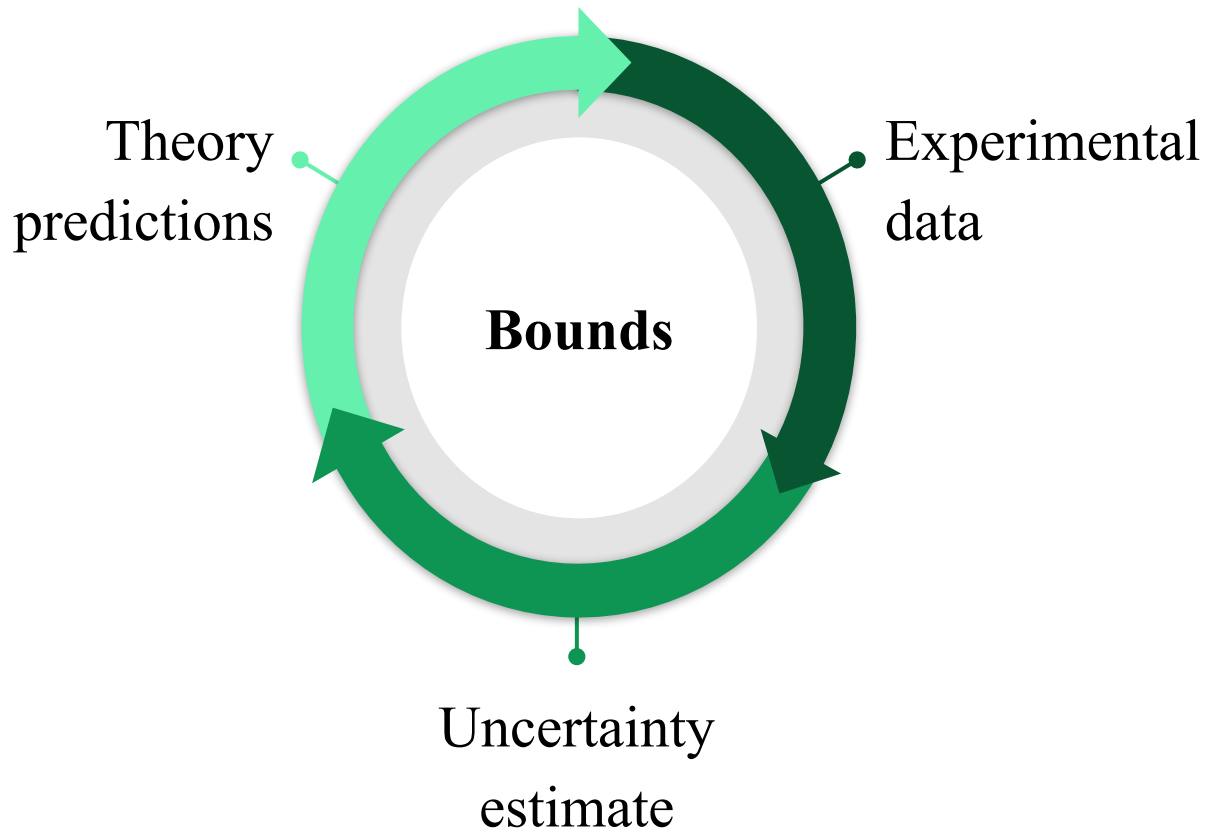
Precise SM predictions

Precise EFT predictions

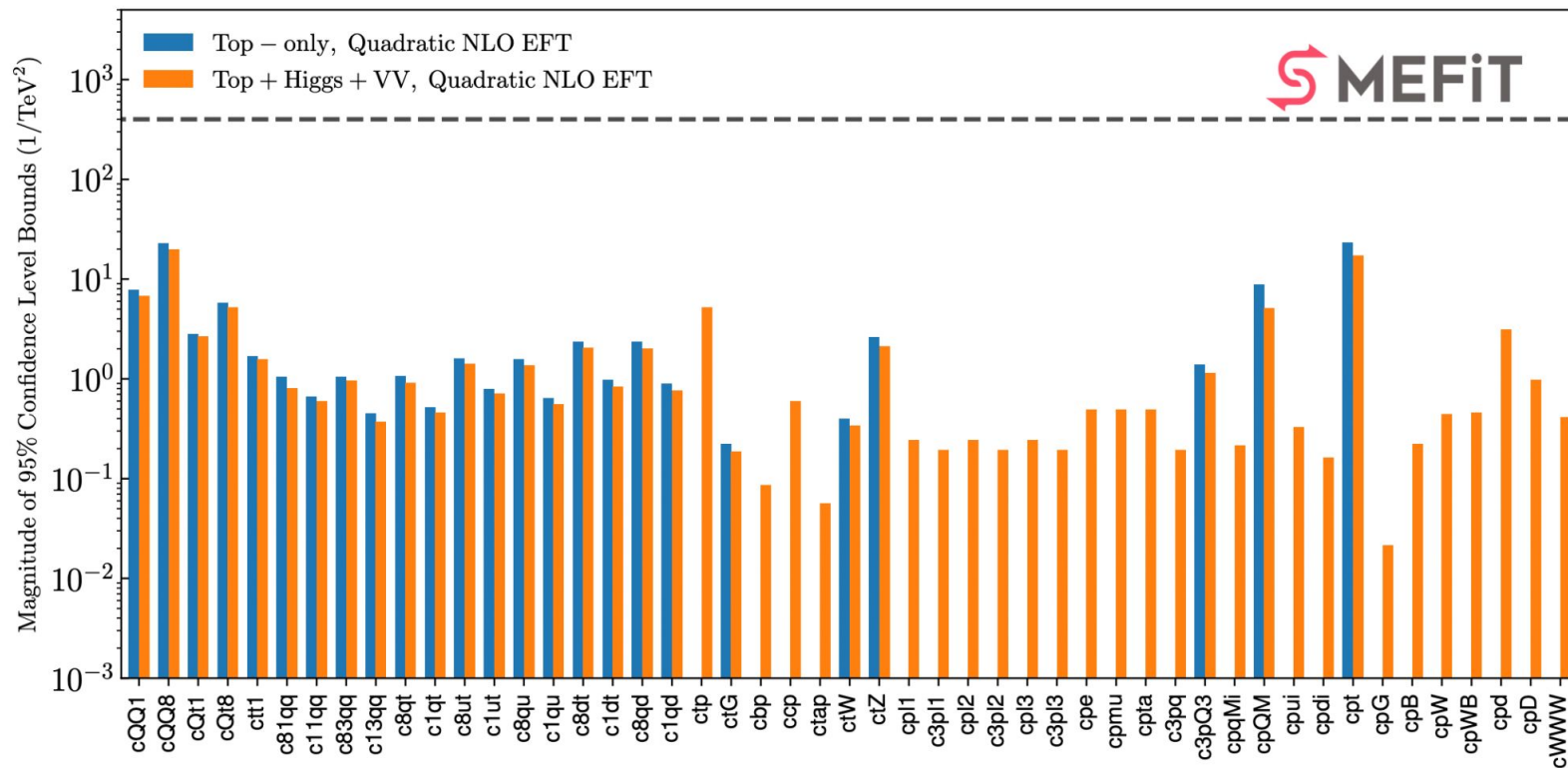
Constraints  $\frac{1}{\Lambda^2} c_i^6(\mu)$

**To constraint SMEFT, we need fits..**

# Global fits



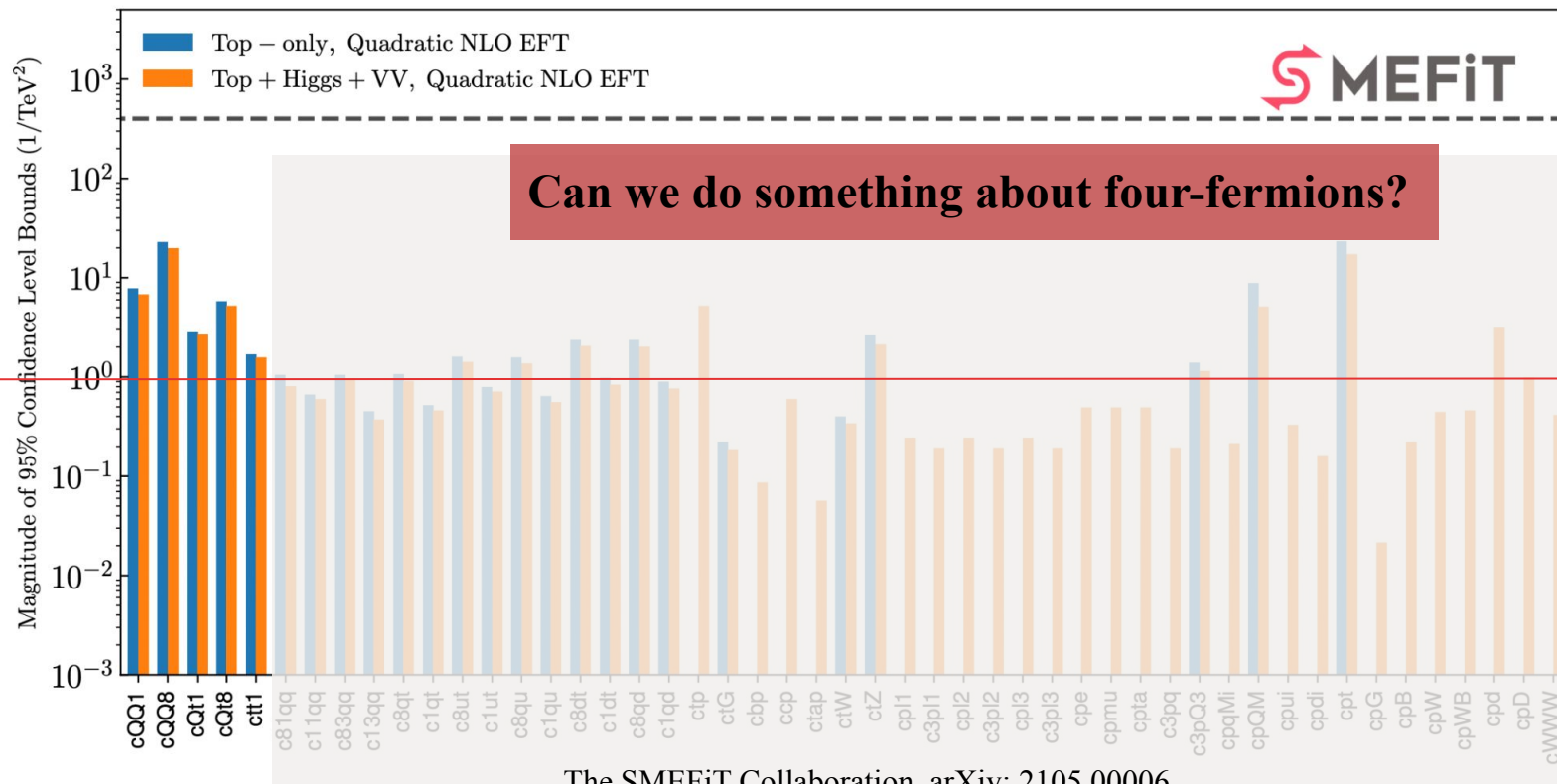
# Global fits: results



The SMEFiT Collaboration, arXiv: 2105.00006



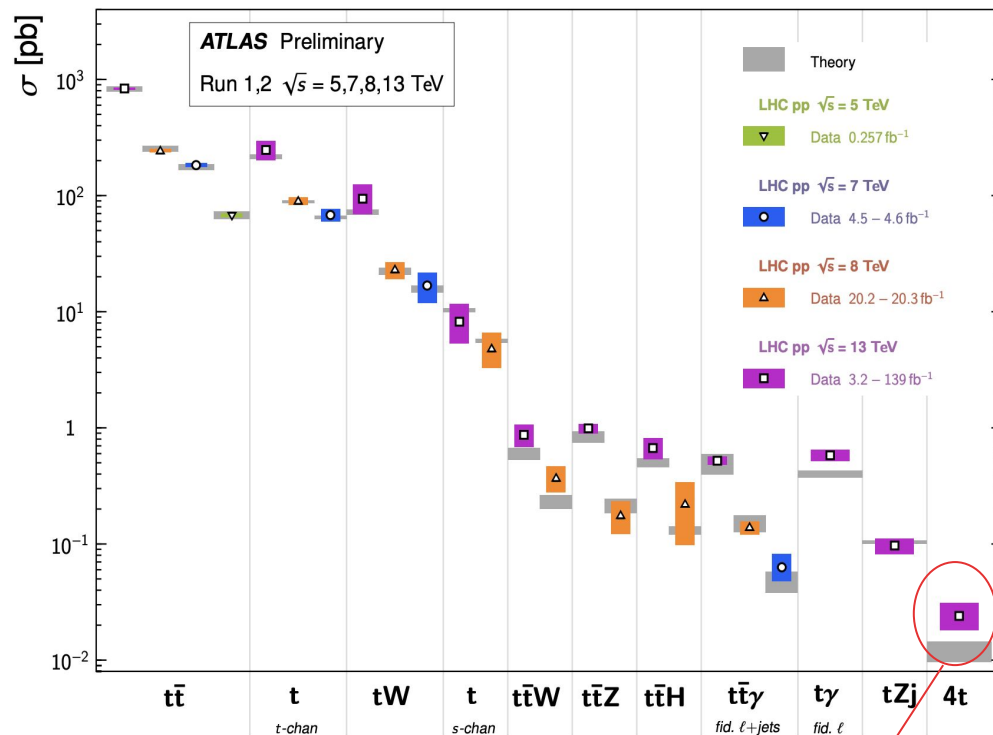
# Global fits: results



# Four tops in SMEFT

## Top Quark Production Cross Section Measurements

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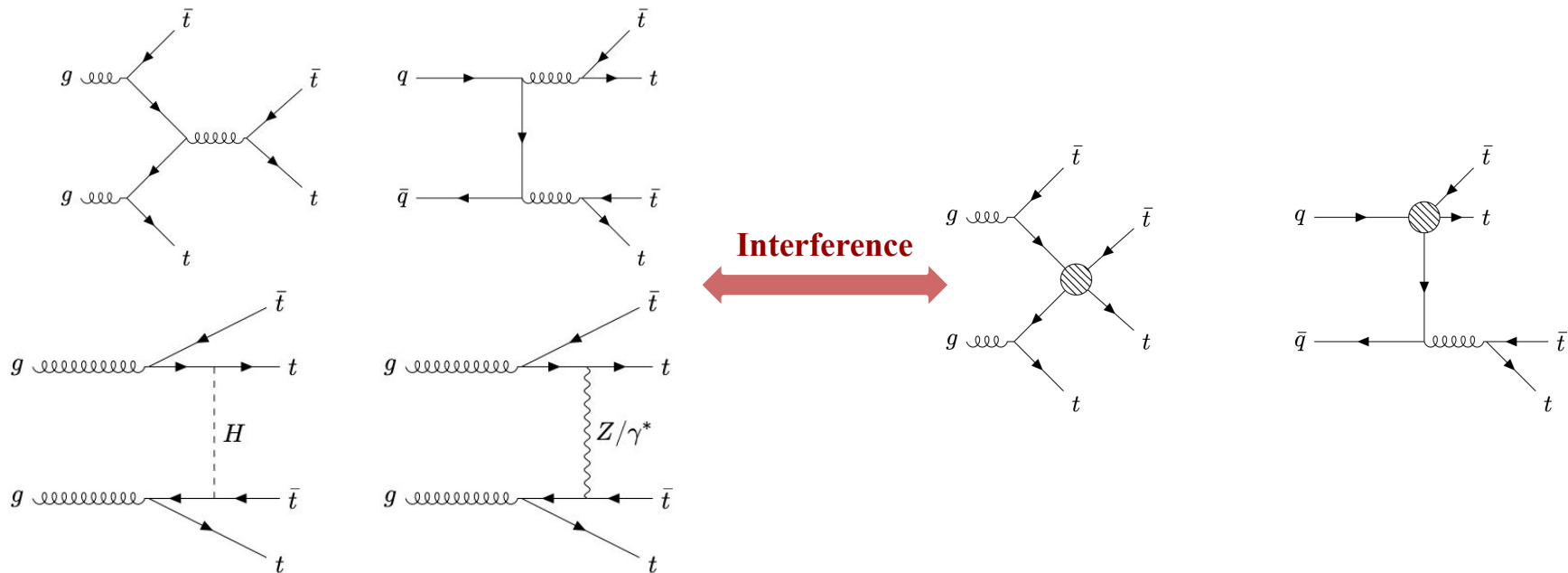
$tttt$  in SM  $\sim$   
0.02 pb

# Be careful when doing four tops

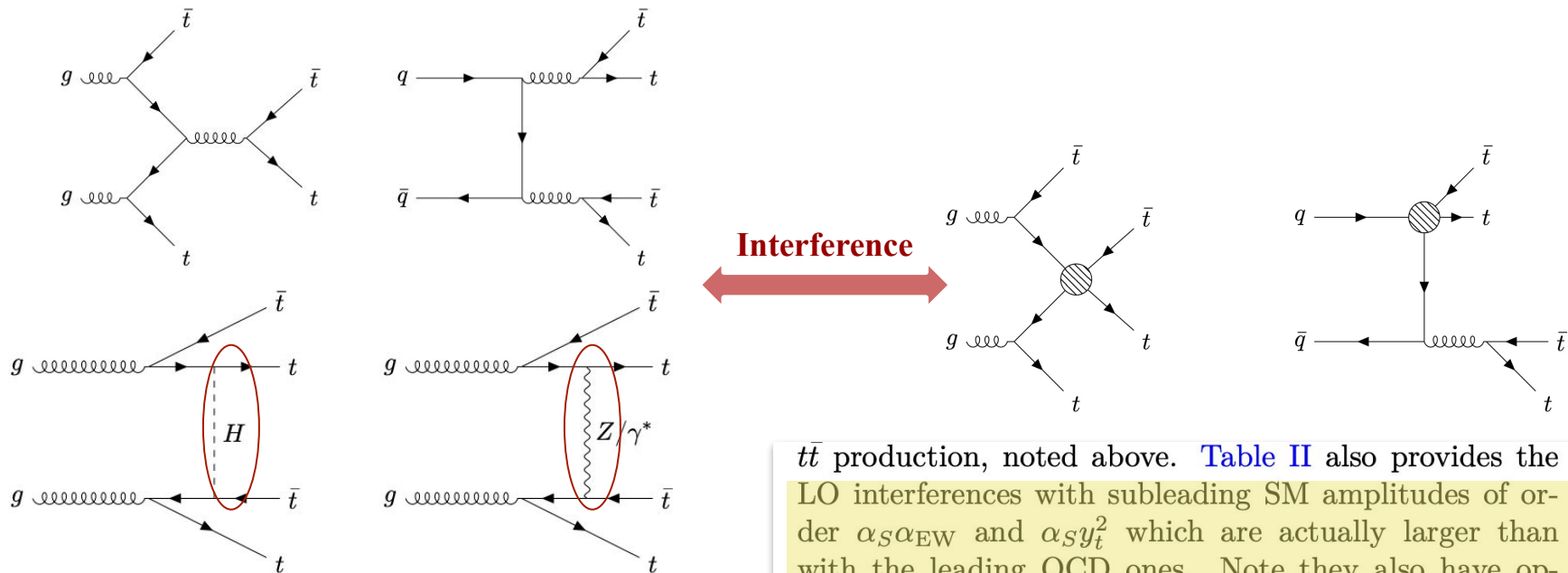
- Cao, Chen, Liu, arXiv: 1602.01934  
*“.. be careful at LO SM”*
- Frederix, Pagani, Zaro, arXiv: 1711.02116  
*“.. be careful at NLO SM”*
- Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, arXiv: 2008.11743  
*“.. be careful at SMEFT for some operators”*
- Aoude, HF, Maltoni, Vryonidou, arXiv: 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, ..]

# Four tops in SMEFT: interference

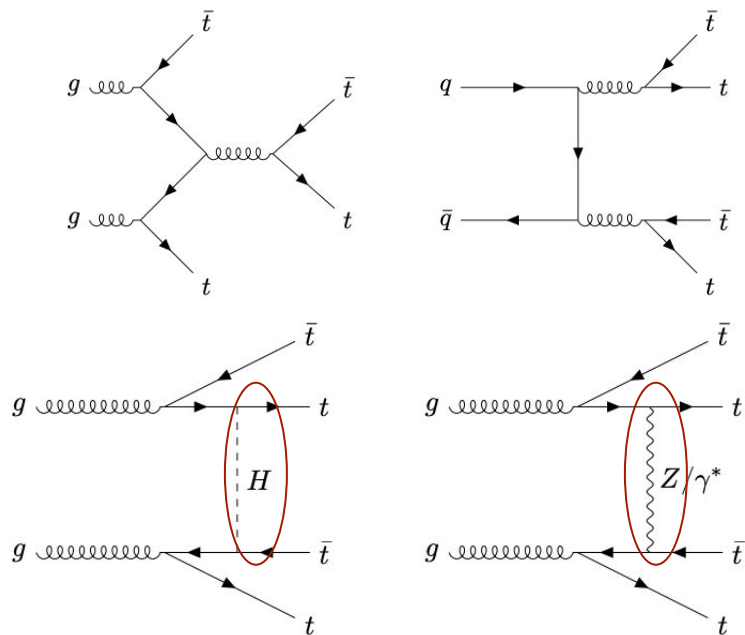


# Four tops in SMEFT: interference



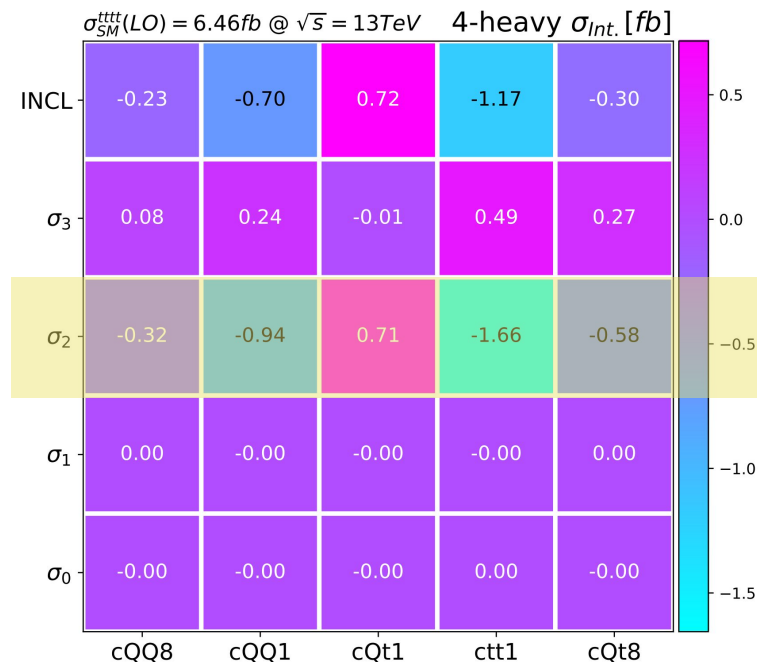
$t\bar{t}$  production, noted above. Table II also provides the LO interferences with subleading SM amplitudes of order  $\alpha_S\alpha_{EW}$  and  $\alpha_S y_t^2$  which are actually larger than with the leading QCD ones. Note they also have opposite signs. At the quadratic level, the NLO enhance-

# Four tops in SMEFT



4-heavy

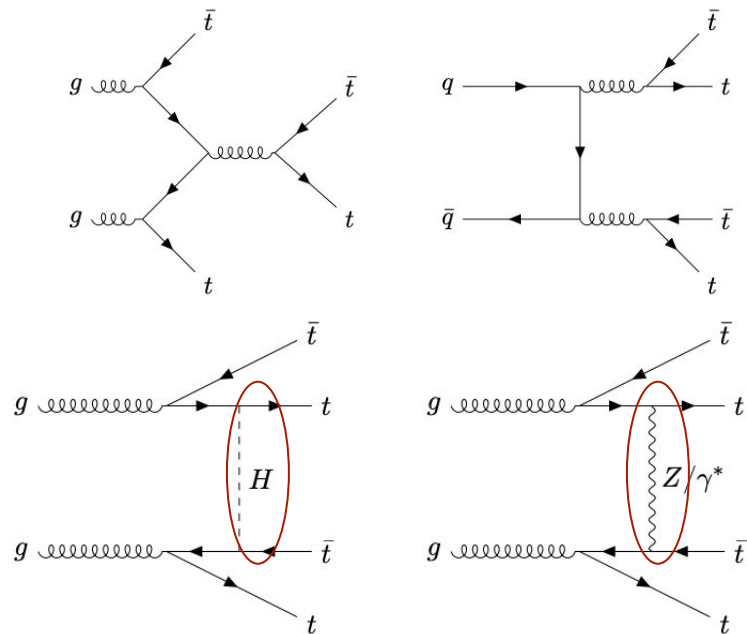
$\mathcal{O}_{QQ}^1$	cQQ1	$2[C_{qq}^{(1)}]^{3333} - \frac{2}{3}[C_{qq}^{(3)}]^{3333}$	$\mathcal{O}_{QQ}^8$	cQQ8	$8[C_{qq}^{(3)}]^{3333}$
$\mathcal{O}_{Qt}^1$	cQt1	$[C_{qu}^{(1)}]^{3333}$	$\mathcal{O}_{Qt}^8$	cQt8	$[C_{qu}^{(8)}]^{3333}$
$\mathcal{O}_{tt}^1$	ctt1	$[C_{uu}^{(1)}]^{3333}$			



**Electroweak contributions are important**

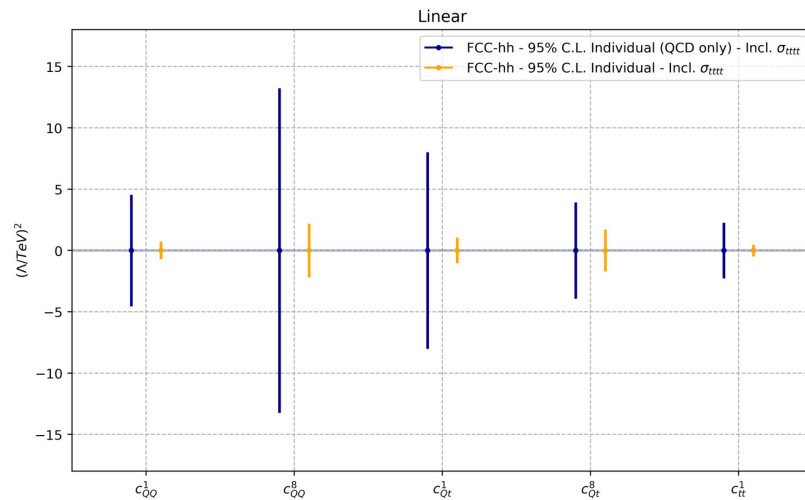
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# Four tops in SMEFT



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# Four tops in SMEFT

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$\mathcal{O}_{tt}^1$	ctt1	$[C_{tu}^{(1)}]_{3333}$			

	4H	2L2H	2F	0F
$\sigma_4$	×	×	$c_{tG}$	$c_G$
$\sigma_3$	-	$c_{Qq}^{83}, c_{Qu}^8, c_{tq}^8, c_{Qd}^8, c_{tu}^8, c_{td}^8, c_{Qq}^{81}$ $c_{Qq}^{11}, c_{Qu}^1, c_{tq}^1, c_{Qd}^1, c_{tu}^1, c_{td}^1$	$c_{t\varphi}, c_{tZ}, c_{tW}$	-
$\sigma_2$	$c_{QQ}^8, c_{QQ}^1, c_{Qt}^8, c_{Qt}^1, c_{tt}^1$	$c_{Qq}^{31}$	$c_{\varphi t}, c_{\varphi Q}^{(-)}$	-
$\sigma_1$	-	-	-	$c_{\varphi G}$
$\sigma_0$	-	-	-	-

sub-leading

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962



Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

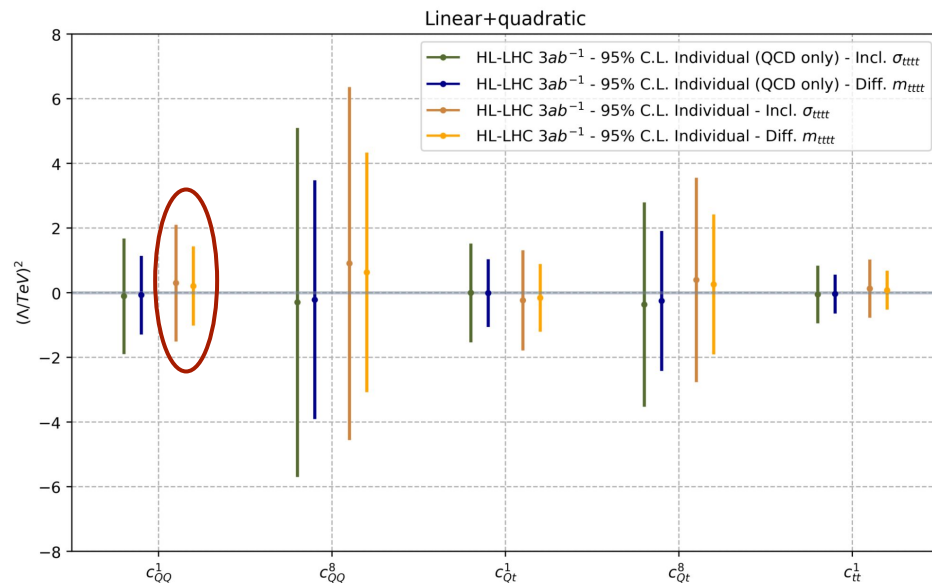
Electroweak contributions are important



# Four tops in SMEFT

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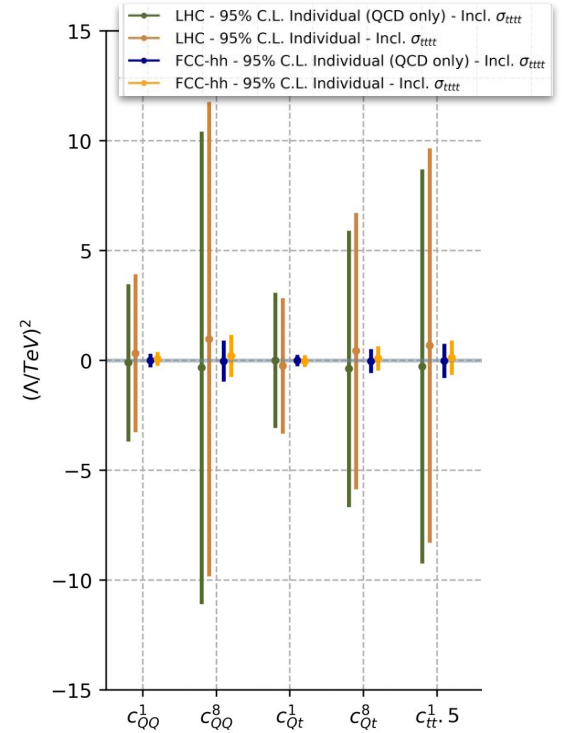
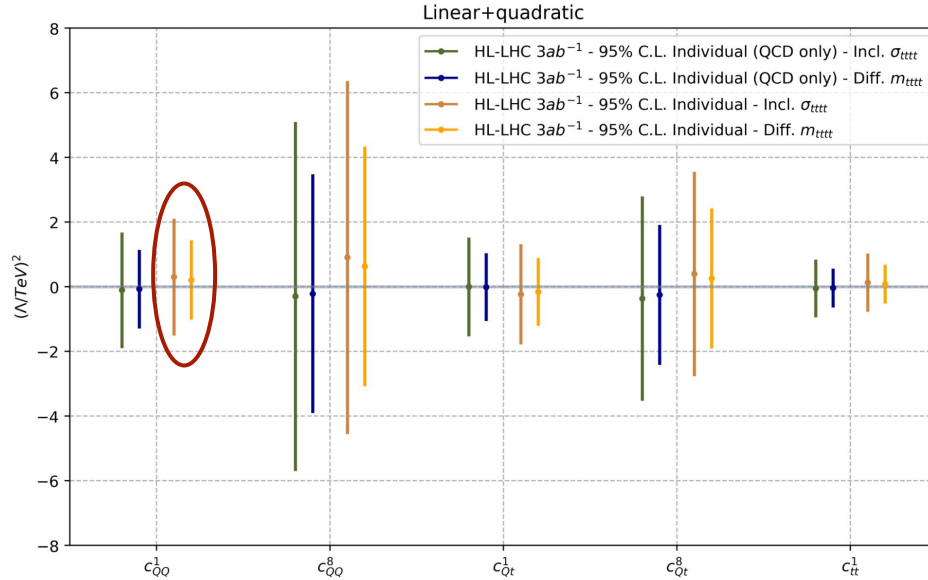
- Differential information is important

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

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$\mathcal{O}_{tt}^1$	ctt1	$[C_{uu}^{(1)}]^{3333}$			



- Differential information is important
- FCC-hh provides a good handle

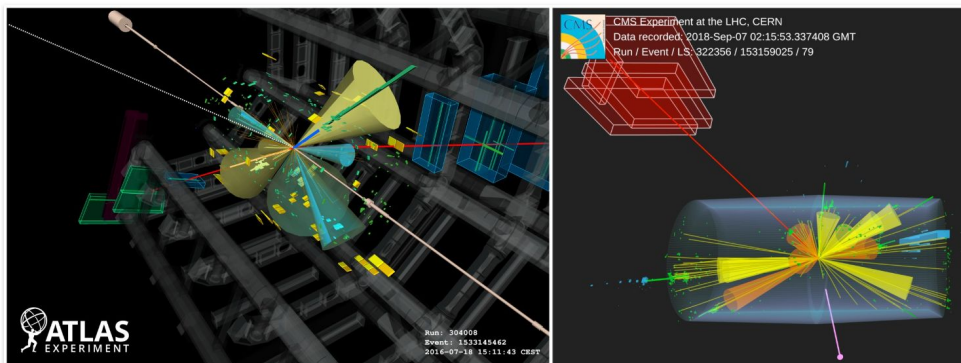
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# Four tops finally observed!

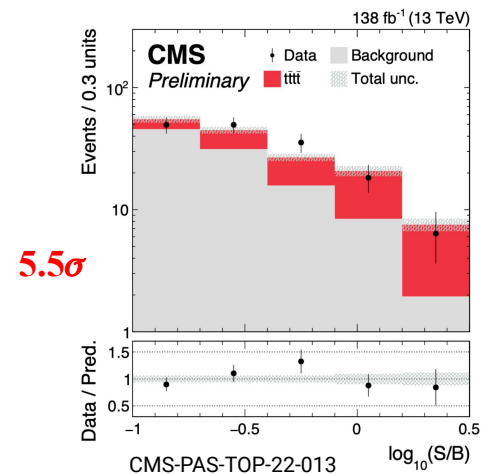
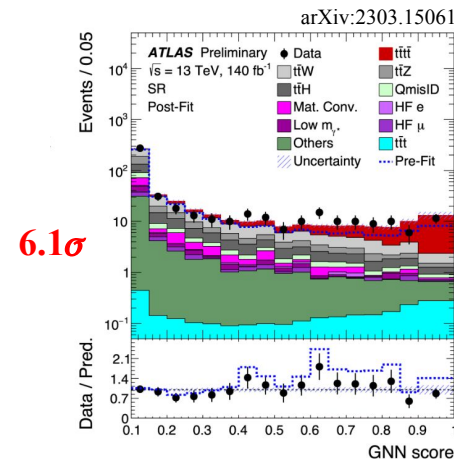
## ATLAS and CMS observe simultaneous production of four top quarks

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).



# Summary

- SMEFT is a tool to **parametrise and constrain** potential new physics systematically
- Four top quark production is a rare process with **exciting features for new physics scenarios**
- Four tops with SMEFT insertions requires **considering predictions with sub-leading orders in the strong coupling**
- Differential information can provide a **firm handle on SMEFT bounds** for four-fermion operators, also FCC-hh energies
- Four tops has been finally **observed**