# Top quark(s) in SMEFT

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MANCHESTER 1824
The University of Manchester

European Research Council
Established by the European Commission

Lunch seminar, King’s College London, April 2023

# Outline

Introduction; top quark in SMEFT and global fits

Two rare top quark processes in SMEFT

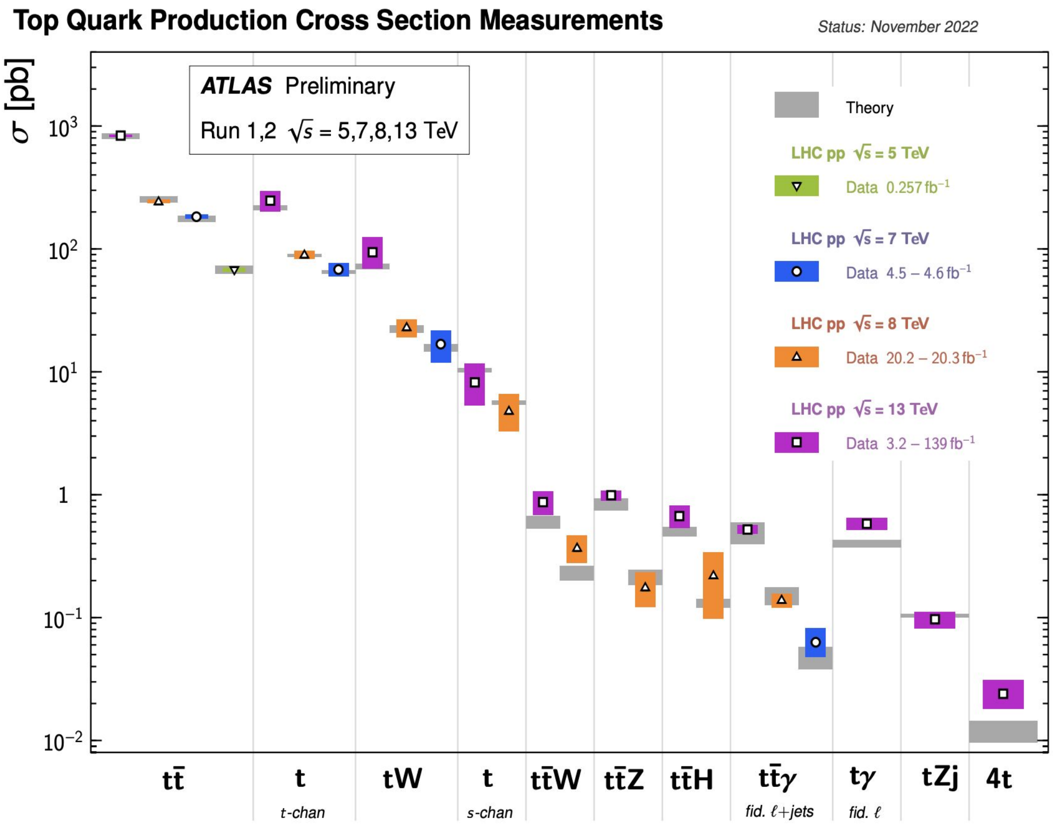
A glimpse of the future

# 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



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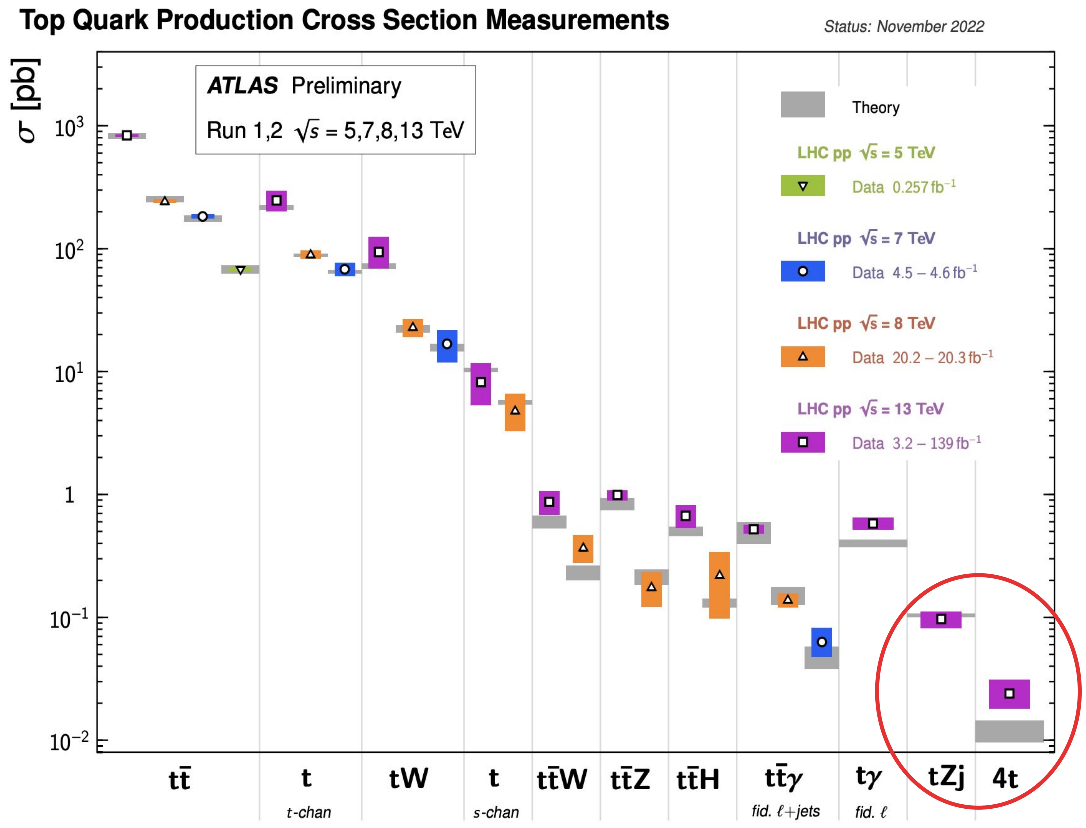


# Into effective field theories and SMEFT

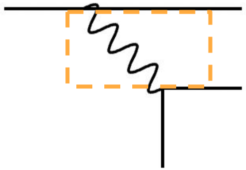
Shutterstock

# EFT in a nutshell

Energy

SM

$$\mathcal{A} = \frac{g_L^2}{2}\overline{x}(k_3)\sigma_\rho x(p)\boxed{\frac{1}{q^2 - m_W^2}}\overline{x}(k_1)\sigma_\rho y(k_2)$$



Low Energy

# EFT in a nutshell

Energy

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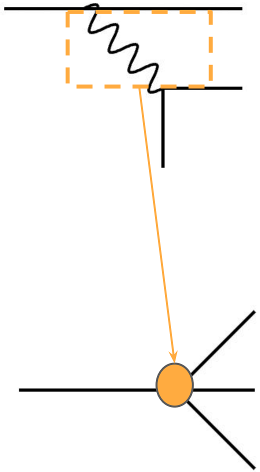
Assume W-boson mass is larger than all other scales...

Low Energy

$$\mathcal{A} \approx -\frac{g_L^2}{\boxed{2m_W^2}}[\overline{x}(k_3)\sigma_\rho x(p)\overline{x}(k_1)\sigma_\rho y(k_2)]\boxed{[1 + \mathcal{O}(q^2/m_W^2)]}$$



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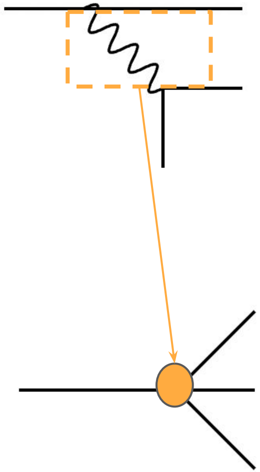


# EFT in a nutshell

*'I have no idea what is going on here. I will call it v.'*

$v = 2m_W/g_L$

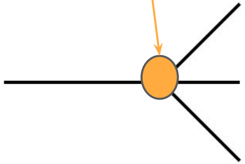
Energy

SM

Low Energy

Assume W-boson mass is larger than all other scales...

$$\mathcal{A} \approx -\frac{g_L^2}{\boxed{2m_W^2}}[\bar{x}(k_3)\sigma_\rho x(p)\bar{x}(k_1)\sigma_\rho y(k_2)]\boxed{[1+\mathcal{O}(q^2/m_W^2)]}$$



# SMEFT in a nutshell

Energy

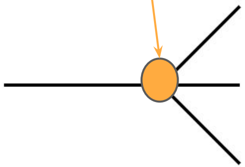
UV

$\Lambda$

Assume new physics is larger than all other scales...

SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum_i \boxed{\frac{c_i}{\Lambda^2} Q_i^{dim-6}} + \dots$$



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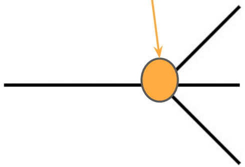


**UV physics projected onto the low-energy dynamics**

# SMEFT in a nutshell

*'We have no idea what is going on here. We will call it $c/\Lambda^2$.'*

Energy

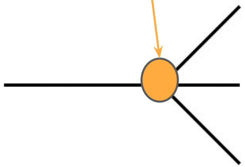
UV

$\Lambda$

Assume new physics is larger than all other scales...

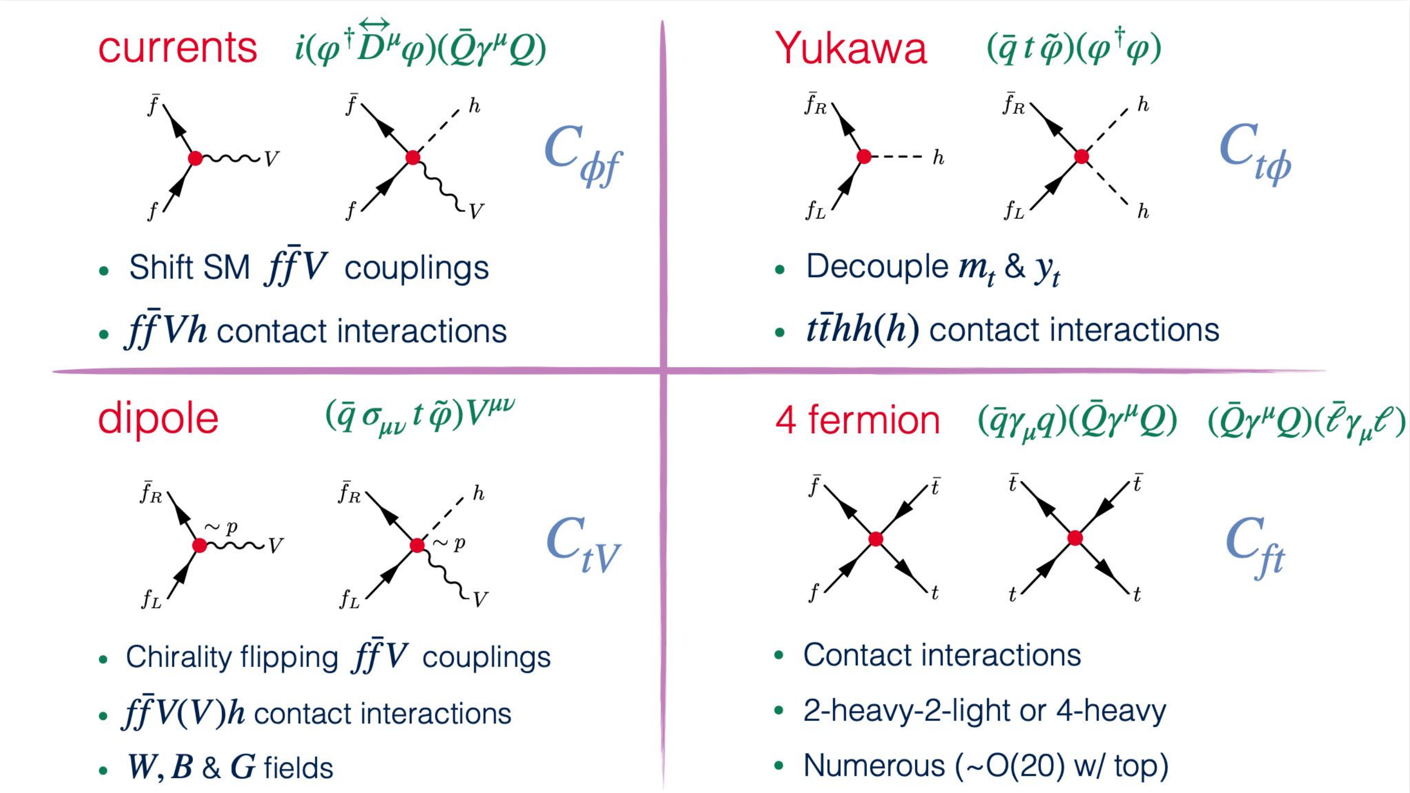
SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum_i \boxed{\frac{c_i}{\Lambda^2} Q_i^{dim-6}} + \ldots$$



**UV physics projected onto the low-energy dynamics**

# Top quark operators in SMEFT




By Ken Mimasu

# Pragmatic SMEFT

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

Precise EFT predictions

Precise SM predictions

Precise experimental measurements

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

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

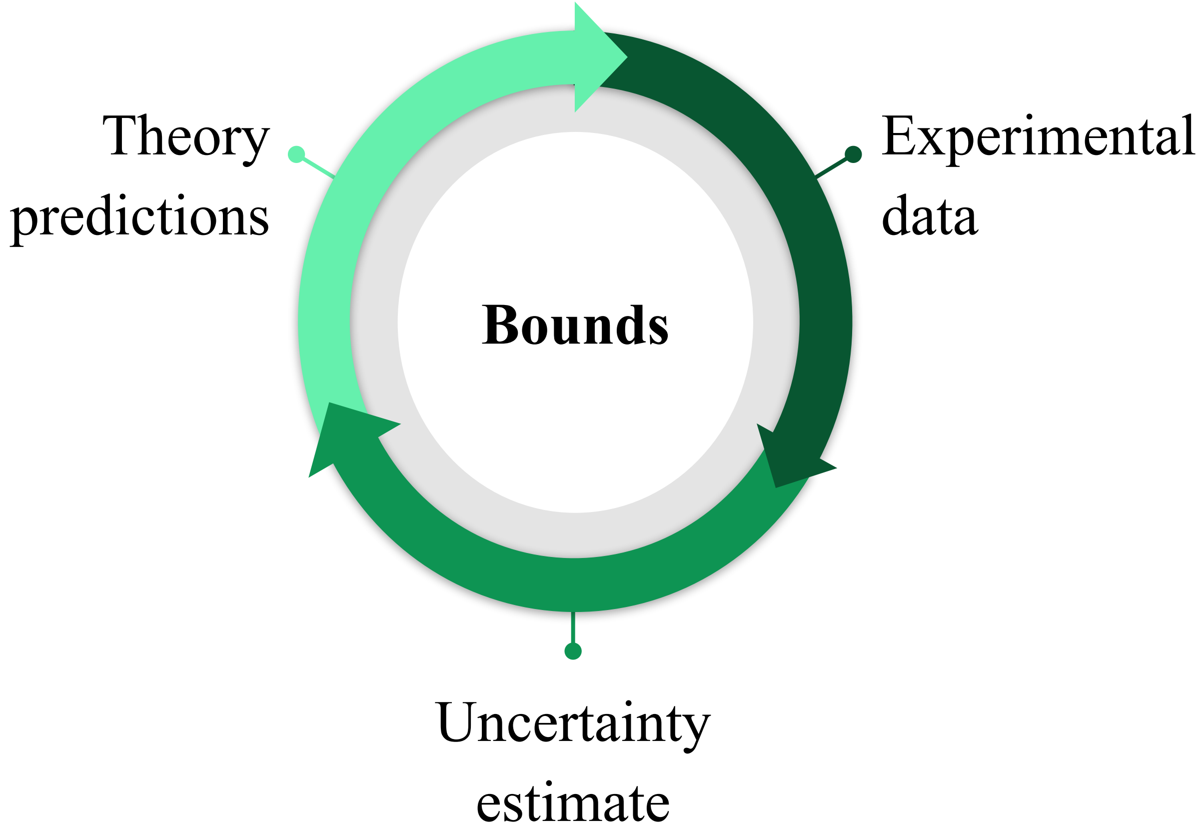
**Adapted from a slide by Eleni Vryonidou**

# Global fits: introduction

The ultimate motivation for doing SMEFT

It is complicated; high-dimensional parameter space leading from a few to hundreds of coefficients to be constrained

# Global fits: introduction



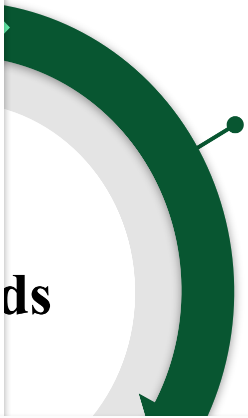
# Global fits: tools [non-exhaustive]

**Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory**

`Fitmaker`

John Ellis,[a,b,c] Maeve Madigan,[d] Ken Mimasu,[a] Veronica Sanz[e,f] and Tevong You[b,d,g]

[a] *Theoretical Particle Physics and Cosmology Group, Department of Physics, King's College London, London WC2R 2LS, UK*
[b] *Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
[c] *National Institute of Chemical Physics & Biophysics, Rävala 10, 10143 Tallinn, Estonia*
[d] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK*
[e] *Instituto de Física Corpuscular (IFIC), Universidad de Valencia-CSIC, E-46980 Valencia, Spain*
[f] *Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK*
[g] *Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, UK*

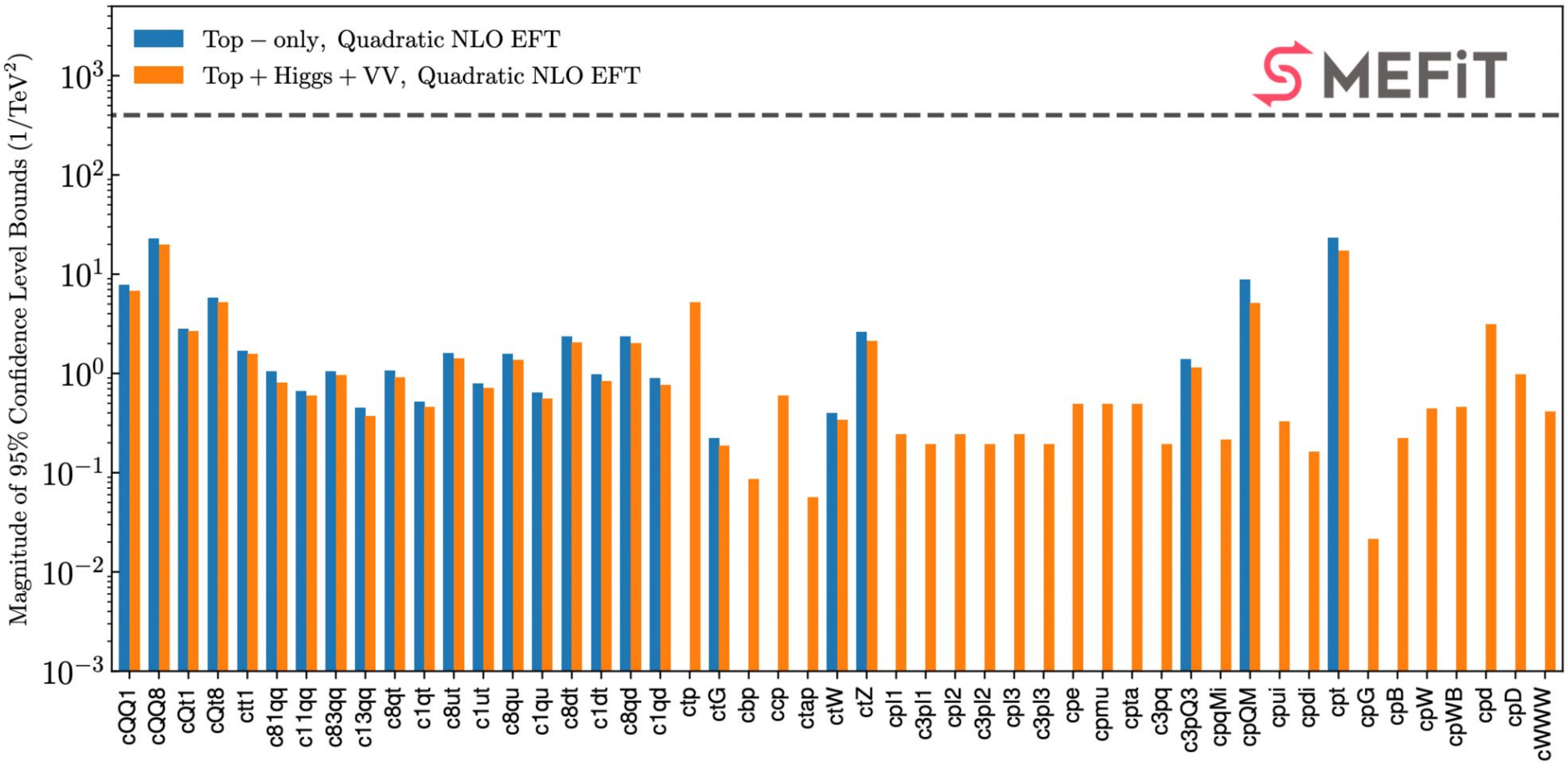



SMEFiT

## Project description

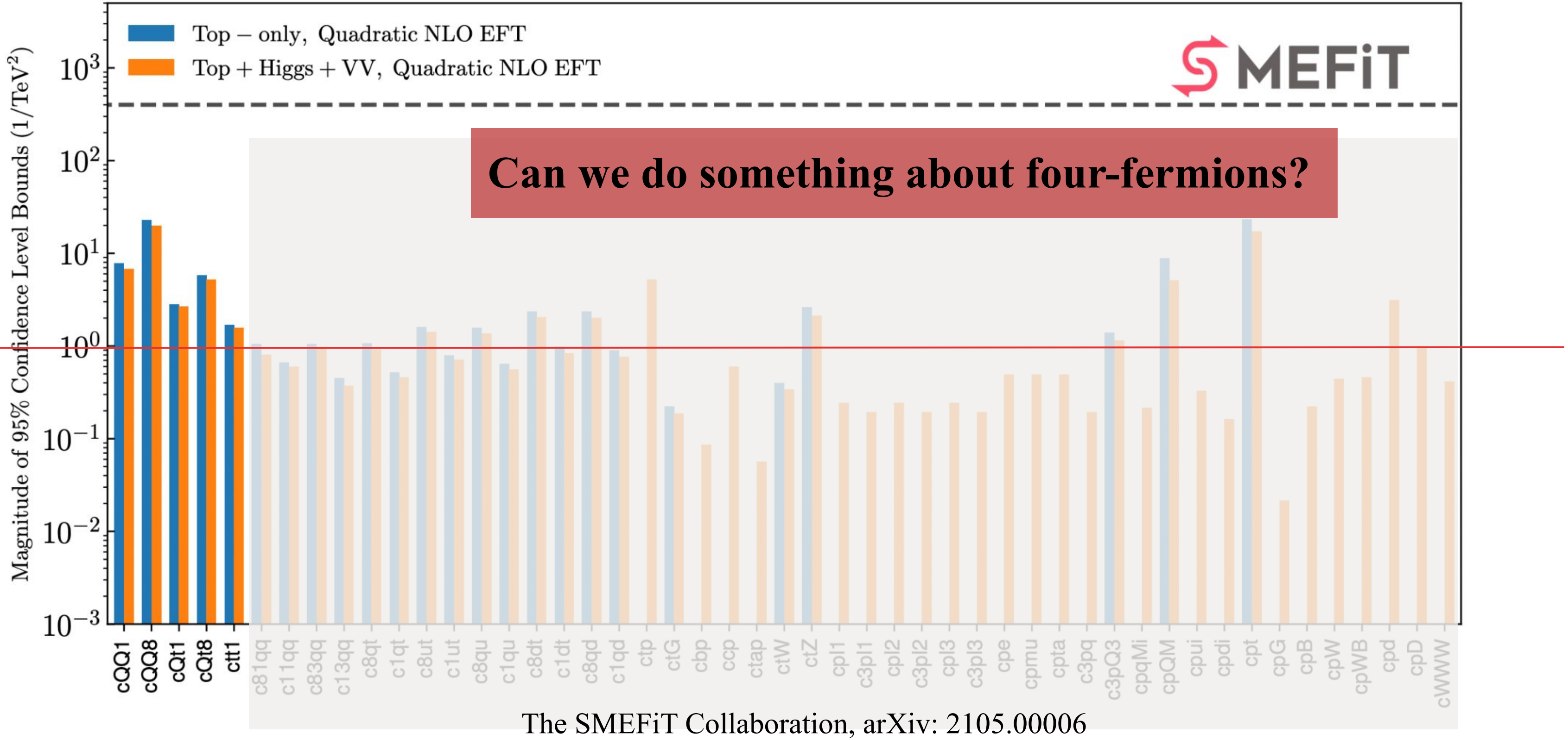
SMEFiT is a Python package for global analyses of particle physics data in the framework of the Standard Model Effective Field Theory (SMEFT). The SMEFT represents a powerful model-independent framework to constrain, identify, and parametrize potential deviations with respect to the predictions of the Standard Model (SM). A particularly attractive feature of the SMEFT is its capability to systematically correlate deviations from the SM between different processes. The full exploitation of the SMEFT potential for indirect New Physics searches from precision measurements requires combining the information provided by the broadest possible dataset, namely carrying out extensive global analysis which is the main purpose of SMEFiT.

# Global fits: results



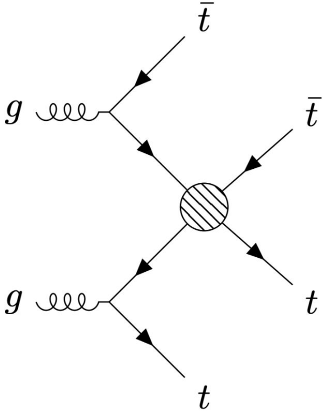

The SMEFiT Collaboration, arXiv: 2105.00006

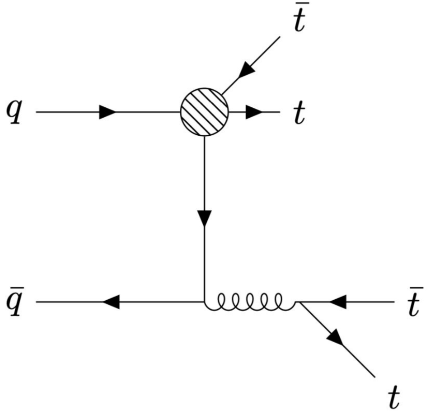
# Global fits: results



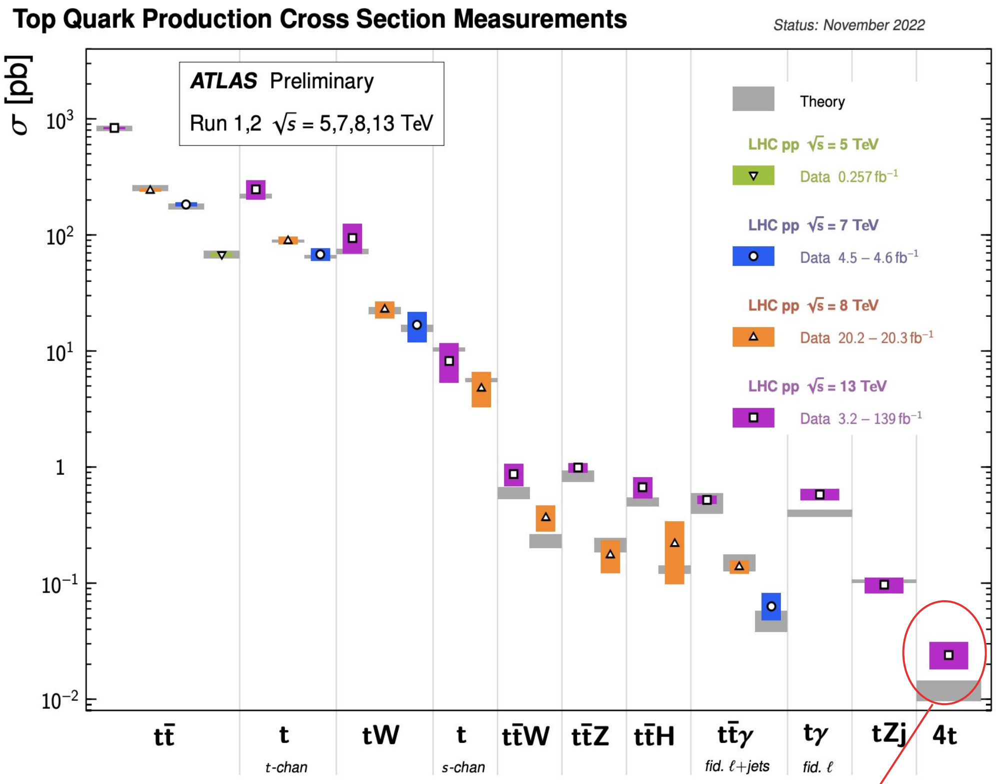

The SMEFiT Collaboration, arXiv: 2105.00006

# Four tops in SMEFT



# Four tops in SMEFT




tttt in SM ~ 0.02 pb

# Be careful when doing four tops

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

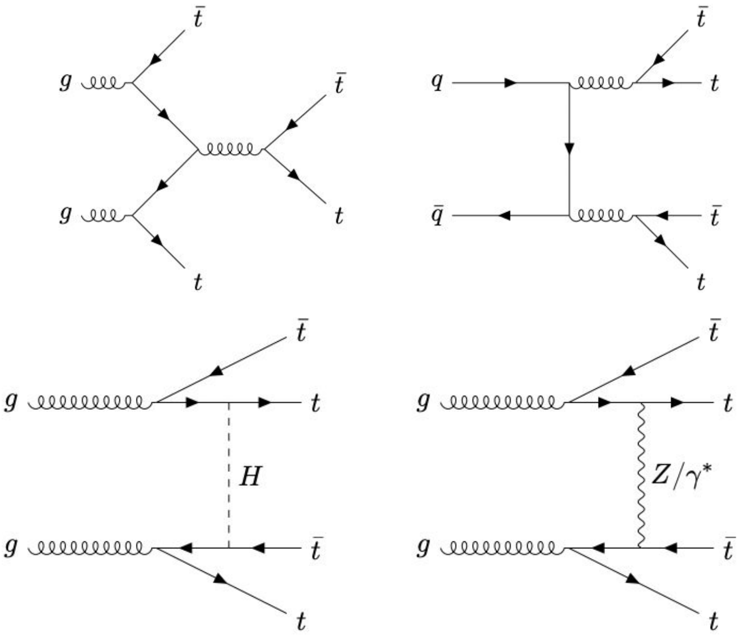
- Frederix, Pagani, Zaro, arXiv: 1711.02116
  *".. be careful at NLO SM"*

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

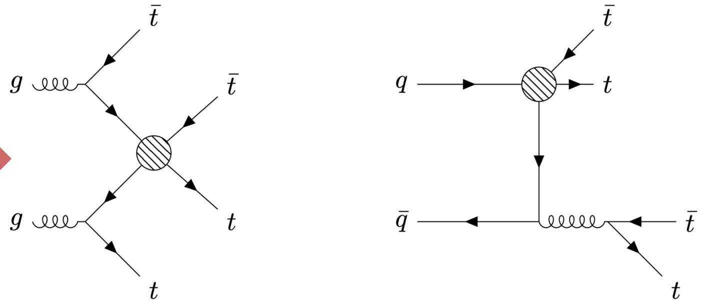
- Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962
  "*..we are being careful at SMEFT for all operators*"

.. 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




Interference



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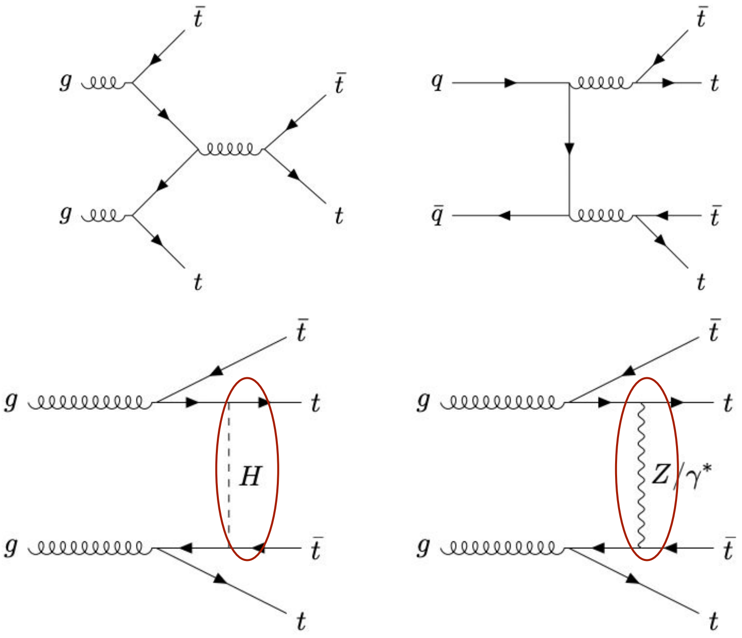
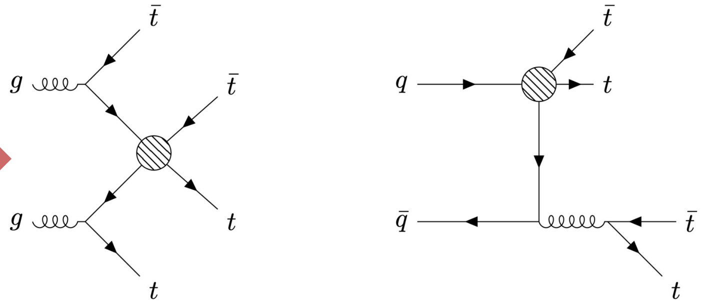



**Interference**



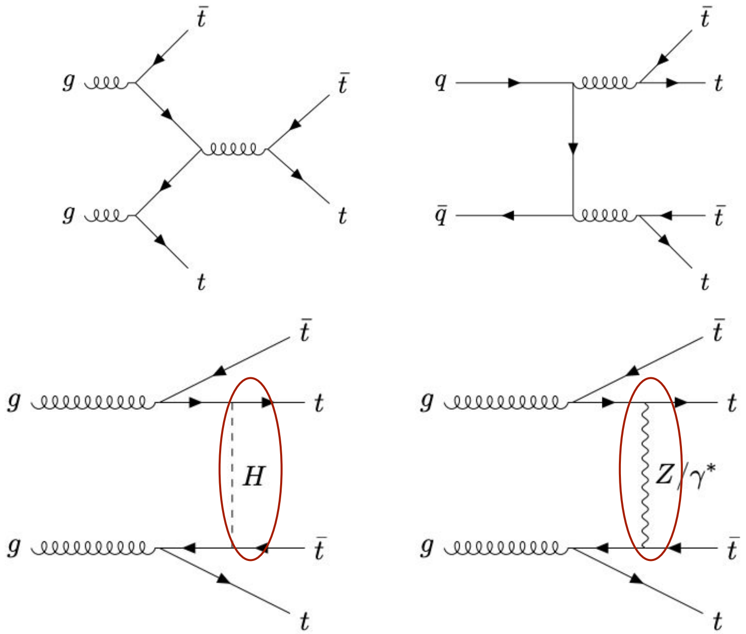

$t\bar{t}$ production, noted above. Table II also provides the LO interferences with subleading SM amplitudes of order $\alpha_S\alpha_{\rm EW}$ and $\alpha_S y_t^2$ which are actually larger than with the leading QCD ones. Note they also have opposite signs. At the quadratic level, the NLO enhance-

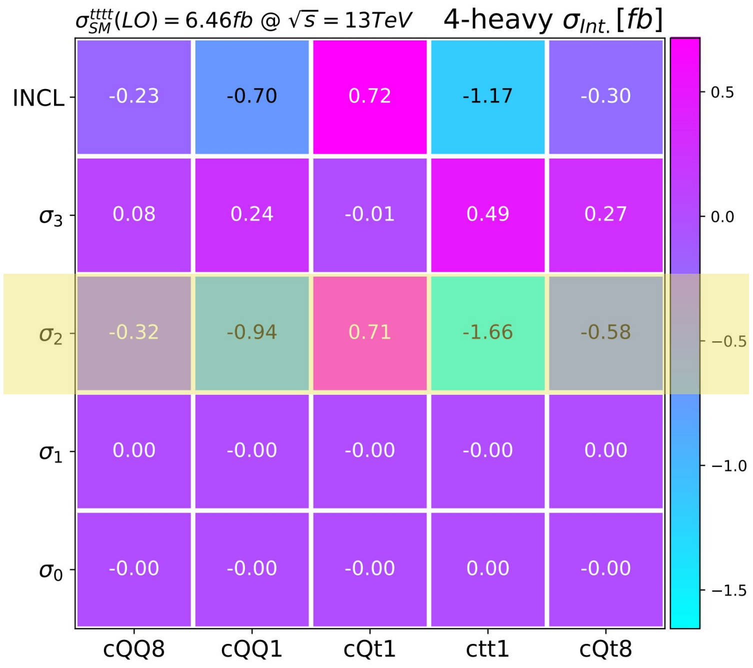
Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, arXiv: 2008.11743

# 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

# Four tops in SMEFT

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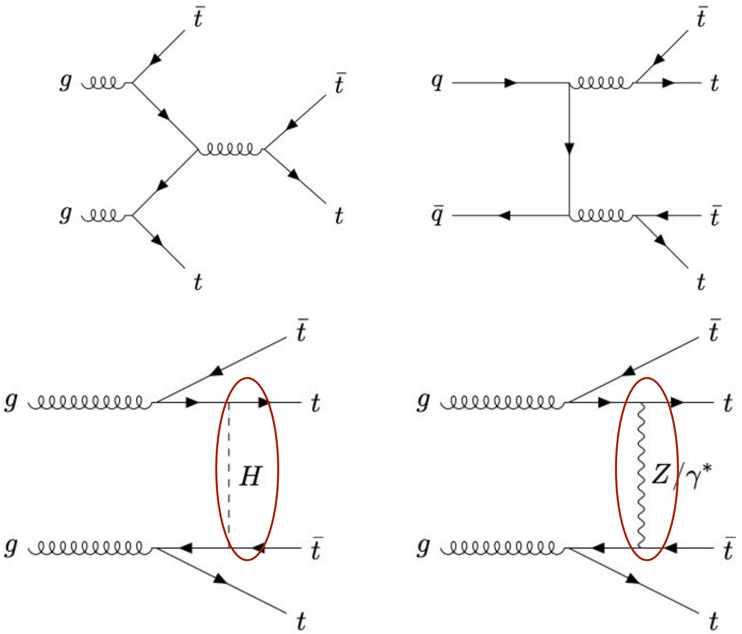


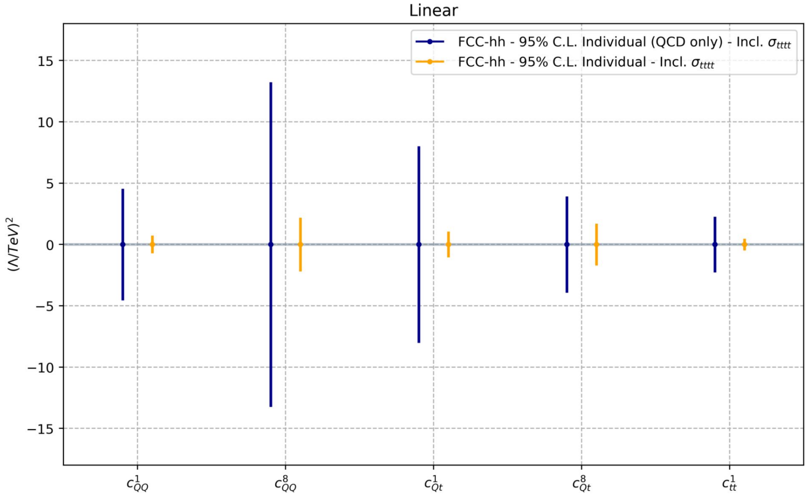


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| $\mathcal{O}^1_{tt}$ | ctt1 | $[C^{(1)}_{uu}]^{3333}$ | | | |

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

**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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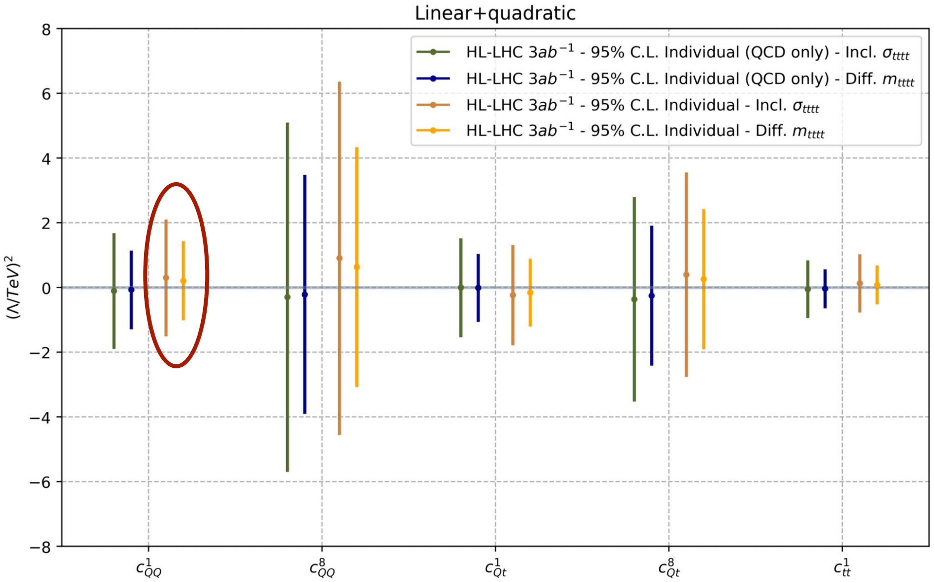


- **Differential information is important**

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

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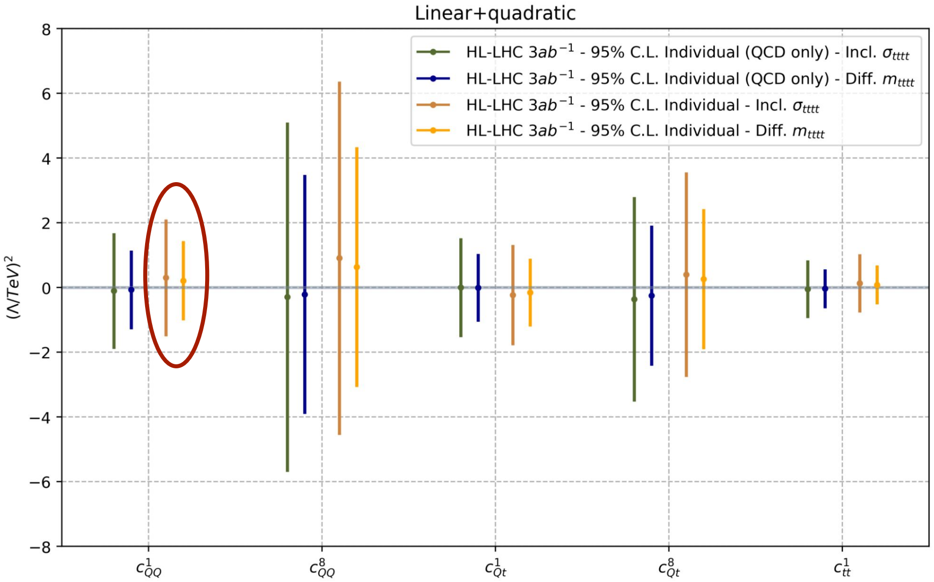
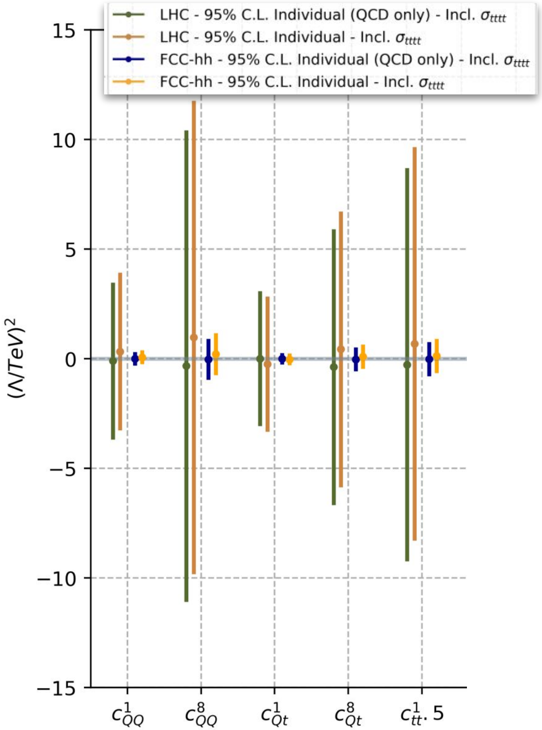
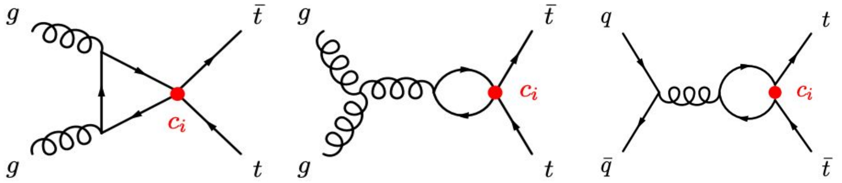


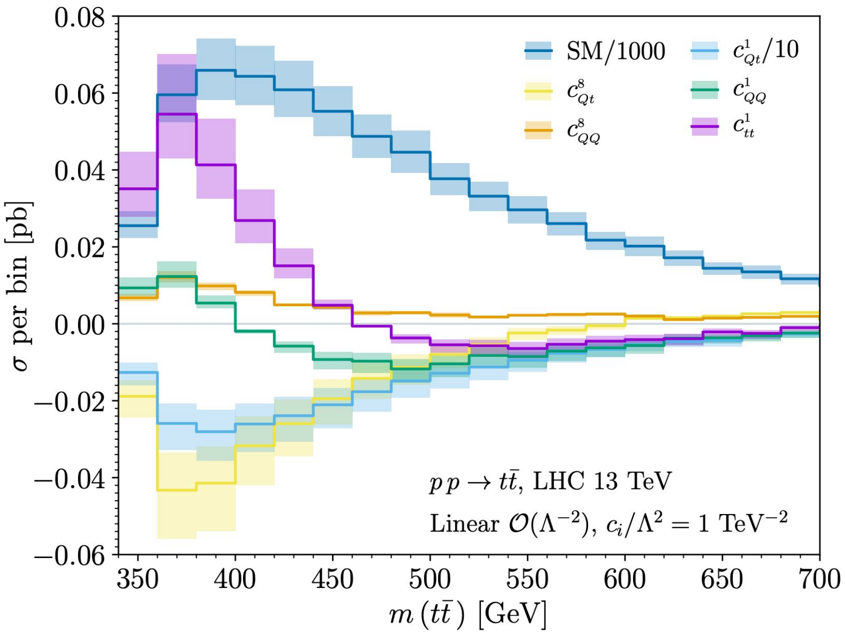

- **Differential information is important**
- **FCC-hh provides a good handle**

Aoude, HF, Maltoni, Vryonidou, arXiv: 2208.04962

# Four-fermion in SMEFT: one loop in top pair

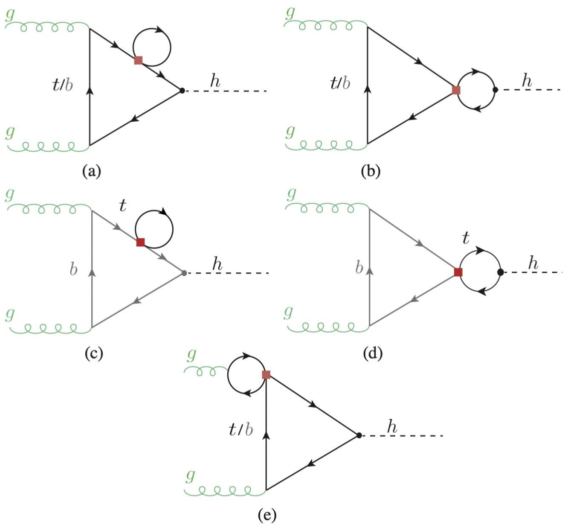


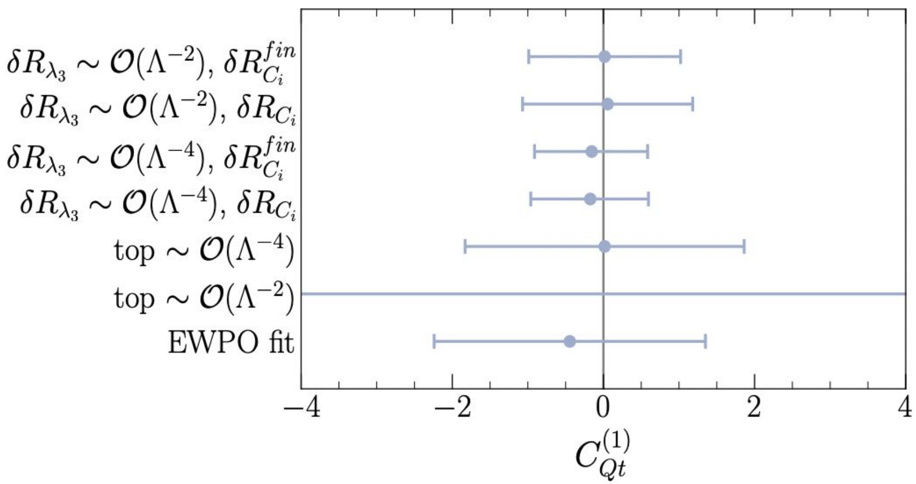

| | | | | | |
|---|---|---|---|---|---|
| $c^8_{QQ}$ | $0.0586^{+27\%}_{-25\%}$ | $0.125^{+10\%}_{-11\%}$ | | $0.00628^{+13\%}_{-16\%}$ | $0.0133^{+7\%}_{-5\%}$ |
| $c^8_{Qt}$ | $0.0583^{+27\%}_{-25\%}$ | $-0.107(6)^{+40\%}_{-33\%}$ | | $0.00619^{+13\%}_{-16\%}$ | $0.0118^{+8\%}_{-5\%}$ |
| $c^1_{QQ}$ | $[-0.11^{+15\%}_{-18\%}]$ | $-0.039(4)^{+51\%}_{-33\%}$ | $[-0.12^{+7\%}_{-5\%}]$ | $0.0282^{+13\%}_{-16\%}$ | $0.0651^{+5\%}_{-6\%}$ |
| $c^1_{Qt}$ | $[-0.068^{+16\%}_{-18\%}]$ | $-2.51^{+29\%}_{-21\%}$ | $[-0.12^{+3\%}_{-6\%}]$ | $0.0283^{+13\%}_{-16\%}$ | $0.066^{+5\%}_{-6\%}$ |
| $c^1_{tt}$ | × | $0.215^{+23\%}_{-18\%}$ | | × | × |




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

# Four-fermion in SMEFT: one loop in single H




| $\langle C_{Qt}^{(1)} \rangle$ | 95% CI |
|---|---|
| 0.0 | [-1.0, 1.0] |
| 0.1 | [-1.1, 1.2] |
| -0.2 | [-0.9, 0.6] |
| -0.2 | [-1.0, 0.6] |
| 0.0 | [-1.8, 1.9] |
| -18.0 | [-195.0, 159.0] |
| -0.4 | [-2.2, 1.4] |

Alasfar, Blas, Gröber, arXiv:2202.02333

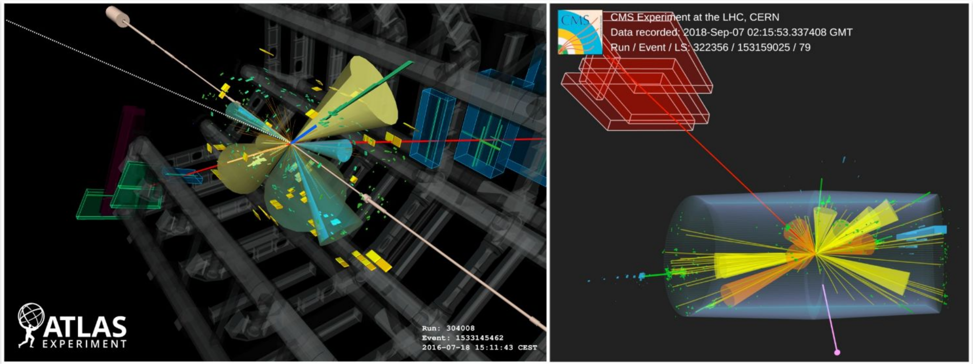
**H data bounds are competitive with ones from top**

# 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**

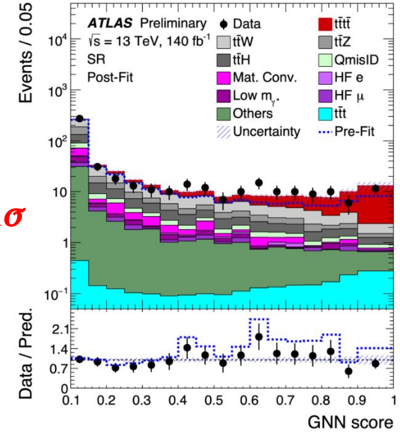
24 MARCH, 2023 | By Naomi Dinmore



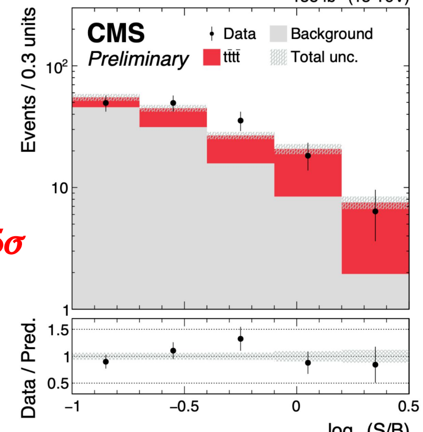

Event displays of four-top-quark production from ATLAS (left) and CMS (right).

arXiv:2303.15061

6.1$\sigma$

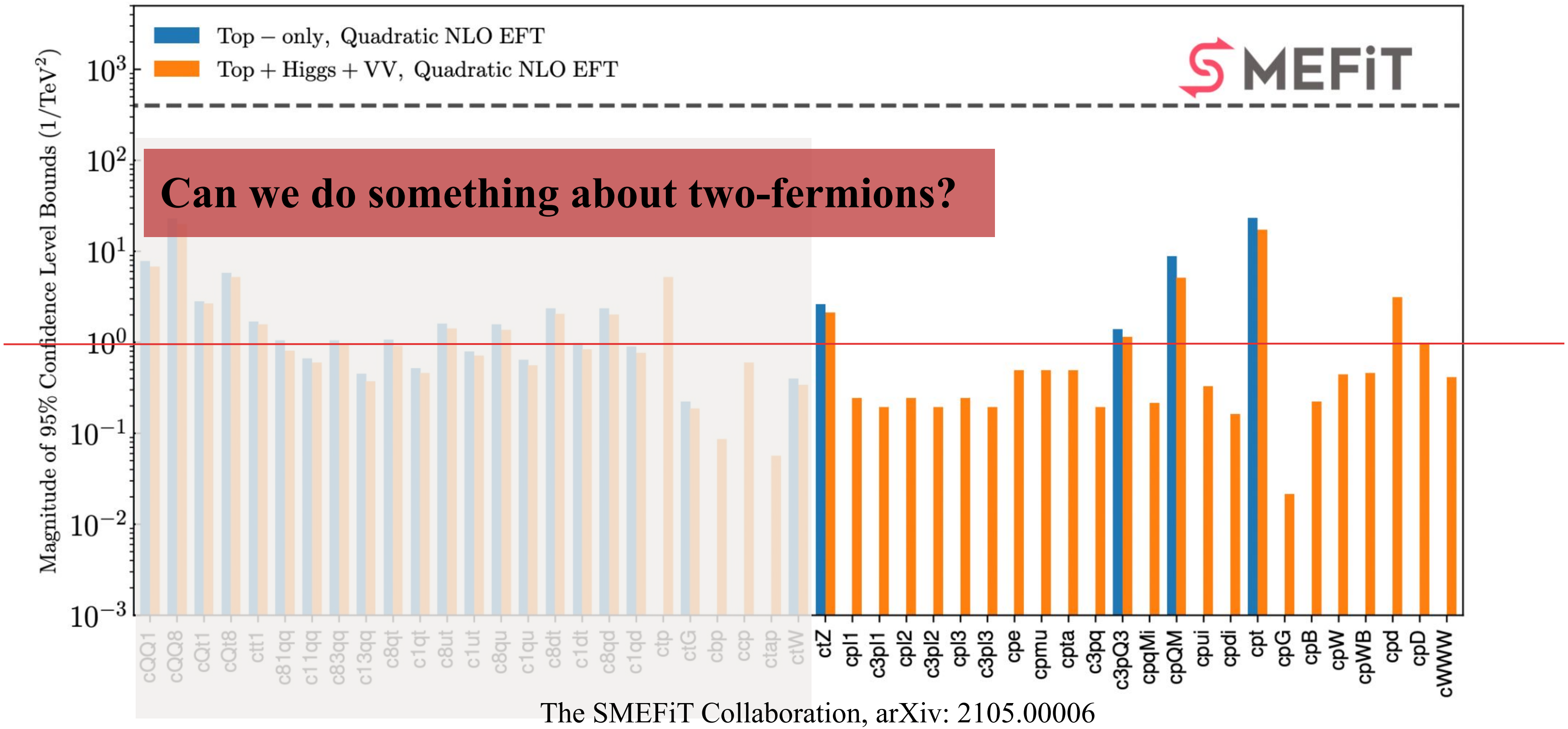



5.5$\sigma$



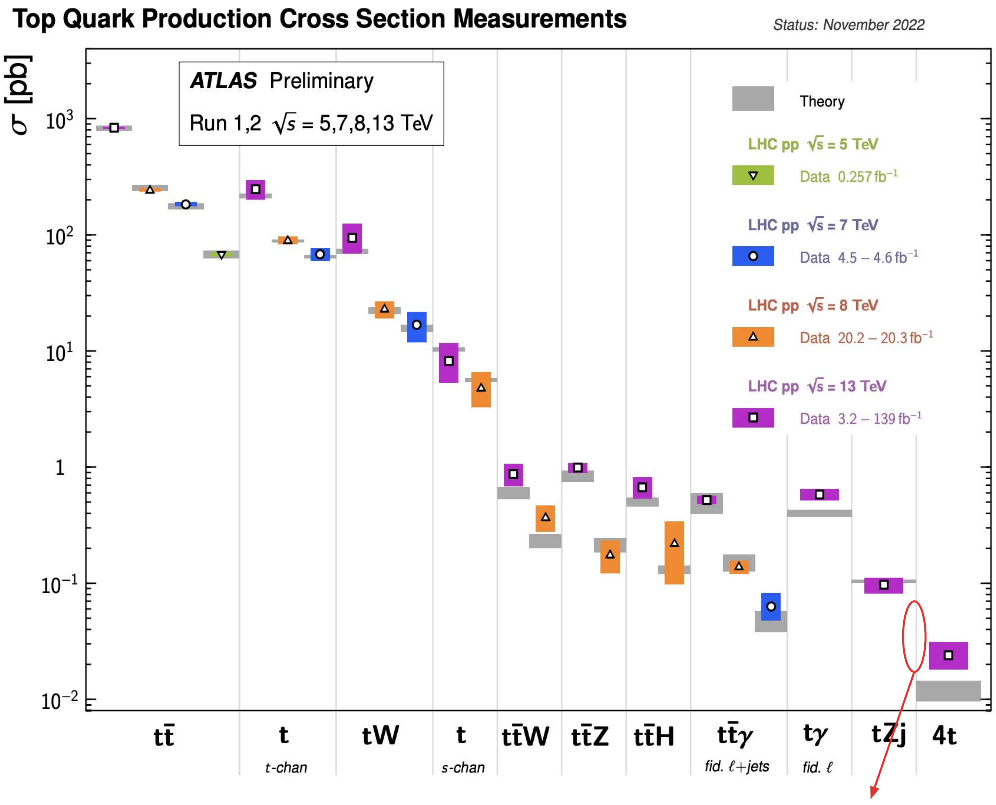

CMS-PAS-TOP-22-013

# Global fits: results




The SMEFiT Collaboration, arXiv: 2105.00006

# tWZ in SMEFT




tWZ in SM
~ 0.1 pb

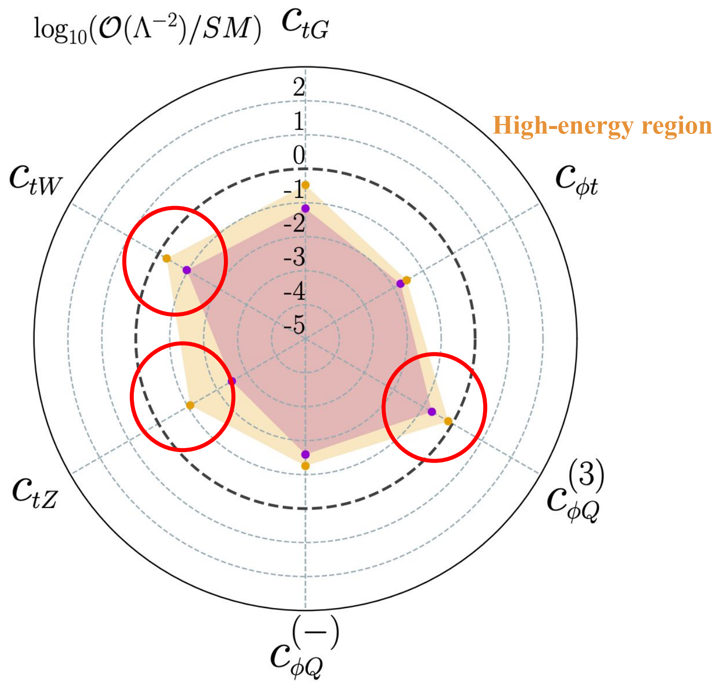
# tWZ in SMEFT: introduction

- tWZ in SMEFT can induce some **energy growth due to unitarity violating behaviour** → new physics effects? [Maltoni, Mantani, Mimasu arXiv:1904.05637]

- **tWZ at NLO in QCD is complicated..**

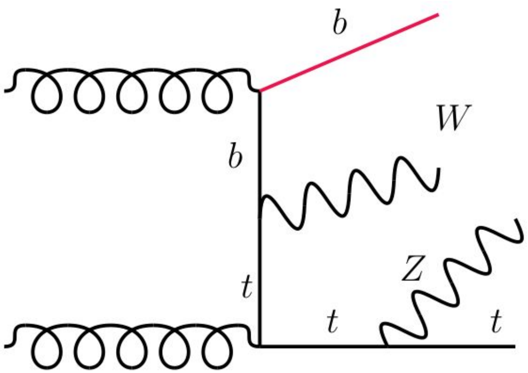
**How to get to this plot?**

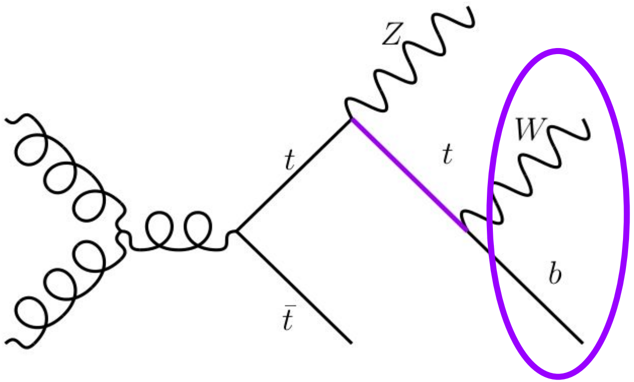
**NLO**



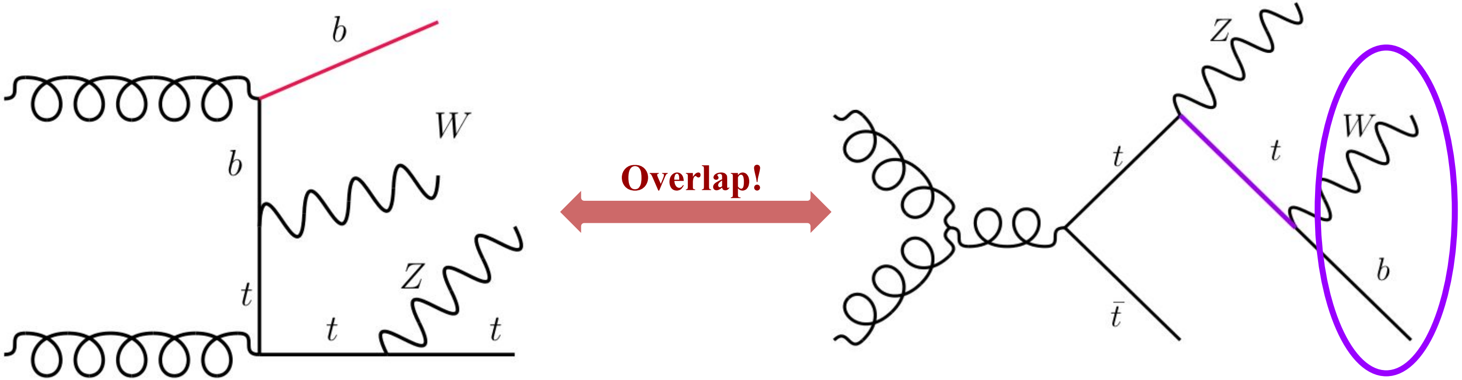

HF, Maltoni, Mimasu, Zaro, arXiv: 2111.03080

# tWZ at NLO in QCD; problem..



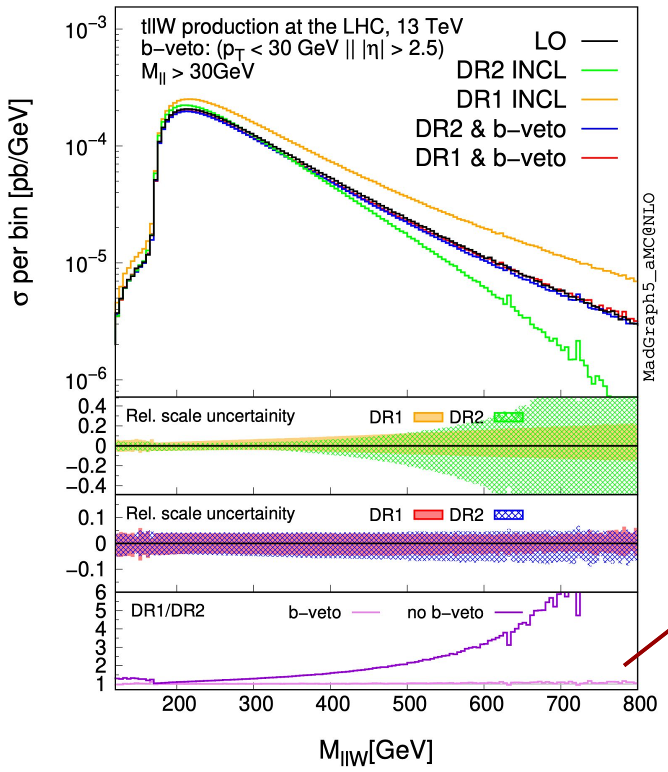



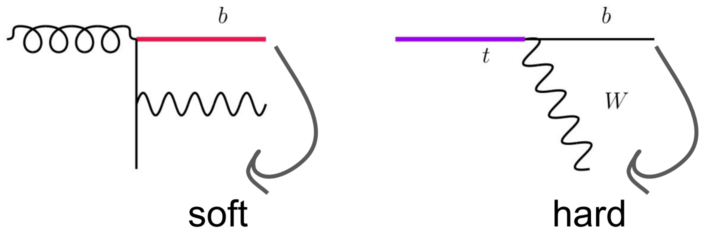
# tWZ at NLO in QCD; problem..




**The resonant structure spoils the perturbative NLO expansion, we have to deal with the overlap**

# Looking for genuine NLO tWZ in the SM

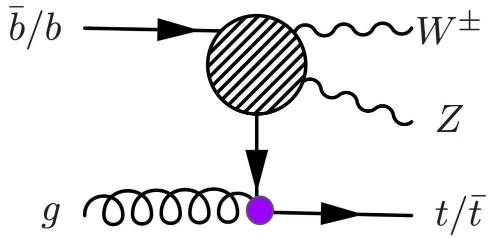


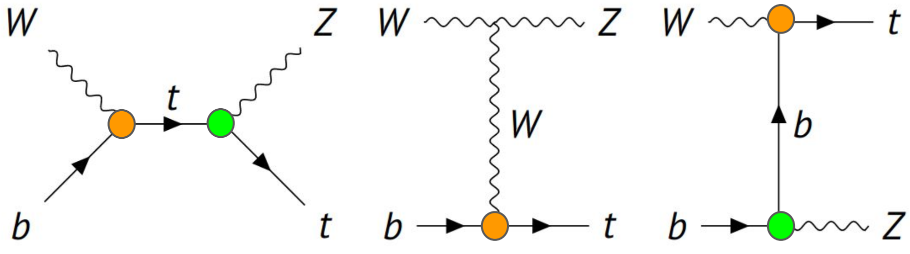




**Vetoing hard b-quarks significantly suppresses contributions from resonant diagrams**

HF, Maltoni, Mimasu, Zaro, arXiv: 2111.03080

# tWZ in SMEFT




$\mathcal{O}^{(3)}_{\varphi Q}, \mathcal{O}^{(-)}_{\varphi Q}, \mathcal{O}_{\varphi t}, \mathcal{O}_{tW}, \mathcal{O}_{tZ}, \mathcal{O}_{tG}$

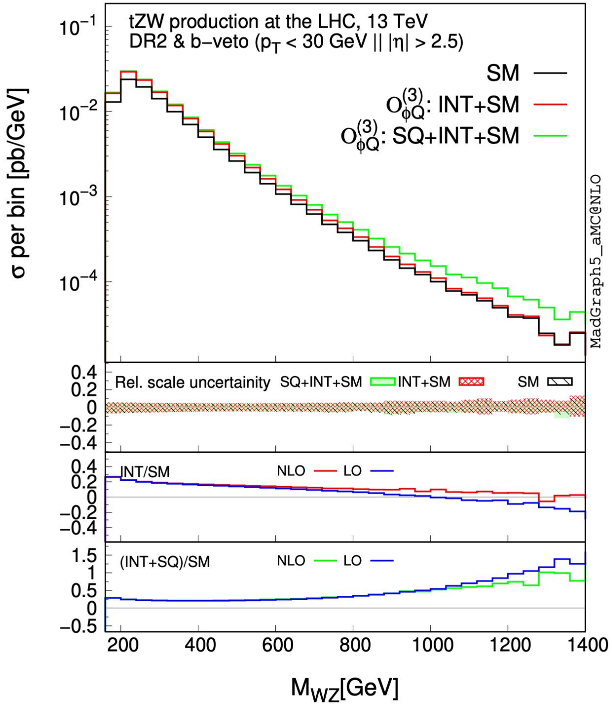
Charged current operator

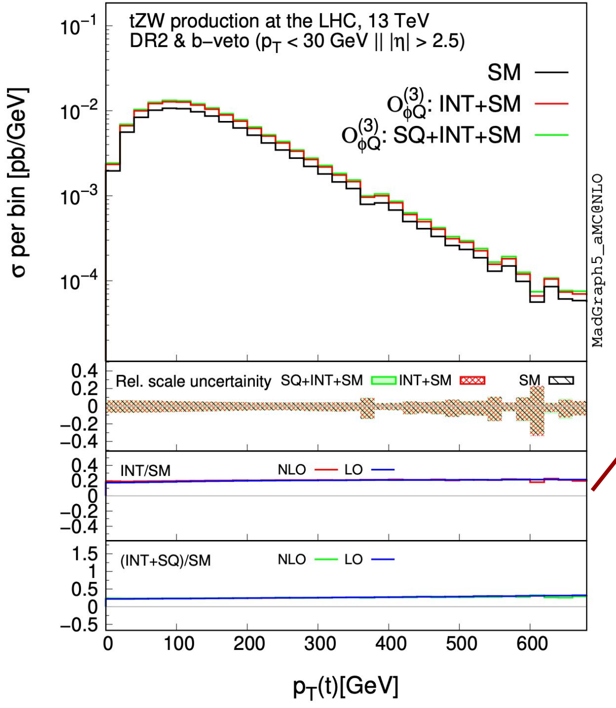
Neutral current operators

Dipoles

Gluon-top

# Looking for genuine NLO tWZ in the SMEFT

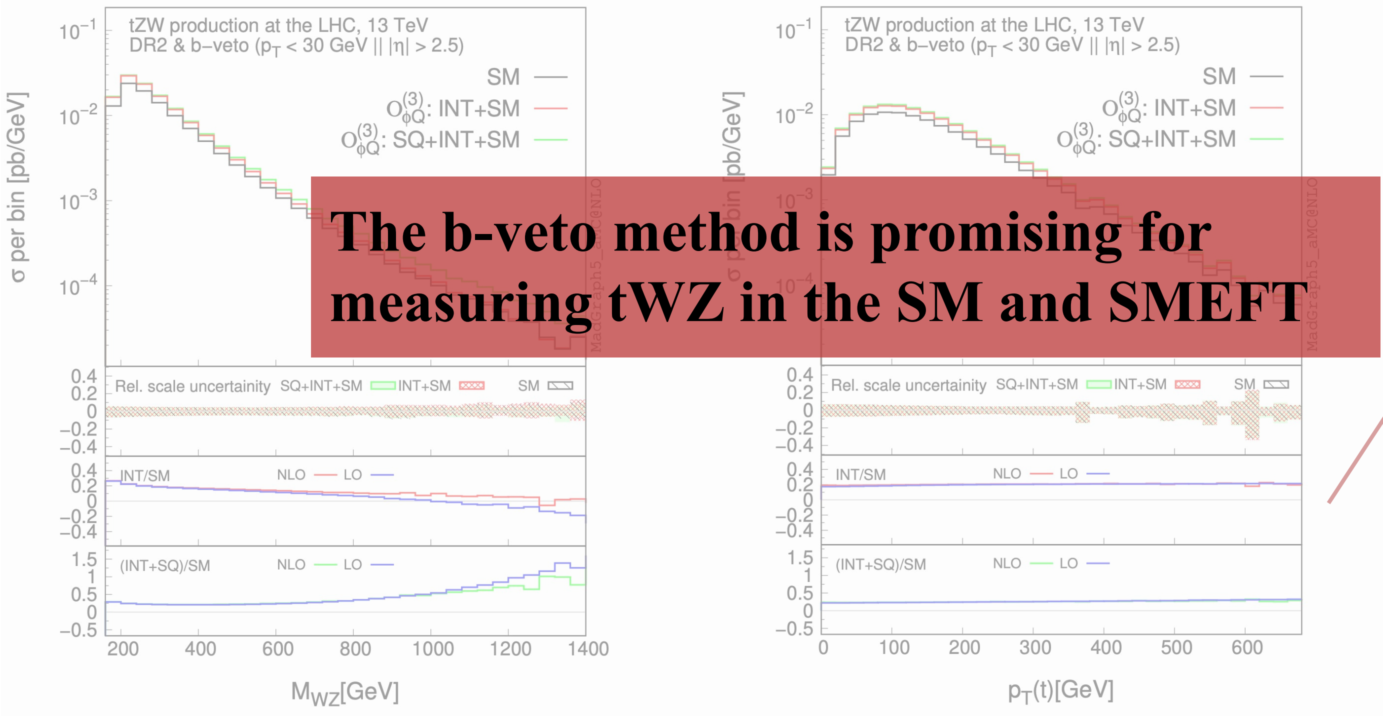



**Relative stable impacts under NLO in QCD**

HF, Maltoni, Mimasu, Zaro, arXiv: 2111.03080

# Looking for genuine NLO tWZ in the SMEFT




**The b-veto method is promising for measuring tWZ in the SM and SMEFT**

Relative stable impacts under NLO in QCD

HF, Maltoni, Mimasu, Zaro, arXiv: 2111.03080

# A glimpse of the future

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# A glimpse of the future [theory perspective]

- **EFT predictions with higher-level of accuracy**
  - **Higher order in EFT**, e.g. squared dim-6, double insertions of dim-6, dim-8
  - **Higher order in QCD and EW**
  - **Including renormalisation group equations (RGE) effects**
- **More SMEFT operators, e.g. different flavour assumptions**
- **More observables, e.g. spin correlations, etc.**

# EFT at higher orders in QCD and EW

**Tree-level**(`SMEFTsim`); https://smeftsim.github.io/

[Brivio, arXiv: 2012.11343]

**NLO in QCD**(`SMEFT@NLO`);
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

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

**NLO in EW; Sudakov EW approximation in SMEFT is an ongoing effort**

[HF, Mimasu, Pagani, Severi, Vryonidou, Zaro, *work in progress*]

# EFT including RGE effects

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

- Observables are typically associated to specific energy scales
- RG Equations (RGE) account for different natural scales of different processes

$$\frac{dc_i(\mu)}{d\log\mu} = \gamma_{ij}\, c_j(\mu)$$

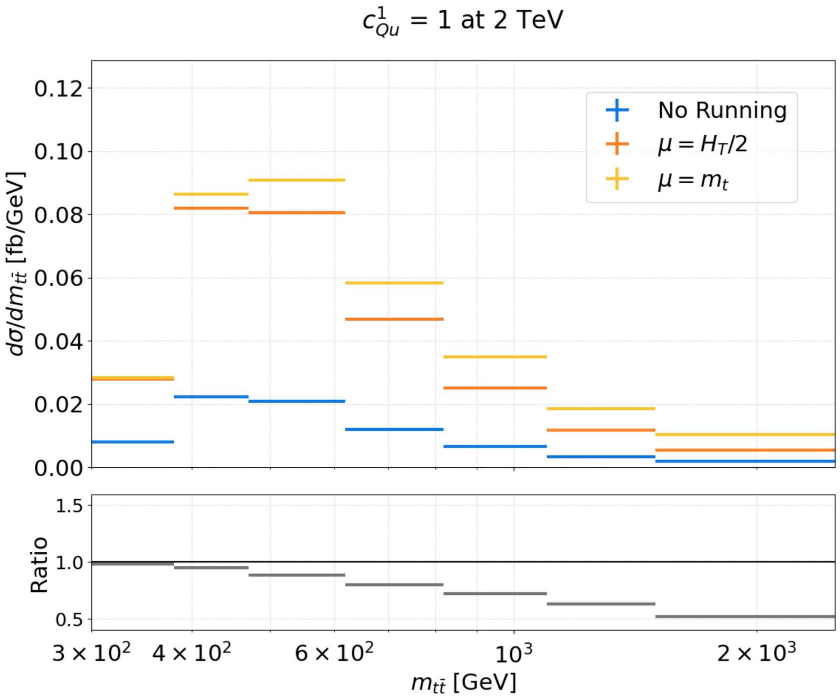
**→ RG evolution is known at dim-6**

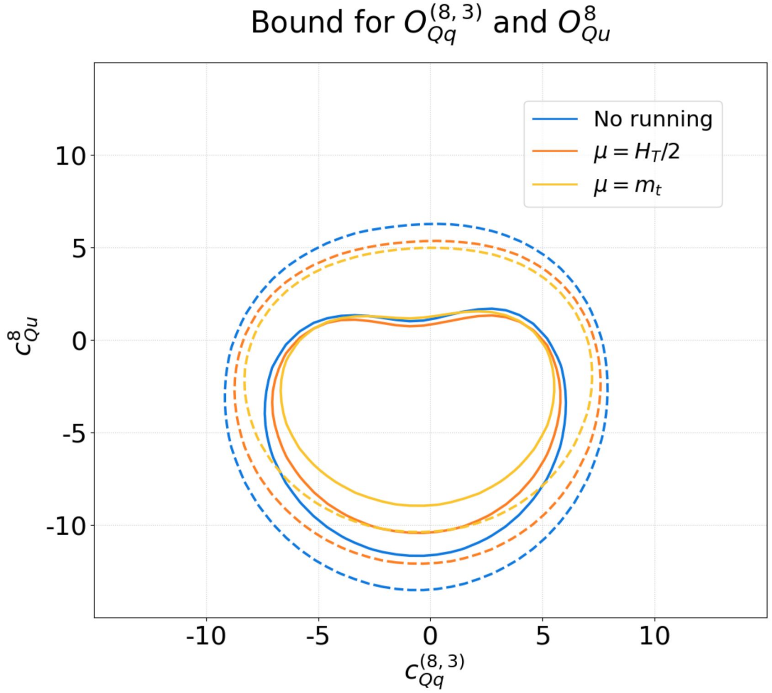
[Jenkins et al., arXiv:1308.2627, 1310.4838] [Alonso et al., arXiv: 1312.2014]

**Recently implemented in MG5**

[Aoude, Maltoni, Mattelaer, Severi, Vryonidou, arXiv:2212.05067]

# EFT including RGE effects




Aoude, Maltoni, Mattelaer, Severi, Vryonidou, arXiv:2212.05067

# Conclusion

- SMEFT is a powerful tool to look for new physics
- Global fits are the ultimate goal, and are always looking for new data
- Studying rare processes in SMEFT encourages their measurements and incorporation into EFT frameworks
- Higgs and top-sectors are strongly connected
- Precise EFT predictions is key to better constraint SMEFT; an ongoing effort (RGE-improved and EW higher-order predictions)