

# Highlights & Summary from the “Discussion on the Physics of Four Tops”

**Ennio Salvioni**  
**CERN**



*LHC Top Working Group Open Meeting, 20th May 2021*

Link to original event (February 19, 2021): <https://indico.cern.ch/event/1004023/>

# Discussion on the physics of Four Tops

Friday 19 Feb 2021, 15:00 → 19:15 Europe/Zurich

Online only (CERN)

Fabio Maltoni (Université Catholique de Louvain and Università di Bologna) , Ennio Salvioni (CERN) ,  
Javi Serra (Technical University of Munich)

Description With the large amount of data gathered by the Run 2 of the LHC, the production of four top quarks has become a very interesting probe of the Standard Model and beyond. What is more, the measurements of this process in multilepton + (b-)jets final states have found an intriguing enhancement with respect to state-of-the-art SM predictions, usually attributed to its ttW background. In this event we invite you to discuss the physics of four tops, both within and beyond the SM. The meeting will consist of a few invited presentations, each followed by ample time for scientific exchange.

Participants

Admir Greljo, Adrian Rubio Jimenez, Afiq Anuar, Ana Ventura Barroso, Andrea Banfi, Andreas Weiler, Anil Sonay, Ankan Biswas, Aurelio Juste Rozas, Barry Dillon, Benjamin Fuks, Bhima Devi Neopaney

Videoconference  
Rooms

zoom Discussion on the physics of four tops Join

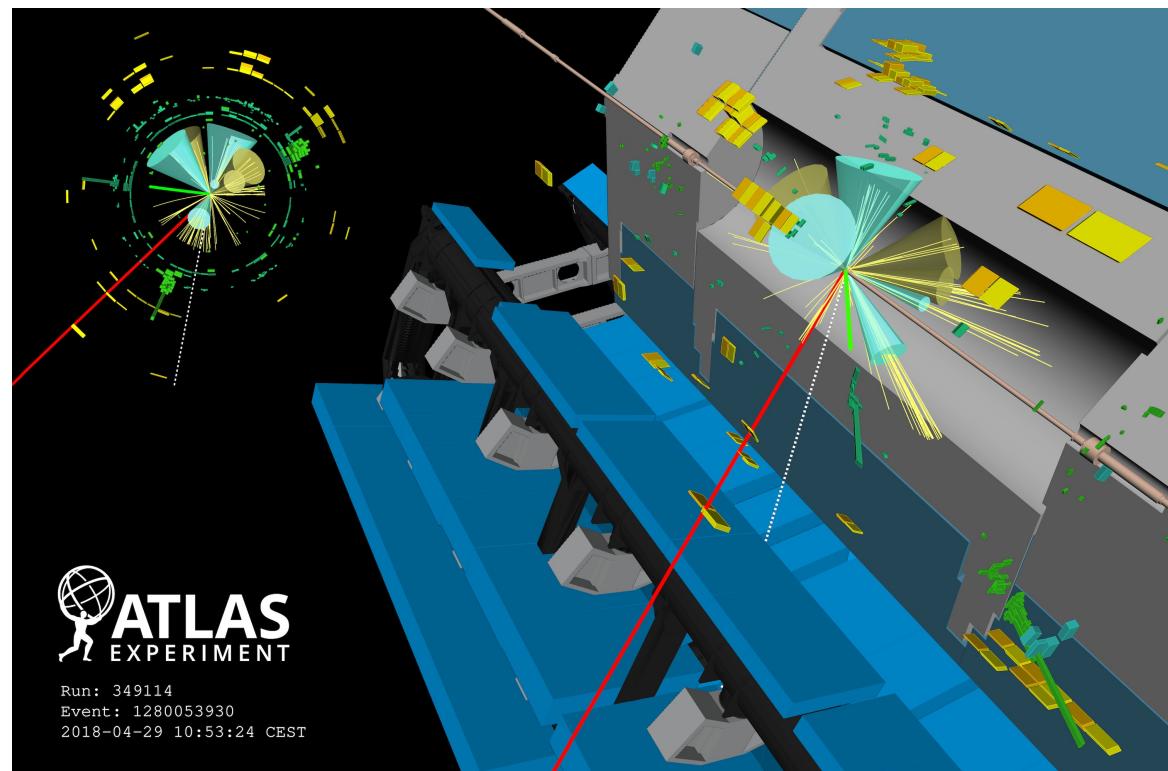
- One-afternoon topical discussion on Zoom. “Rapid response” to EXP and TH developments
- Presentations by ATLAS, CMS + 5 theory talks
- Up to ~ 90 simultaneous participants, very lively exchange
- Special thanks to ATLAS & CMS speakers and Top Conveners, for acting on ~ 2 weeks’ notice!

# The Four Tops have a long history...



The Four Tops in 1968

The Four Tops in 2018



elected to Rock&Roll Hall of Fame in 1990

Ennio Salvioni

# ... so why discuss Four Tops now?

- **Theory:** important motivations for BSM effects, possibly as first manifestation of new physics. Several papers out in late 2020

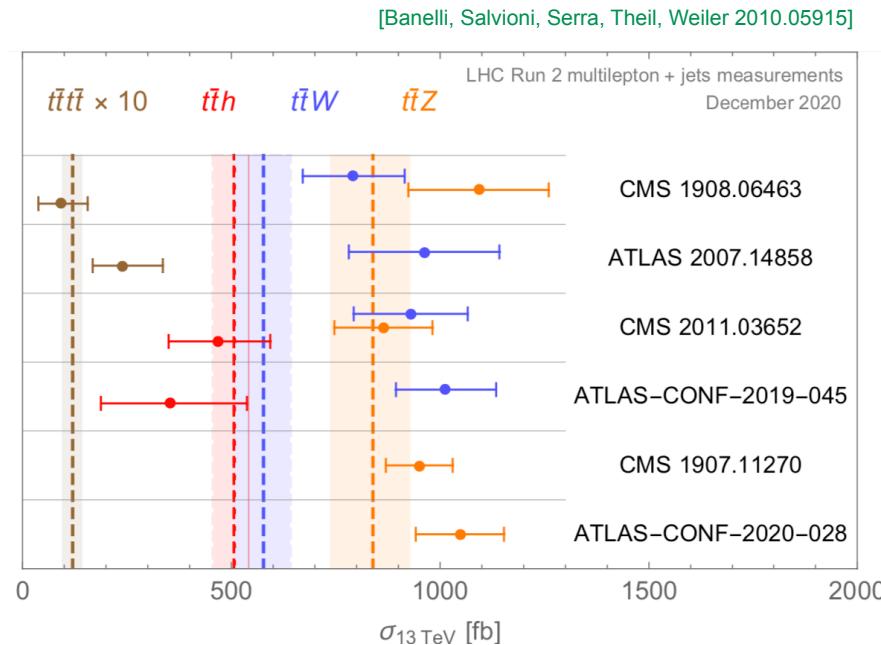
Even within SM, complex interplay of QCD and EW amplitudes

- **Experiment:** very rare process ( $\sigma_{13\text{ TeV}}^{\text{SM}} = 12 \text{ fb}$ ), ATLAS and CMS have “just begun” to see evidence

Status after Run 2 is intriguing: excesses  
in multilepton +  $b$ -jets final states  
( $t\bar{t}W + \text{jets}$  is key background)

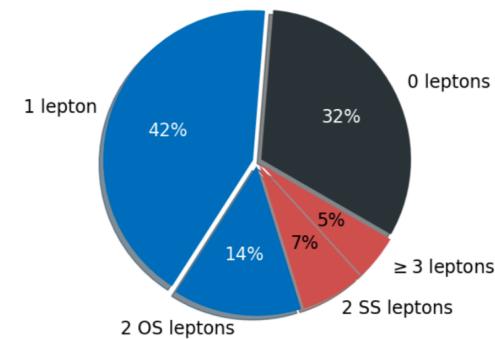
see also talks by Quake Qin yesterday,  
Manfred Kraus today

$(80 - 140) \text{ fb}^{-1}$   
@ 13 TeV



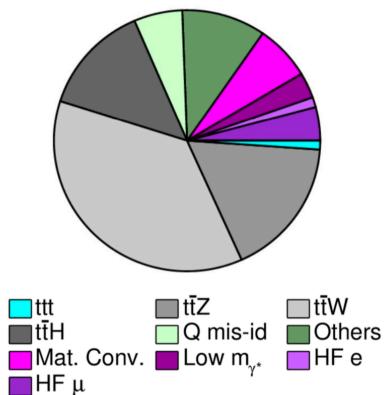
# Plan of discussion

- ATLAS: [Simon Berlendis](#) (SSL/multileptons)
- CMS: [Emanuele Usai](#) (SSL/multileptons & 1L/OSL)
- SM theory: [Rikkert Frederix](#) (complete NLO prediction)
- BSM theory:
  - ▶ [Tobias Theil](#) (four-top operators in EFT)
  - ▶ [Ken Mimasu](#) (SMEFT@NLO and indirect constraints)
  - ▶ [Luc Darmé](#) (from EFT to on-shell top-philic resonances)
  - ▶ [Manuel Szewc](#) (a light  $Z'$  to explain multilepton + jet excesses)



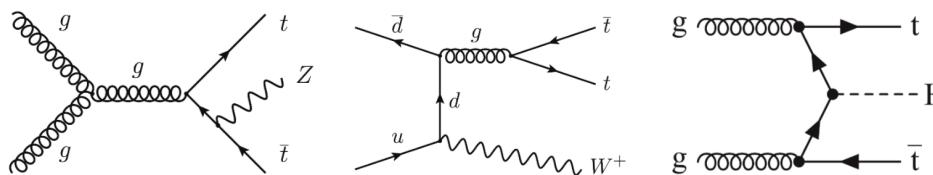
Multilepton + jets analyses probe **multiple** processes of high interest for BSM:

*Background composition*  
 $\geq 6 \text{ jets}, \geq 2 b\text{-jets}, H_T \geq 500 \text{ GeV}$

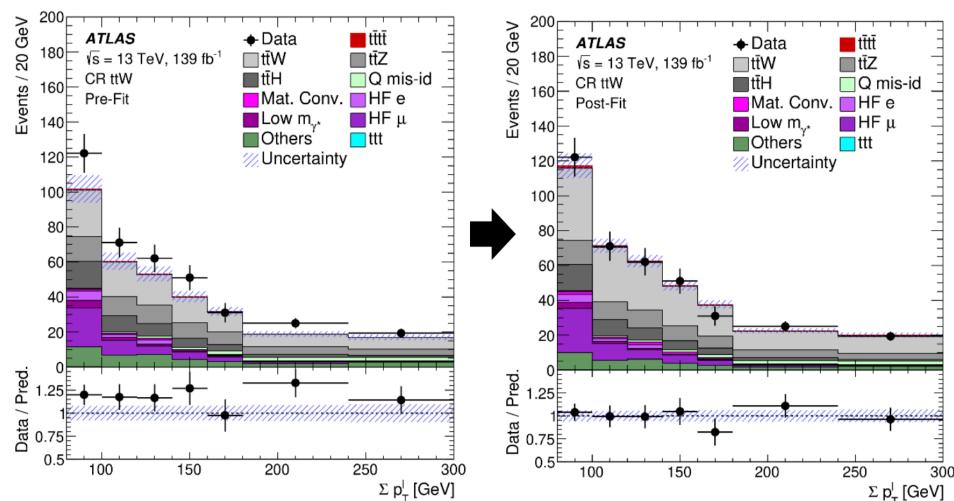


Physics background, e.g.  $t\bar{t}+X$  ( $\sim 80\%$ ):

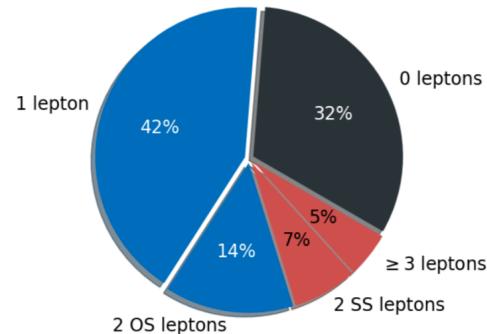
- Irreducible background – process leading to the same final states
- Estimated using Monte Carlo simulations



Simultaneous fitting to control regions:  
 $t\bar{t}W$  normalisation factor of  $1.6 \pm 0.3$   
extracted from likelihood fit



[ATLAS 2007.14858]

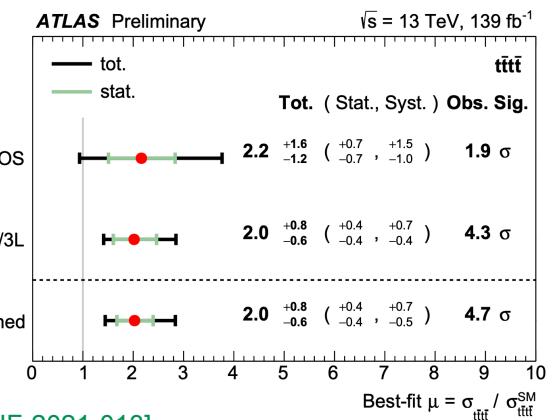


Multilepton + jets analyses probe **multiple** processes of high interest for BSM:

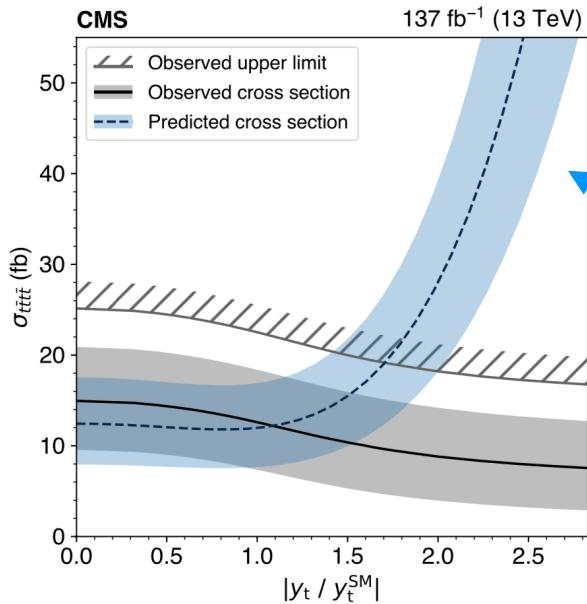
Uncertainty source	$\Delta\mu$	
<b>Signal modelling</b>		
$t\bar{t}t\bar{t}$ cross section	+0.56	-0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	-0.09
<b>Background modelling</b>		
$t\bar{t}W$ +jets modelling	+0.26	-0.27
$t\bar{t}t$ modelling	+0.10	-0.07
Non-prompt leptons modelling	+0.05	-0.04
$t\bar{t}H$ +jets modelling	+0.04	-0.01
$t\bar{t}Z$ +jets modelling	+0.02	-0.04
Other background modelling	+0.03	-0.02
Charge misassignment	+0.01	-0.02
<b>Instrumental</b>		
Jet uncertainties	+0.12	-0.08
Jet flavour tagging (light-flavour jets)	+0.11	-0.06
Simulation sample size	+0.06	-0.06
Luminosity	+0.05	-0.03
Jet flavour tagging ( $b$ -jets)	+0.04	-0.02
Jet flavour tagging ( $c$ -jets)	+0.03	-0.01
Other experimental uncertainties	+0.03	-0.01
Total systematic uncertainty	+0.70	-0.44
<b>Statistical</b>	+0.42	-0.39
Non-prompt leptons normalisation (HF, Mat. Conv., Low $m_{\gamma^*}$ )	+0.05	-0.04
$t\bar{t}W$ normalisation	+0.04	-0.04
Total uncertainty	+0.83	-0.60

### Leading uncertainties:

- **Signal modelling uncertainty:**
  - On the theoretical cross section ( $\sim 20\%$ )
  - On the choice of the parton shower
- **Limited statistics of the run-2 data**
- **$t\bar{t}W$  background modelling**
  - Discussions in a few slides
- **Instrumental background**
  - Jet energy scale and resolution
  - $b$ -tagging efficiencies on light jets

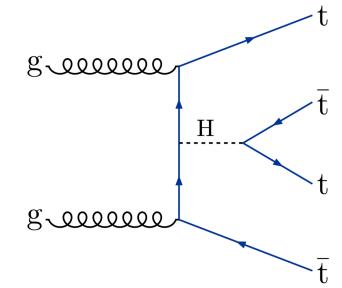
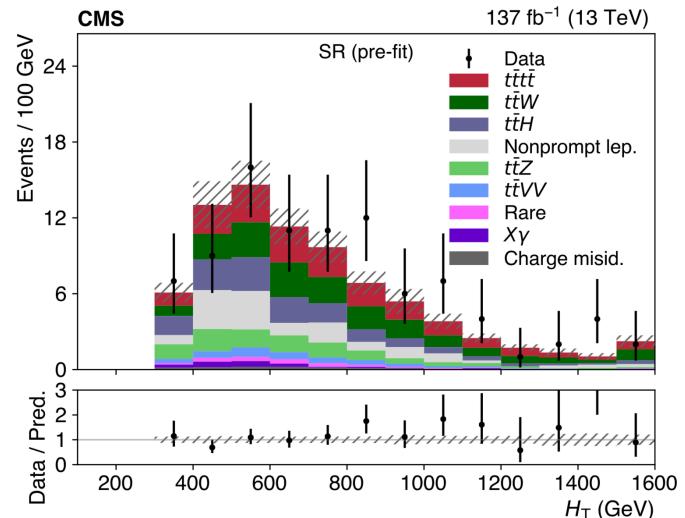


- Multilepton + jets analysis reports both BDT and cut-and-count versions, very useful for theory recasts ([see later](#))
- $t\bar{t}W$  and  $t\bar{t}Z$  normalizations float in the fit, find  $1.3 \pm 0.2$  for both
- BDT:  $\sigma_{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2}$  fb       $2.6\sigma$  obs ( $2.7\sigma$  exp)



dependence on  $ht\bar{t}$  coupling

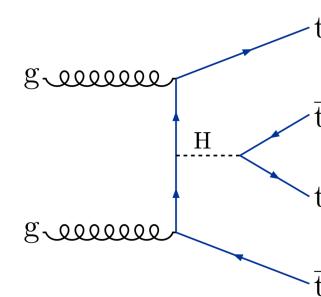
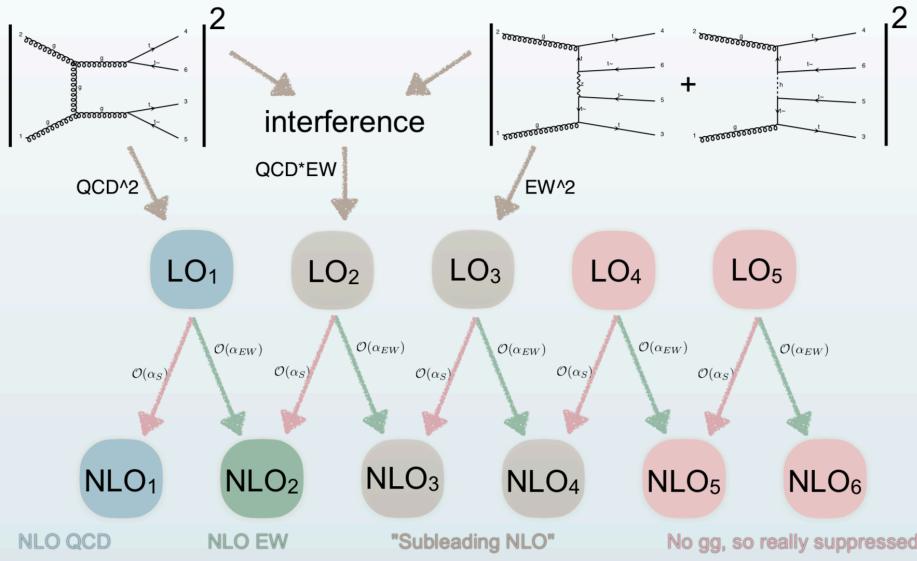
$t\bar{t}h$  background rescaled  $\propto y_t^2$



but how to handle NLO corrections?

# SM theory

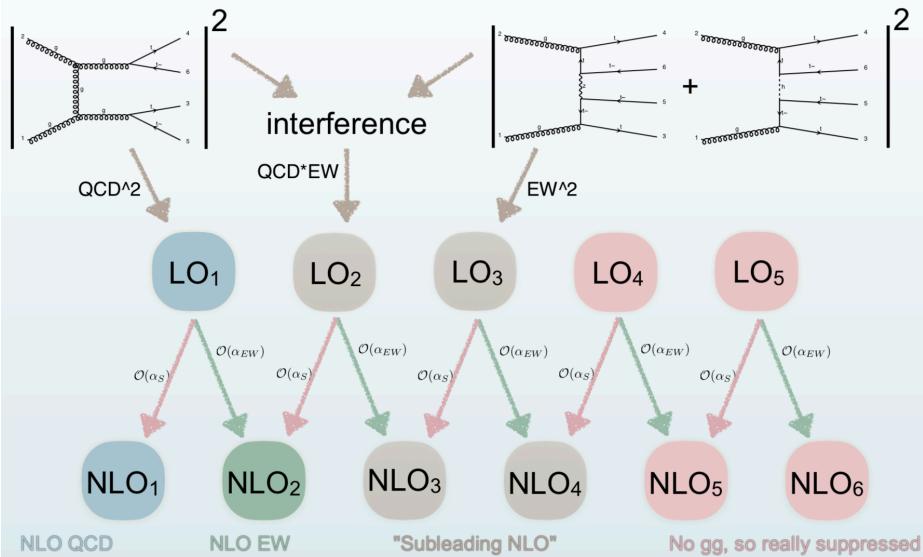
## Perturbative expansion at NLO



- Not possible to single out the Higgs Yukawa coupling and compute QCD corrections to those separately
  - When computing EW corrections, the Yukawa is linked to the top mass and other EW couplings through renormalisation: they are not independent
  - Need complete SMEFT to be able to compute NLO corrections and study in the impact of NLO corrections: currently beyond our capabilities
  - At NLO, also contributions that have single, triple, quintuple powers of the Yukawa coupling (and not only double or quadruple)
- Compute NLO corrections in the Standard Model

# SM theory

## Perturbative expansion at NLO



$\sigma[\text{fb}]$	$\text{LO}_{\text{QCD}}$	$\delta_{(N)\text{LO}_i}(\mu) = \frac{\Sigma_{(N)\text{LO}_i}(\mu)}{\Sigma_{\text{LO}_{\text{QCD}}}(\mu)}$		
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
$\text{LO}_2$	-26.0	-28.3	-30.5	10%
$\text{LO}_3$	32.6	39.0	45.9	1%
$\text{LO}_4$	0.2	0.3	0.4	0.1%
$\text{LO}_5$	0.02	0.03	0.05	0.01%
$\text{NLO}_1$	14.0	62.7	103.5	10%
$\text{NLO}_2$	8.6	-3.3	-15.1	1%
$\text{NLO}_3$	-10.3	1.8	16.1	0.1%
$\text{NLO}_4$	2.3	2.8	3.6	0.01%
$\text{NLO}_5$	0.12	0.16	0.19	0.001%
$\text{NLO}_6$	< 0.01	< 0.01	< 0.01	0.0001%
$\text{NLO}_2 + \text{NLO}_3$	-1.7	-1.6	0.9	

Naive expectation

$13 \text{ TeV}$

- Large cancellations between  $\text{LO}_2$  and  $\text{LO}_3$
- Large cancellations between  $\text{NLO}_2$  and  $\text{NLO}_3$  (also at differential level). Surprising!
- Not possible to estimate effect in BSM, e.g. modified top Yukawa. Still a cancellation?
- Would require complete NLO corrections in SMEFT, currently out of reach

# BSM: four-top operators

- Scenarios with composite Higgs and top, new mass scale  $m_*$  and coupling  $g_*$
- Strongly coupled new physics: sizable EFT effects even if  $m_*$  is out of direct reach

$$\frac{g_*^2}{m_*^2} (\partial_\mu |H|^2)^2$$

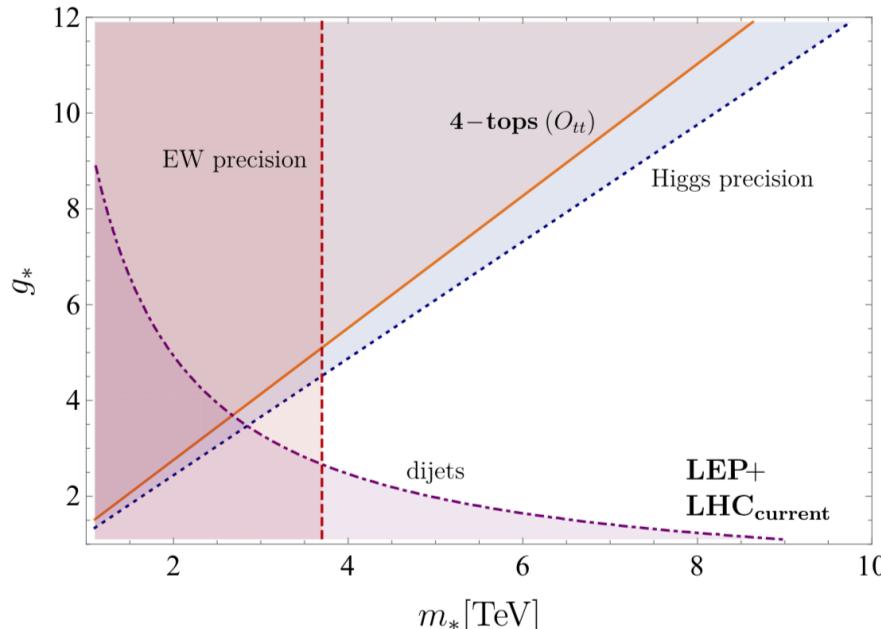
$$\mathcal{L} = \mathcal{L}_{\text{SM}, \leq 4} + \mathcal{L}_6$$

$$\frac{g_*^2}{m_*^2} (\bar{t}_R \gamma^\mu t_R)^2$$

genuine sign of  
Higgs compositeness

genuine sign of  
top compositeness

## WHY CARE FOR FOUR-TOP PRODUCTION NOW...



[Banelli, Salvioni, Serra,  
Theil, Weiler 2010.05915]

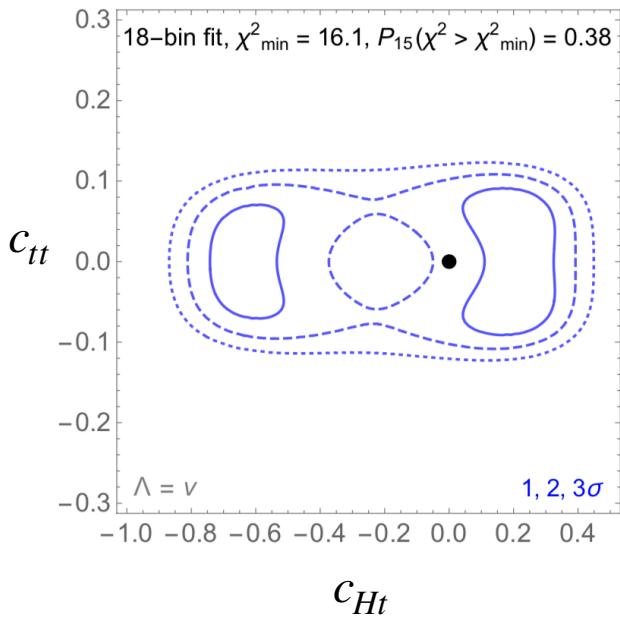
- Not a global fit
- $O_{tt}$  comparable to constraints from Higgs observables

$$O_{tt} : \frac{m_*}{g_*} > 730 \text{ GeV}$$

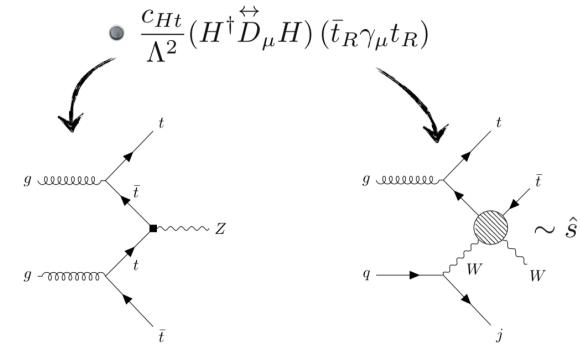
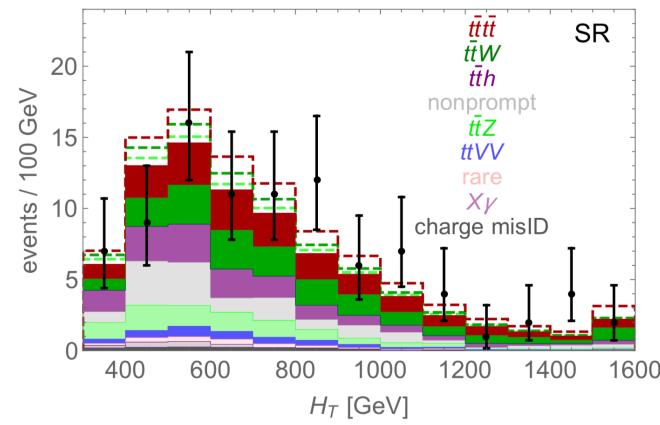
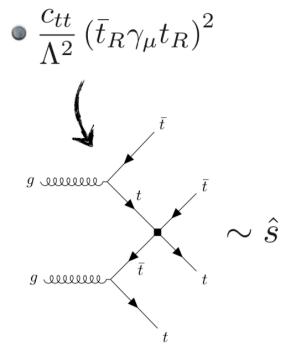
$$O_H : \frac{m_*}{g_*} > 820 \text{ GeV}$$

# BSM: four-top operators

## FURTHER MOTIVATION: LHC MULTILEPTON + JETS “EXCESSES”



- Our fit suggests  $m_*/g_* \gtrsim 750$  GeV
- Roughly consistent with experimental constraints
- Motivation for heavy, top-philic new physics



- At future colliders (both hadron and lepton), four-top operators provide **leading sensitivity to compositeness scale**

$$\left( \frac{m_*}{g_*} \right)_{\text{FCC}} > 6.5 \text{ TeV}, \quad \left( \frac{m_*}{g_*} \right)_{\text{CLIC}} > 7.7 \text{ TeV}$$

better than Higgs precision

# BSM: SMEFT@NLO

[Degrande, Durieux, Maltoni, KM, Vryonidou & Zhang; arXiv:2008.11743]

## SMEFT@NLO

<http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO>

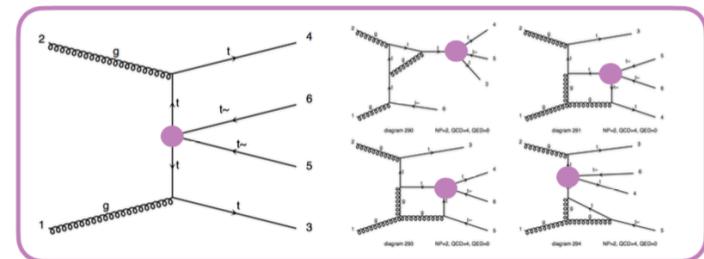
Standard Model Effective Theory at One-Loop in QCD

- Effects of four-top operators on  $t\bar{t}t\bar{t}$  production at NLO in QCD:

## 4 top results

[Degrande, Durieux, Maltoni, KM, Vryonidou & Zhang; arXiv:2008.11743]

$$\sigma(pp \rightarrow t\bar{t}t\bar{t}) [\text{fb}], c_i/\Lambda^2 = 1 \text{ TeV}^{-2}$$



! different from arXiv version !

$c_i$	Interference $\mathcal{O}(\Lambda^{-2})$			$K$	Square $\mathcal{O}(\Lambda^{-4})$		
	LO	NLO	$K$		LO	NLO	$K$
$c_{QQ}^8$	$0.081^{+55\%}_{-33\%}$	$[-0.277]$	$0.090^{+4\%}_{-11\%}$	1.1	$0.115^{+46\%}_{-29\%}$	$0.158^{+4\%}_{-11\%}$	1.37
$c_{Qt}^8$	$0.274^{+54\%}_{-33\%}$	$[-0.365]$	$0.311^{+5\%}_{-10\%}$	1.14	$0.342^{+46\%}_{-29\%}$	$0.378^{+4\%}_{-13\%}$	1.10
$c_{QQ}^1$	$0.242^{+55\%}_{-33\%}$	$[-0.826]$	$0.24(3)^{+3\%}_{-18\%}$	0.99	$1.039^{+47\%}_{-29\%}$	$1.41^{+4\%}_{-11\%}$	0.93
$c_{Qt}^1$	$-0.0098(10)^{+38\%}_{-33\%}$	$[0.852]$	$-0.003(30)$	—	$1.406^{+46\%}_{-30\%}$	$1.86^{+4\%}_{-10\%}$	1.32
$c_{tt}^1$	$0.483^{+55\%}_{-33\%}$	$[-1.38]$	$0.53(8)^{+3\%}_{-10\%}$	1.10	$4.154^{+47\%}_{-29\%}$	$5.61^{+4\%}_{-11\%}$	1.35

called  $c_{tt}$  in previous slide



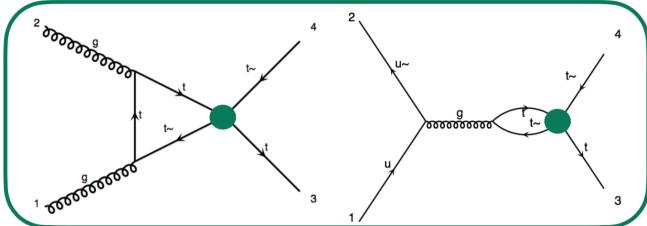
Reduction of scale uncertainty, relatively lower than SM

K-factors lower than SM

$$\text{SM} = 11.1^{+25\%}_{-25\%} \text{ fb } (K = 1.83)$$

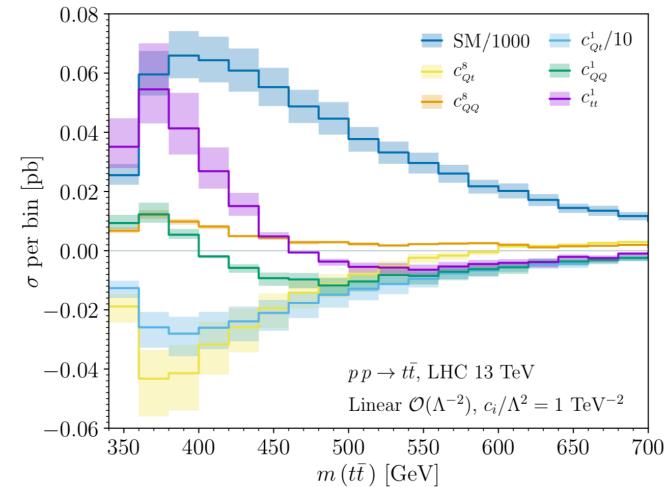
# BSM: SMEFT@NLO

- Also evaluated impact on  $t\bar{t}$  production at one loop:



## Lack of energy growth

- Sign changes over phase space lead to suppressions
- Quark and gluon channels often have opposite sign
- Optimistic: need few percent precision near threshold



- Complementarity to  $t\bar{t}t\bar{t}$ :  $t\bar{t}b\bar{b}$  production. Can also access top helicity information

$$\sigma_{\text{SM}} = 3 \text{ pb}$$

**Virtues of ttbb**

- New sensitivity to 4Q operators
- Breaks degeneracy from four-top ( $c_{QQ}^1, c_{QQ}^8$ )
- Sufficiently large cross section to exploit differential observables

[Zhang; Chin. Phys. C42 (2018) 023104]

300 fb<sup>-1</sup> projections from 4-top

Our study

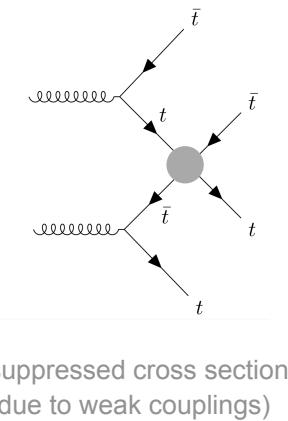
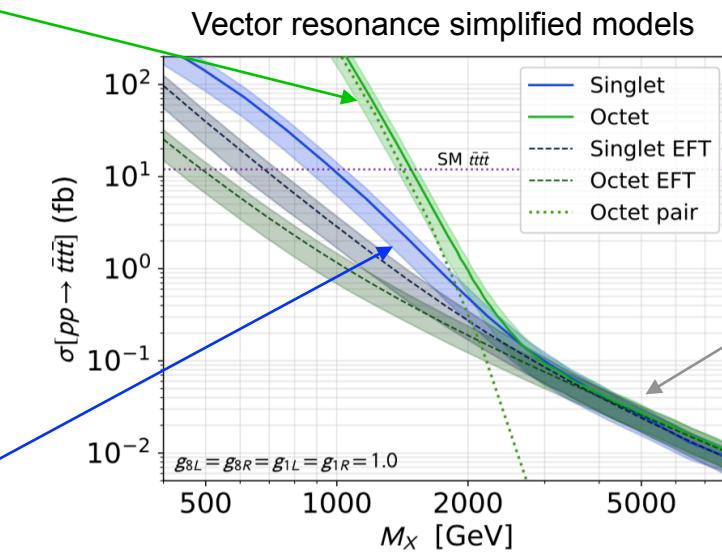
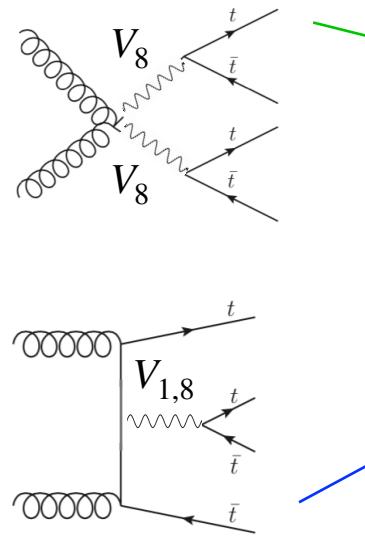
Operator	4-top ( $M_{\text{cut}} = 2 \text{ TeV}$ )	4-top ( $M_{\text{cut}} = 3 \text{ TeV}$ )	4-top ( $M_{\text{cut}} = 4 \text{ TeV}$ )	this work ( $M_{\text{cut}} = 2 \text{ TeV}$ )
$C_{QQ}^1$	[-3.9, 3.5]	[-2.9, 2.6]	[-2.8, 2.5]	[-2.1, 2.3]
$C_{QQ}^8$	[-11.8, 10.5]	[-8.8, 7.8]	[-8.4, 7.4]	[-4.5, 3.1]
$C_{Qt}^1$	[-3.2, 3.3]	[-2.4, 2.4]	[-2.2, 2.3]	[-2.1, 2.3]
$C_{Qt}^8$	[-7.4, 5.8]	[-5.4, 4.3]	[-5.1, 4.1]	[-3.9, 3.8]

Competitive/better individual limits from ttbb!

# BSM: top-philic resonances

- For lighter resonances, on-shell production dominates

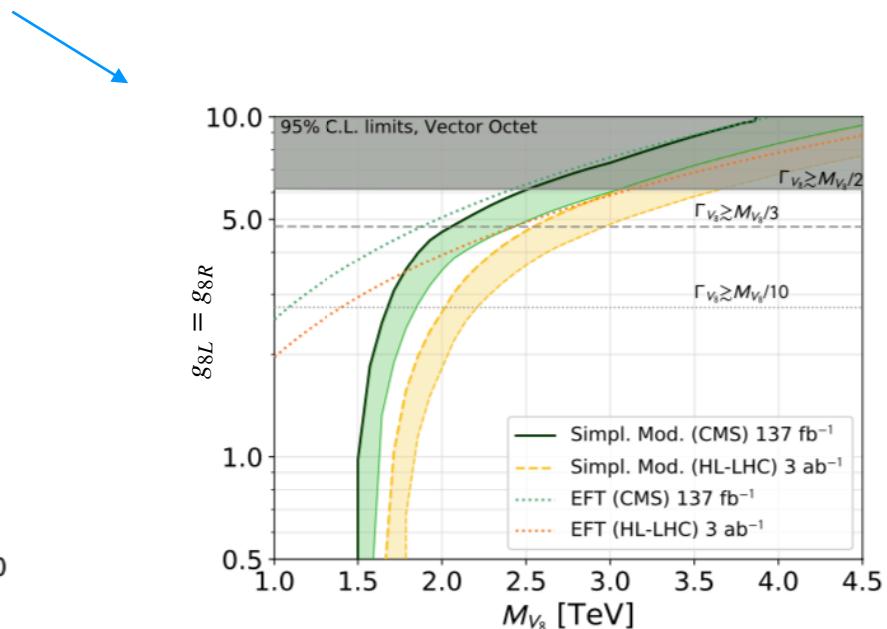
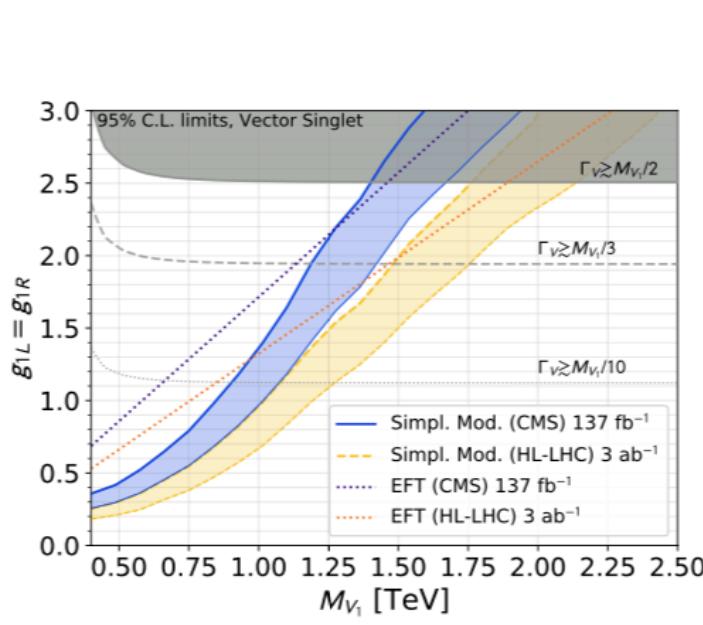
[Darmé, Fuks, Maltoni 2104.09512]



- Again, reliability of NLO predictions is uncertain. Use LO as reference

# BSM: top-philic resonances

- Full-fledged recast of CMS multilepton four-top analysis
- Add extra signal region at very high  $H_T > 1.2$  TeV:  
strong impact for **pair production** in  $M_X \sim 1$  to 2 TeV range, different signal topology



- On-shell production shows distinct features in kinematics of four tops

# BSM: ATLAS multilepton anomalies

But let's take a detour:  $t\bar{t}W^\pm$

YR4: cross-section reported in  
arXiv:1610.07922. It's 600.8 fb

[Alvarez, Juste, Szewc,  
Vazquez-Schroeder 2011.06514]

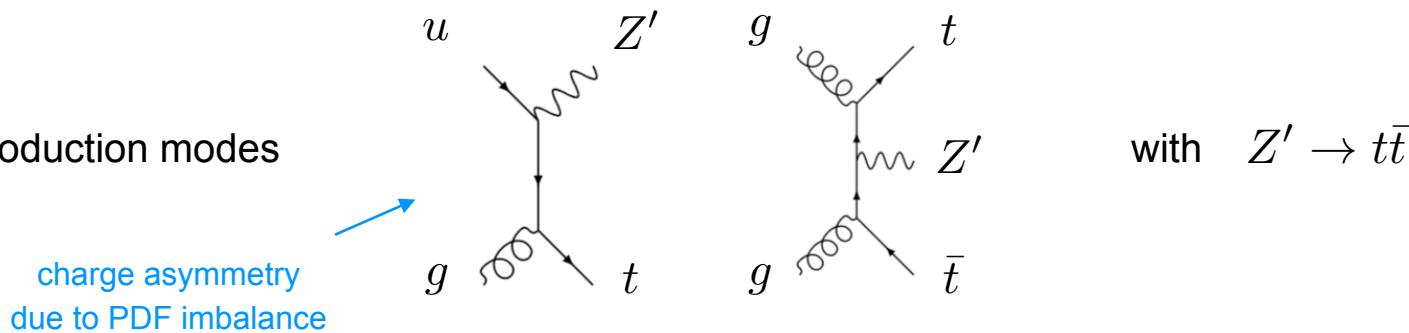
Search	$\mathcal{L}$ [fb $^{-1}$ ]	$\sigma_{\text{ref}}$ [pb]	$\mu$ or NF	$\mu_{\text{YR4}}$ or NF $_{\text{YR4}}$
$t\bar{t}W$ ATLAS	36.1	$0.60 \pm 0.07$	$1.44 \pm 0.32$	$1.44 \pm 0.32$
$t\bar{t}W$ CMS	35.9	$0.628 \pm 0.082$	$1.23^{+0.3}_{-0.28}$	$1.29^{+0.31}_{-0.29}$
$t\bar{t}H$ ATLAS	80	$0.727 \pm 0.092$	$1.39^{+0.17}_{-0.16}$	$1.68^{+0.21}_{-0.19}$
$t\bar{t}H$ CMS	137	0.650	$1.43 \pm 0.21$	$1.55 \pm 0.23$
4-tops ATLAS	139	0.601	$1.6 \pm 0.3$	$1.6 \pm 0.3$
4-tops CMS	137	0.610	$1.3 \pm 0.2$	$1.3 \pm 0.2$

- ← observed lepton charge asymmetry
- ← also included in fit

- Phenomenological approach: light  $Z'$  coupled to up-type quarks

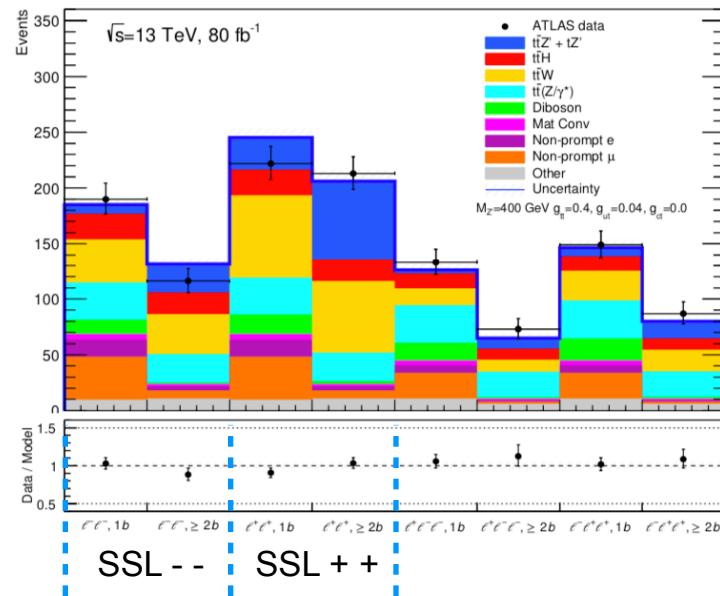
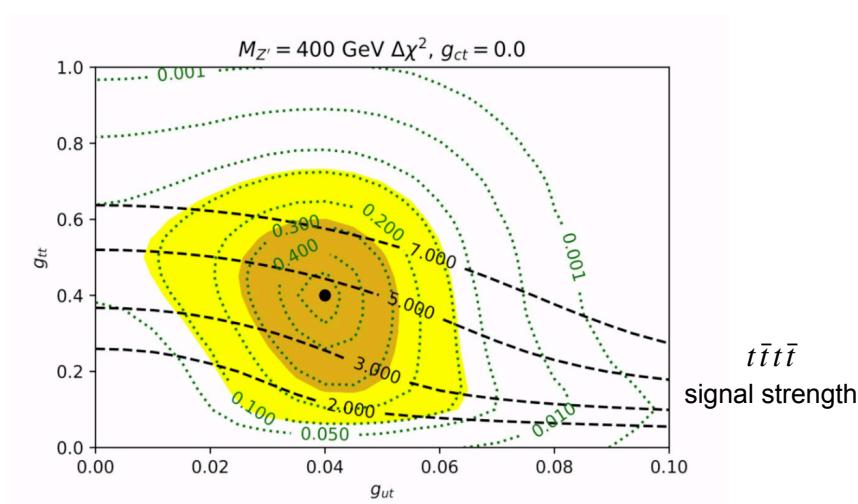
$$\mathcal{L}_{\text{BSM}} \ni g_{tt}\bar{t}_R\gamma^\mu t_R Z'_\mu + (g_{ut}\bar{t}_R\gamma^\mu u_R Z'_\mu + \text{h.c.})$$

- Main production modes



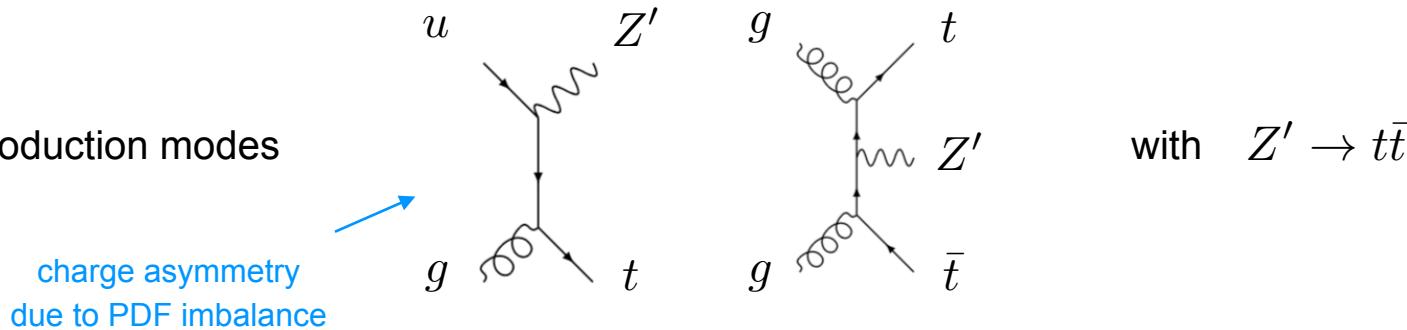
# BSM: ATLAS multilepton anomalies

( $M_{Z'} = 400$  GeV; couplings @ best fit for  $t\bar{t}h$  search only)



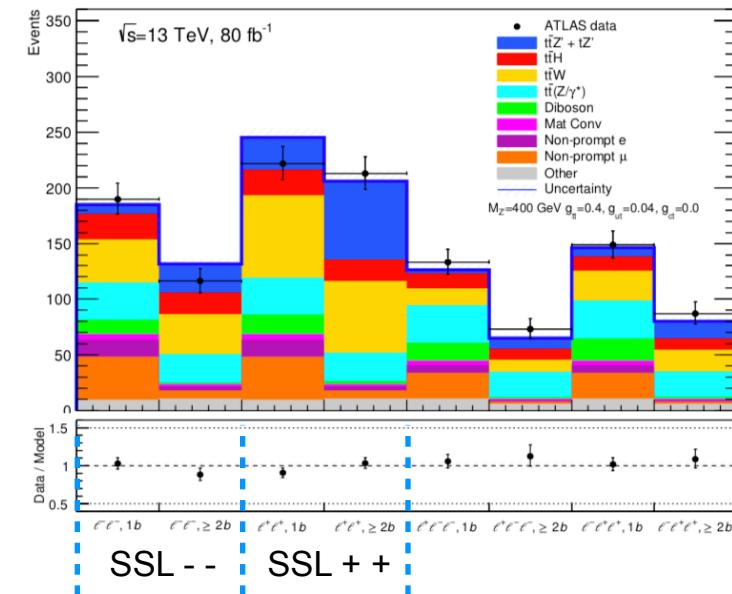
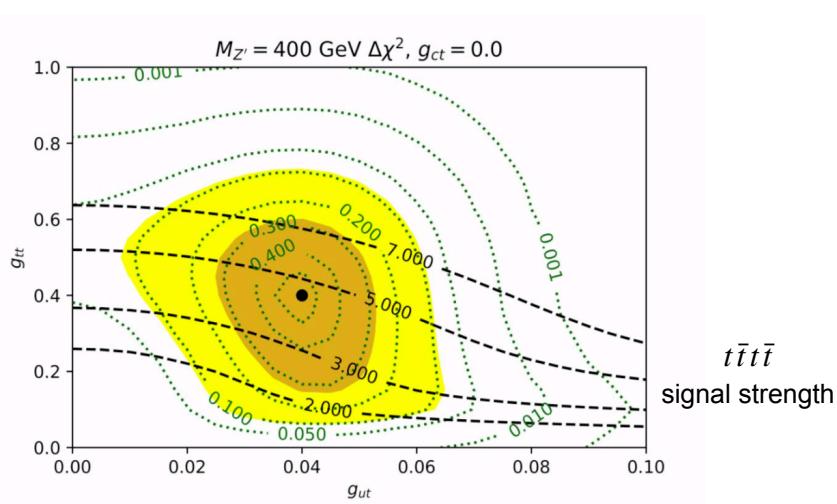
$$\mathcal{L}_{\text{BSM}} \ni g_{tt}\bar{t}_R\gamma^\mu t_R Z'_\mu + (g_{ut}\bar{t}_R\gamma^\mu u_R Z'_\mu + \text{h.c.})$$

- Main production modes



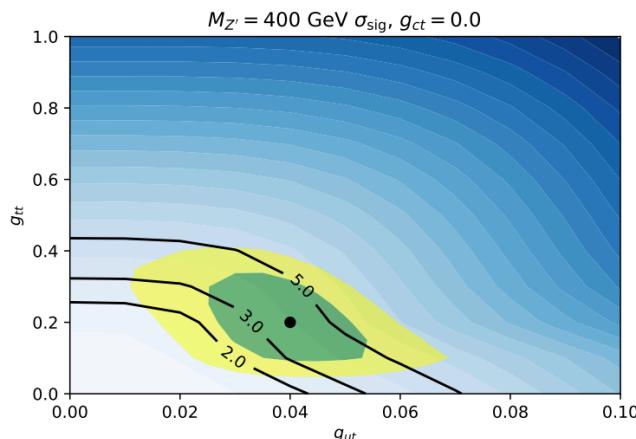
# BSM: ATLAS multilepton anomalies

( $M_{Z'} = 400$  GeV; couplings @ best fit for  $t\bar{t}h$  search only)



- Light resonance could be “mistaken” for rescaling of  $t\bar{t}W$  normalization
- Also discussed a global analysis, introducing new variable

$\text{MaxMin}(\ell, b) =$  The maximum of the minimum  $\Delta R$ -distances between the same-sign leptons and a  $b$ -jet



# Final comments

- Four tops has risen to prominence in LHC top physics program.  
Exciting experimental status + important motivations from theory, **much more to learn in Run 3**
- A lot more was presented and discussed on February 19, all slides are on Indico
- **Lesson learned:** for a focused, “rapid response” event Zoom is actually an advantage,  
~ 100 experts gathered on 2 weeks’ notice!
- May repeat in the future for other hot topics.  $t\bar{t}W + \text{jets}$  within and beyond the SM?