5th Red LHC Workshop, May 10-12, 2021

Topping-up multilepton plus b-jets anomalies at the LHC with a Z' boson

Based on: E. Alvarez, AJ, M. Szewc, T. Vazquez-Schroeder, arxiv:2011.06514

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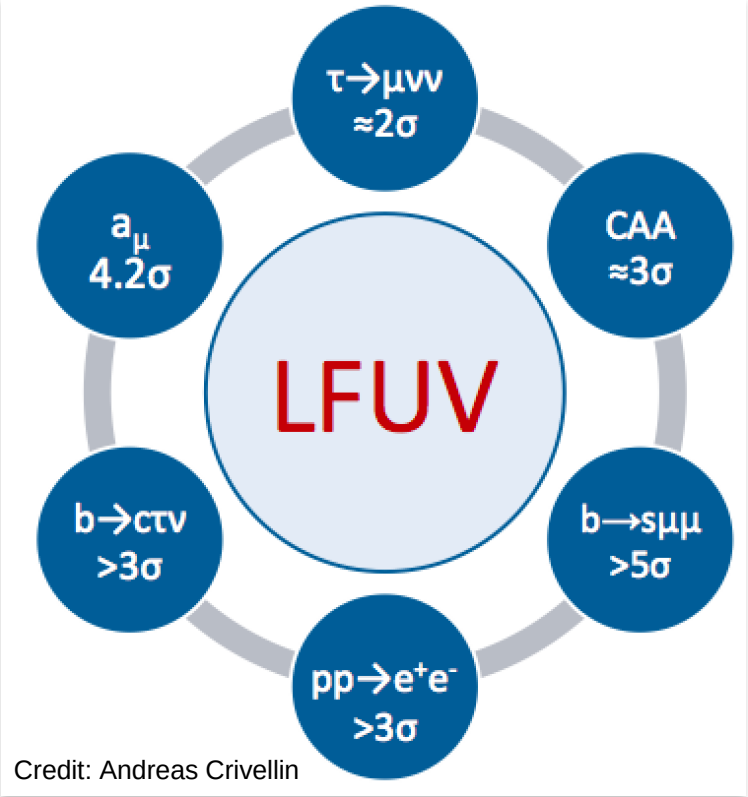
EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

The Era of Anomalies



Credit: Andreas Crivellin

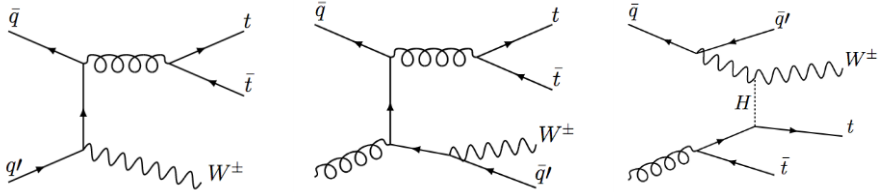
- These are exciting times, with multiple anomalies that point to LFUV.
- If real, at least some of these anomalies may have implications for the high-p_T experiments (ATLAS and CMS) with new particles at or below the TeV scale that may be discovered in the future.

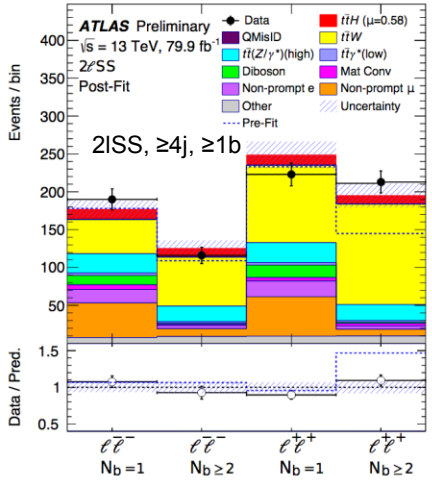
- The main challenge for the LHC is to discover the unexpected. New Physics (NP) signals may have signatures similar to SM processes and be confused with them.

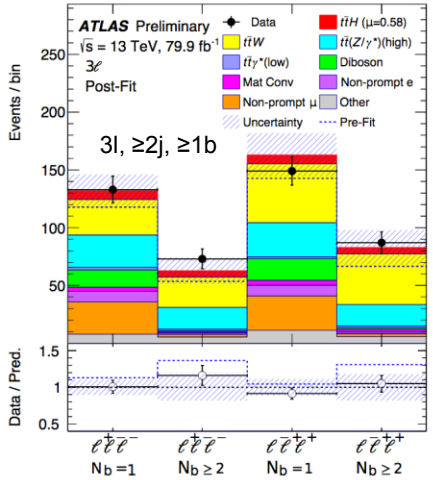
- Today will discuss about a different kind of anomalies, in multilepton+b-jets final states, which have been coming and going over the years.
- Multilepton+b-jets is a signature particularly sensitive to NP, so it's worth considering carefully how our analysis biases and procedures may lead to us missing those signals.

Multilepton+b-jets “anomalies”: ttW

ATLAS-CONF-2019-045







- ttW is an important background to several SM processes of interest (e.g. ttH, 4-tops) and BSM searches.
- Over the years a number of analyses have found the ttW yield to be in excess relative to the state-of-art theoretical prediction:

  SM prediction (YR4): σ_{ttW} = 601 ± 76 fb (NLO QCD+leading NLO EW)

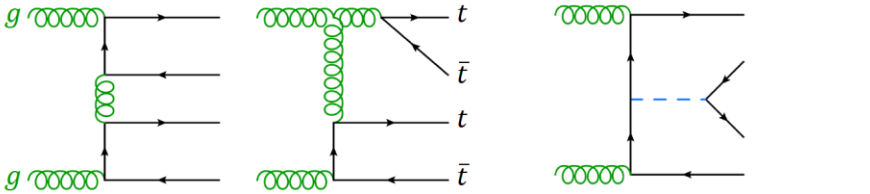
  (NLO QCD to ttW+1j: x1.1; subleading NLO EW: x1.09)

Search	$\mathcal{L}$ [fb^{-1}]	σ_{ref} [pb]	μ	μ_{YR4}
$t\bar{t}W^{\pm}$ ATLAS [1]	36.1	0.60 ± 0.07	1.44 ± 0.32	1.44 ± 0.32
$t\bar{t}W^{\pm}$ CMS [2]	35.9	0.628 ± 0.082	$1.23^{+0.30}_{-0.28}$	$1.29^{+0.31}_{-0.29}$
$t\bar{t}H$ ATLAS [3]	80	0.727 ± 0.092	$1.39^{+0.17}_{-0.16}$	$1.68^{+0.21}_{-0.19}$
$t\bar{t}H$ CMS [4]	137	0.650	1.43 ± 0.21	1.55 ± 0.23
four-top-quarks ATLAS [5]	139	0.601	1.6 ± 0.3	1.6 ± 0.3
four-top-quarks CMS [6]	137	0.610	1.3 ± 0.2	1.3 ± 0.2

- Furthermore, ATLAS ttH ML search finds odd data features as a function of total charge of the SS lepton pair and the b-jet multiplicity.

  Hard to explain: theoretical prediction of charge asymmetry is robust and unrelated to associated HF production.

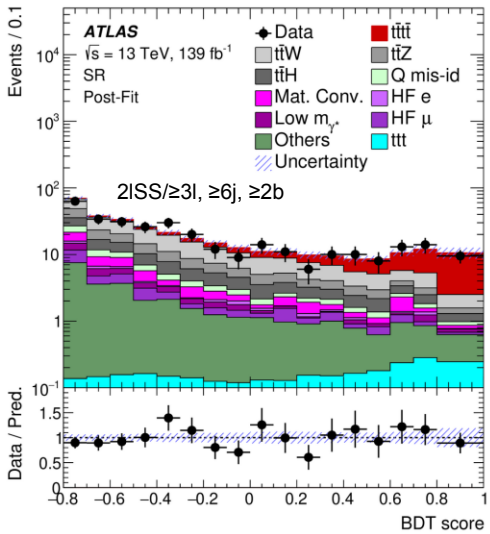
Multilepton+b-jets “anomalies”: 4-top

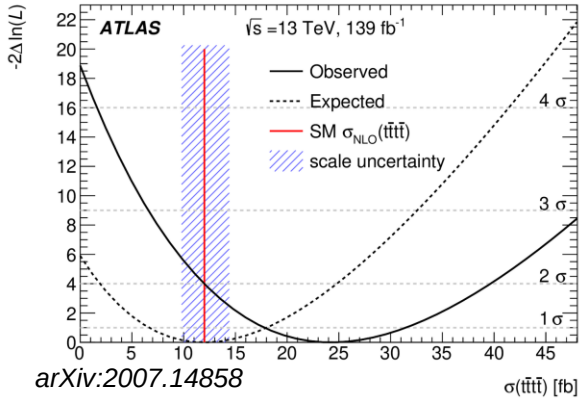


leading diagram from QCD: $\mathcal{O}(\alpha_S^2)$ sub-leading from EW: $\mathcal{O}(\alpha_S \alpha)$, $\mathcal{O}(\alpha_S y_t^2)$

- Rare process in the SM. Not observed yet.
- SM prediction: σ_{4t}=12.0 ± 2.4 fb (NLO QCD+NLO EW).
- Most recent ATLAS search in ML final states reached evidence with an observed (expected) significance of 4.3σ (2.4σ).

  Measured cross section a x2 larger than the SM prediction but consistent with it within 1.7σ.





arXiv:2007.14858

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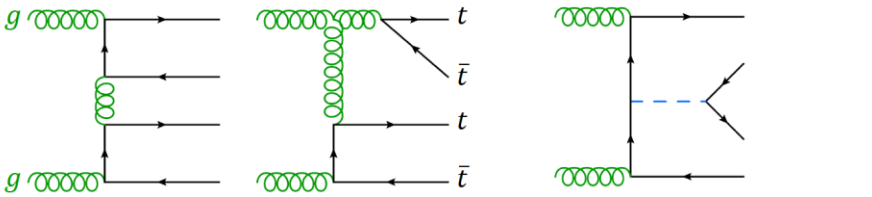

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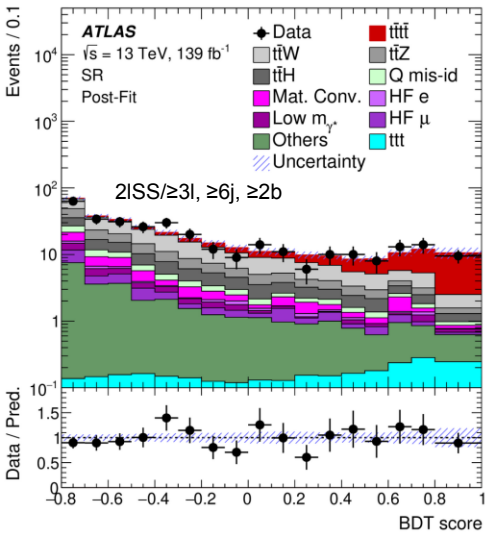
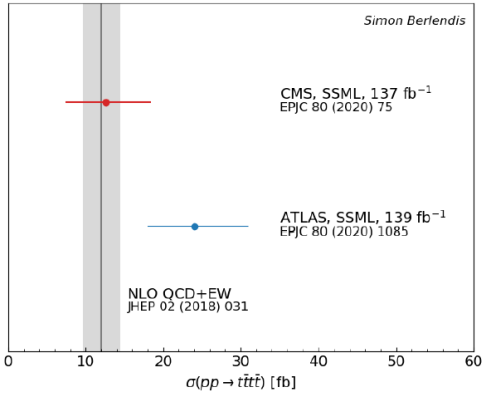
- The equivalent CMS analysis in ML final states measures a cross section very consistent with the SM.





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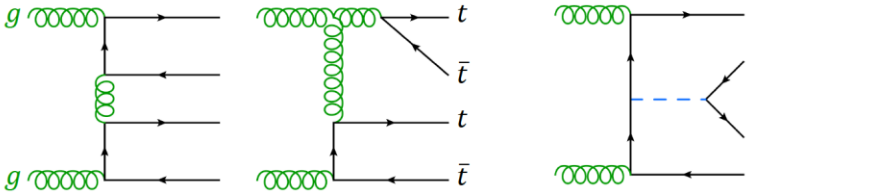

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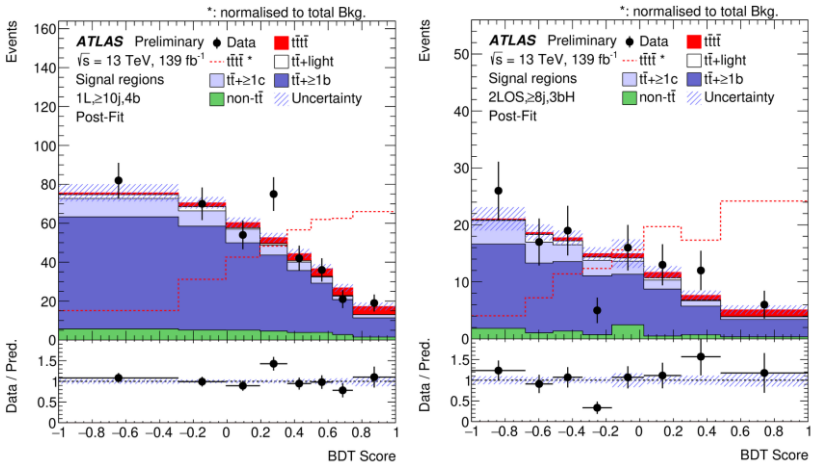
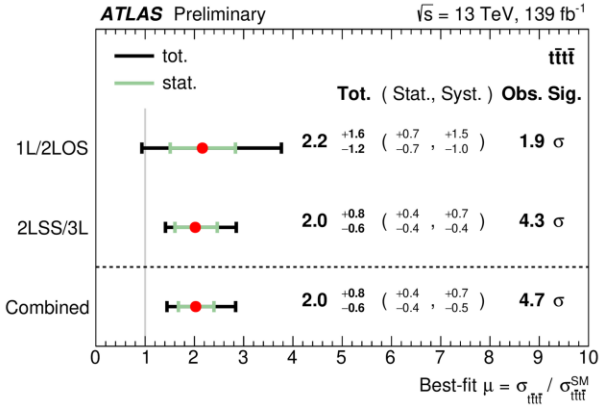
- Measured cross section a x2 larger than the SM prediction but consistent with it within 1.7σ.
- The equivalent CMS analysis in ML final states measures a cross section very consistent with the SM.
- However, the most recent ATLAS analysis in 1l/2lOS final states also measures a high cross section, albeit with a large uncertainty.

More data needed!



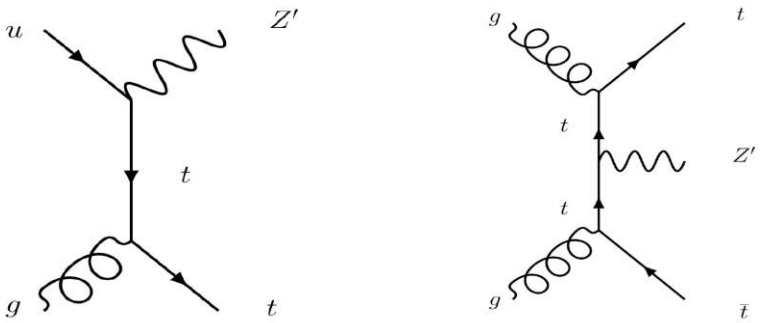


ATLAS-CONF-2021-013

Model and phenomenology

- A top-philic Z' with $m_{Z'}>m_t$ and the following interaction Lagrangian has the basic ingredients needed to explain these anomalies:

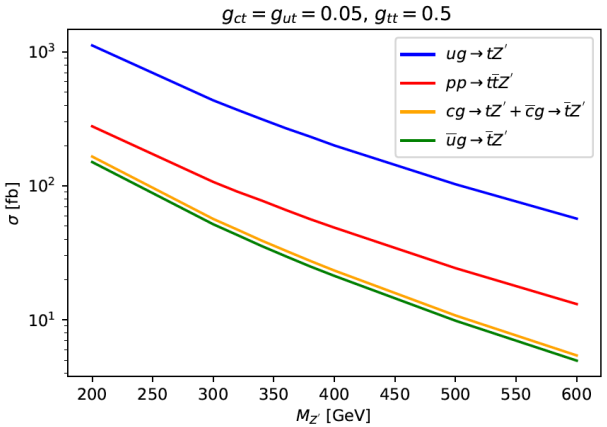
$$\mathcal{L}_{int} \supseteq Z'_\mu \left(g_{ut}\, \bar{t}_R \gamma^\mu u_R + g_{ct}\, \bar{t}_R \gamma^\mu c_R + g_{tt}\, \bar{t}_R \gamma^\mu t_R \right) + \text{h.c.}$$

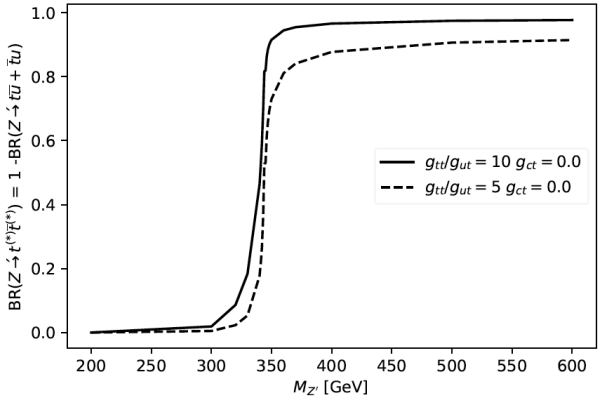


Charge-asymmetric production of 2SS tops, 2SS tops+1j and 3-tops.

Charge-symmetric production of 3-tops+1j and 4-tops.

Production cross sections and BRs modulated by g_{ut}, g_{ct} and g_{tt}.





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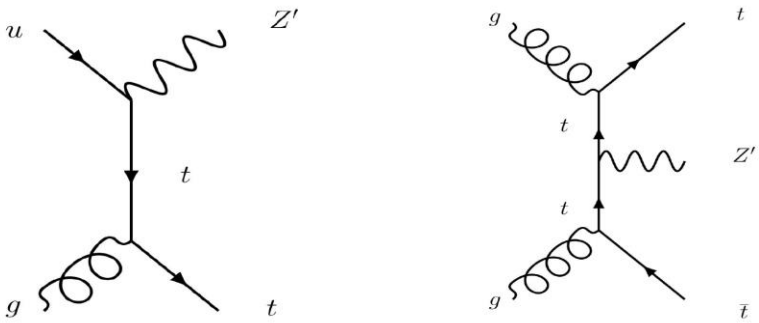

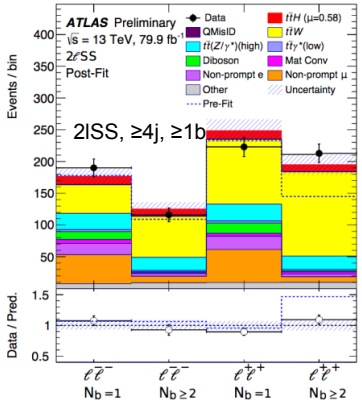

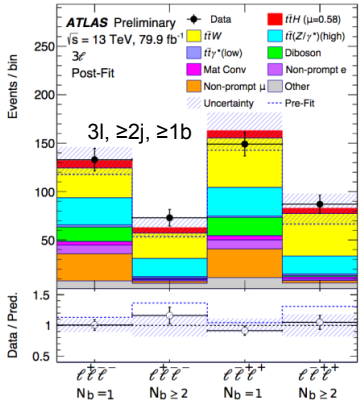

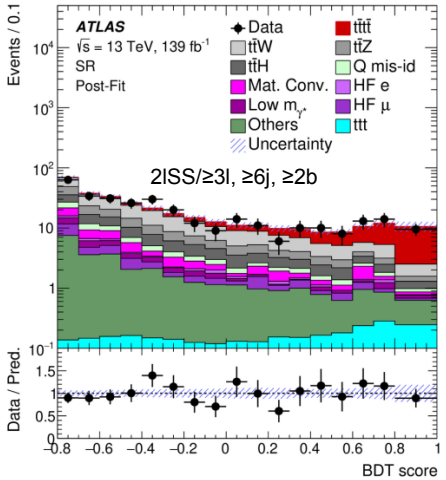

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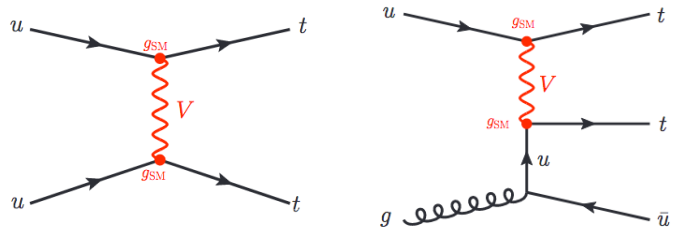
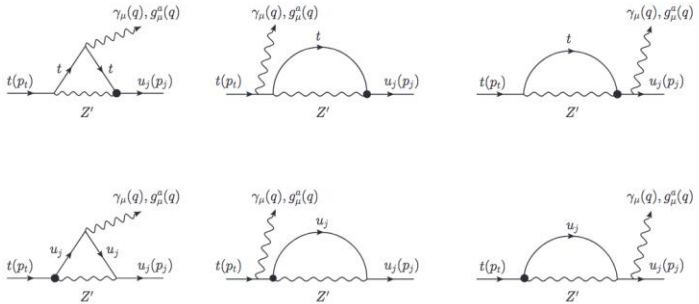
Production cross sections and BRs modulated by g_{ut}, g_{ct} and g_{tt}.

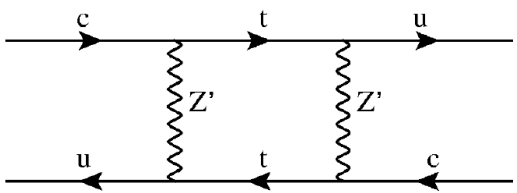
Constraints

- For the range of parameters considered $0 \leq g_{ut/ct} \leq 0.1$, $0 \leq g_{tt} \leq 1$ many constraints are evaded:
  - ttbar non-resonant effects are below experimental uncertainty.
  - Same-sign top pair production, both prompt and with an associated jet, are suppressed due to our couplings (besides, search targeted higher masses).
  - Resonant Z'→tj production is absent due to absent g_{uu}, g_{cc}. Moreover, radiative tZ'j production is suppressed due to non-existent left-handed couplings.
  - Rare top branching ratios are below current limits due to the value of the couplings and the chiral structure.
  - The main constrain comes from D-meson mixing:
  - Although we do not have an exact SM calculation to use, we ask that the BSM effect is smaller than the experimental uncertainty:

$$g_{ut}g_{ct} < 2.0\ (4.5) \times 10^{-3} \text{ for } M_{Z'}=400\ (600) \text{ GeV}$$



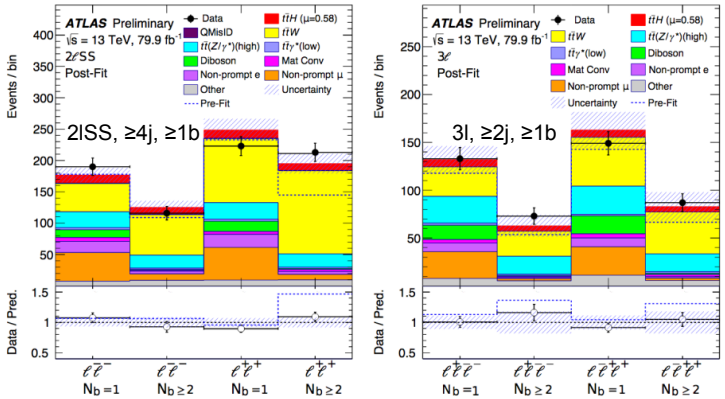


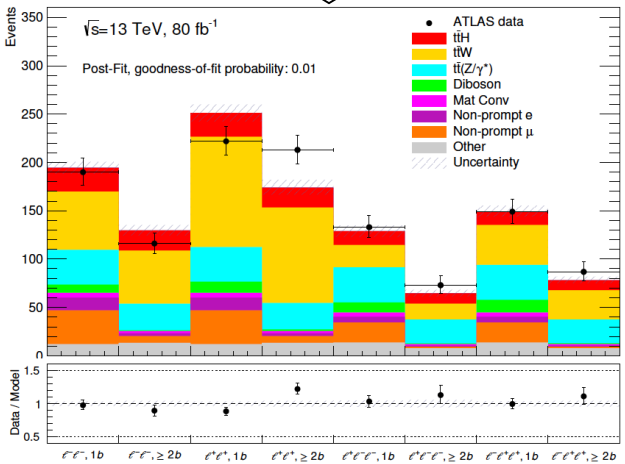


Fit to ATLAS data

- Focus on the ATLAS ttH search:
  - It has higher luminosity that the dedicated ttW measurement and the signal region is similar.
  - It provides a detailed breakdown of the data-to-MC comparison as a function of lepton multiplicity, total lepton charge and b-jet multiplicity.
  - Selection: 2lSS/3l, ≥4j/≥2j, ≥1b (no τ_{had}).
  - Goal: perform a fit to the ATLAS yields across the 8 analysis channels and determine compatibility of the data with different BSM signal hypotheses parameterized by (g_{tu}, g_{tc}, g_{tt}, $M_{Z'}$).
  - Implement normalization uncertainties per process similar to those in the ATLAS search.
  - Remove free-floating ttW normalization parameter and implement constraint from theoretical cross section.
  - Drop adhoc uncertainties introduced to accommodate tensions with the data.

    ➔ SM-only fit has goodness-of-fit probability of 1%.





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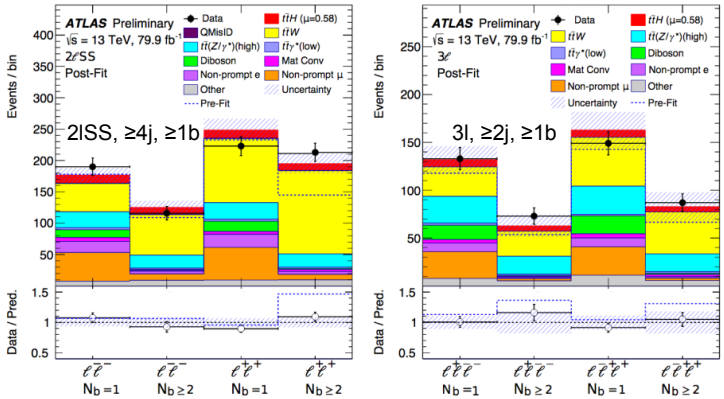
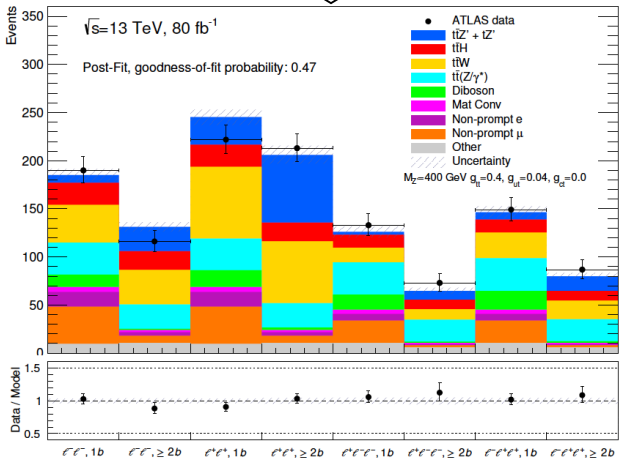
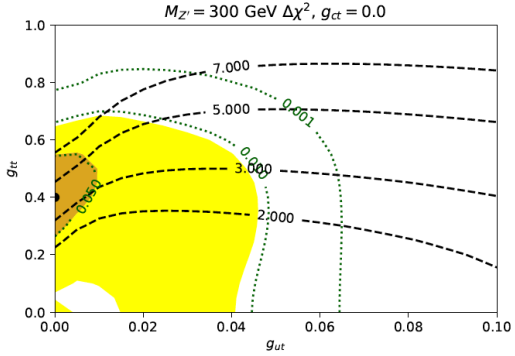
    ➔ SM+ BSM fit has goodness-of-fit probability of 47% for (g_{tu}, g_{tc}, g_{tt}, $M_{Z'}$)=(0.04, 0.0, 0.4, 400 GeV)





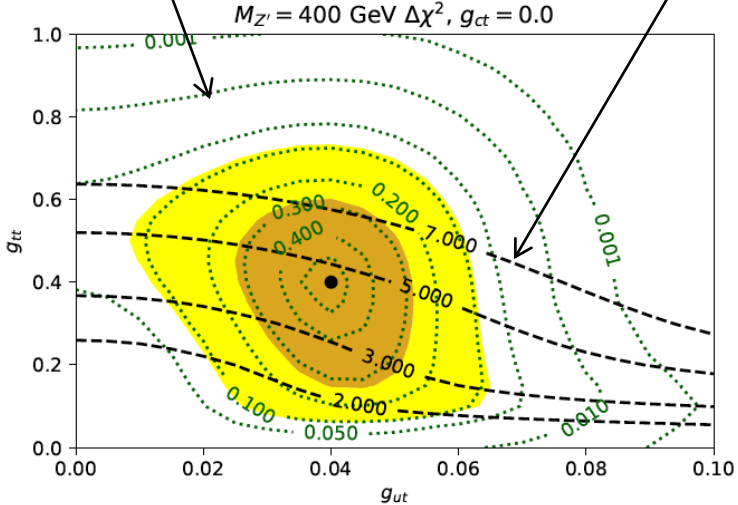
Fit to ATLAS data

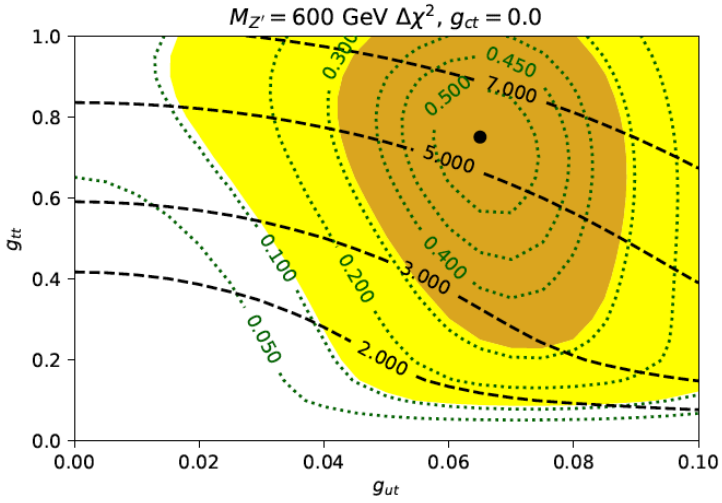
- For $M_{Z'}$<2mt the BSM fit is no better than the SM ➔ need Z'→tt decays!
- Good fit for $M_{Z'}$≥400 GeV, typically at g_{ut}~g_{tt}/10.
- Draw also isolines corresponding to the expected excess in 4-top like events (2lSS/≥3l, ≥6j, ≥3b) using the same selection cuts as the ATLAS SM 4-top analysis (i.e. the equivalent of their best-fit μ_{4t}).



Goodness-of-fit probability

$$\frac{N^{\text{4–top sel}}_{SM+BSM}}{N^{\text{4–top sel}}_{SM}}$$





Fit to ATLAS data

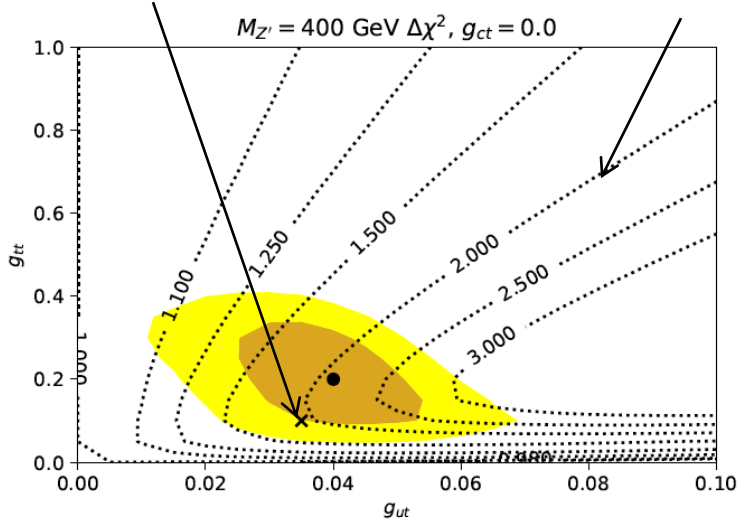
- Incorporate constraint from ATLAS SM 4-top (2lSS/≥3l): $\mu_{4t} = 2.0^{+0.8}_{-0.6}$

  ➔ Best-fit g_{tt} drops by x2, but still good fit to ttW data.
- Expect charge asymmetry in measured μ_{4t} because of 3-top contamination from gu→tZ'(→tt).
- So far assumed g_{ct}=0, but g_{ct}~g_{ut} also compatible with the data and allowed by D-mixing constraint.

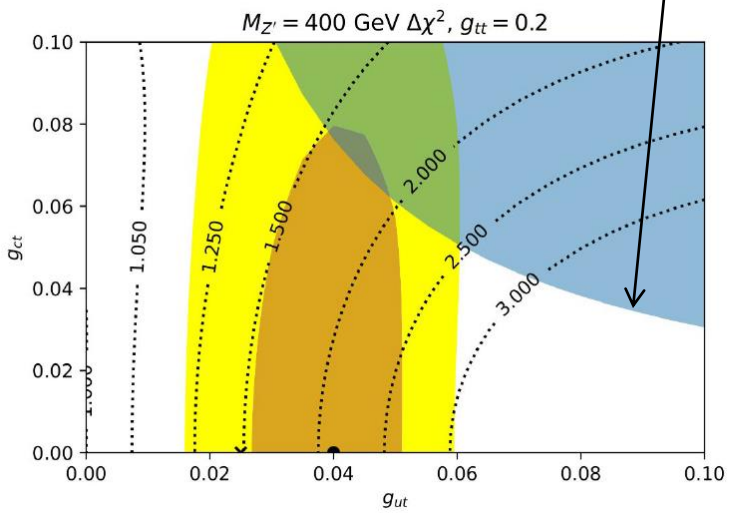
Best-fit point if using as constraint naïve ATLAS+CMS average

$\mu_{4t} = 1.4 \pm 0.3$

$\frac{N^{\text{4–top sel, Q>0}}_{SM+BSM}}{N^{\text{4–top sel, Q<0}}_{SM+BSM}}$

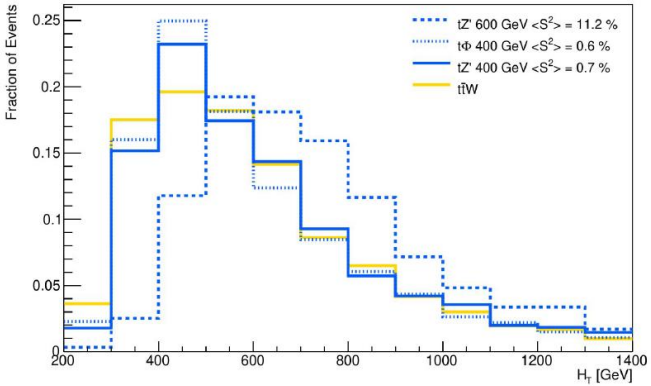


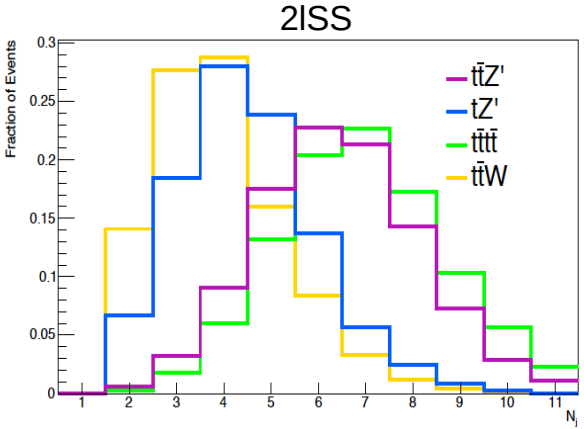
D-mixing constraint: $g_{ut}g_{ct} < 2.0 \times 10^{-3}$

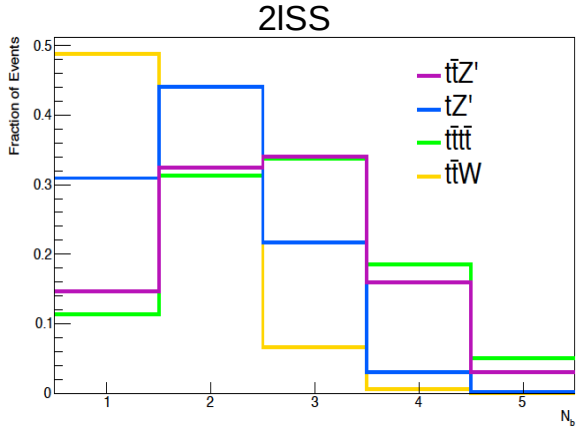


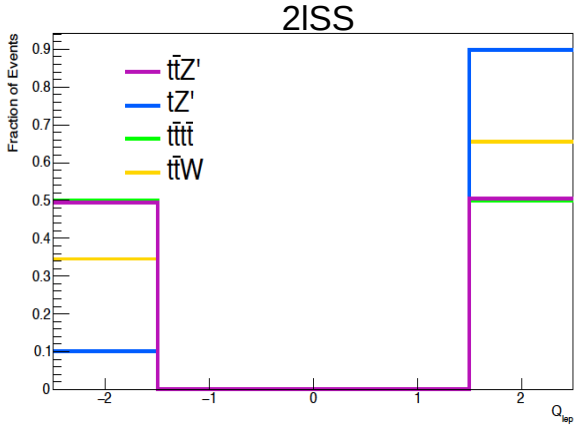
Uncovering hidden signals

- We have shown that a relatively light resonance with mass of ~400-600 GeV can easily hide in the ttW, ttH and 4-top searches, and be confused with the need for scaling up the SM processes.
- Kinematically, tZ' and ttZ' are similar to SM ttW and 4-top, respectively.
- However, there are significant differences in jet and b-jet multiplicities, and charge asymmetry!



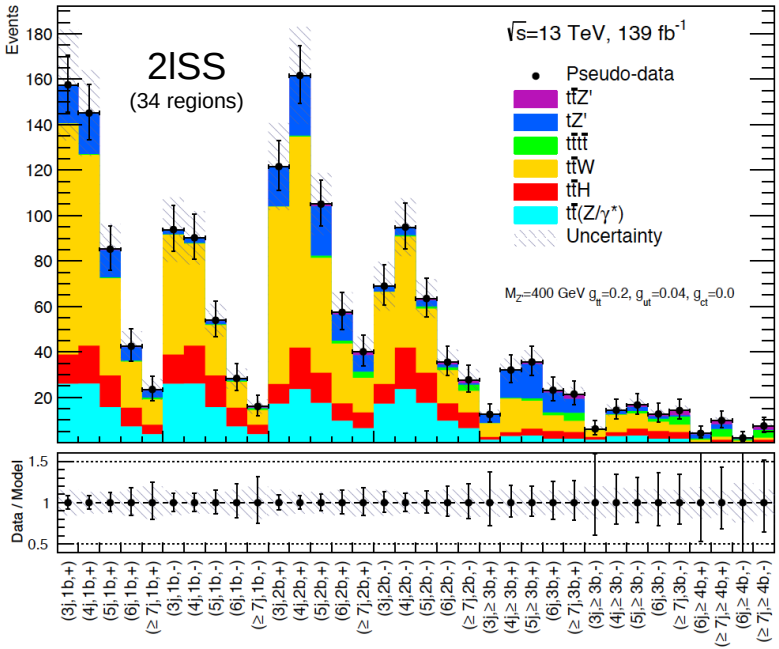


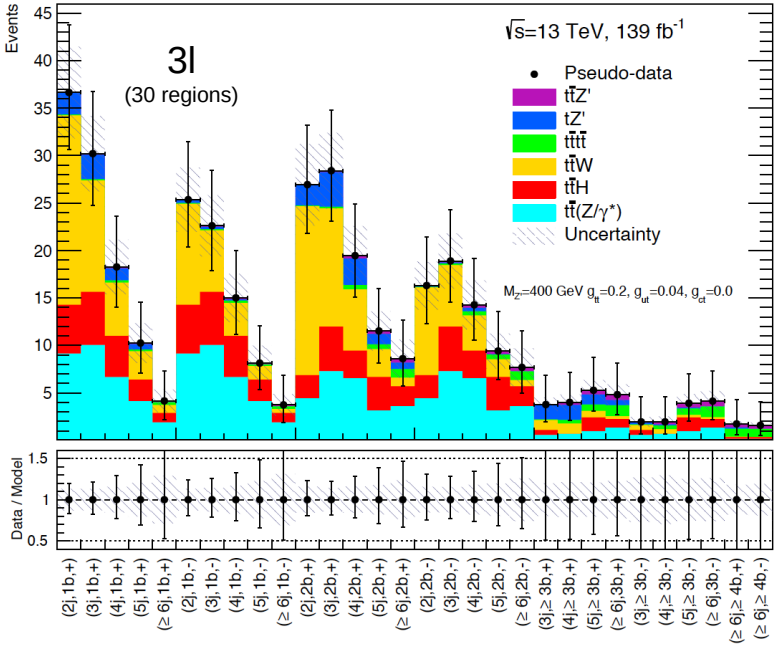




A global analysis

- To extract the signals while properly normalizing SM backgrounds need a global analysis (in addition to the best possible SM predictions!).
- Categorize events by lepton, jet, b-jet multiplicities, as well as total lepton charge.
- Perform combined fit across all bins, including a sophisticated systematic model for the background.





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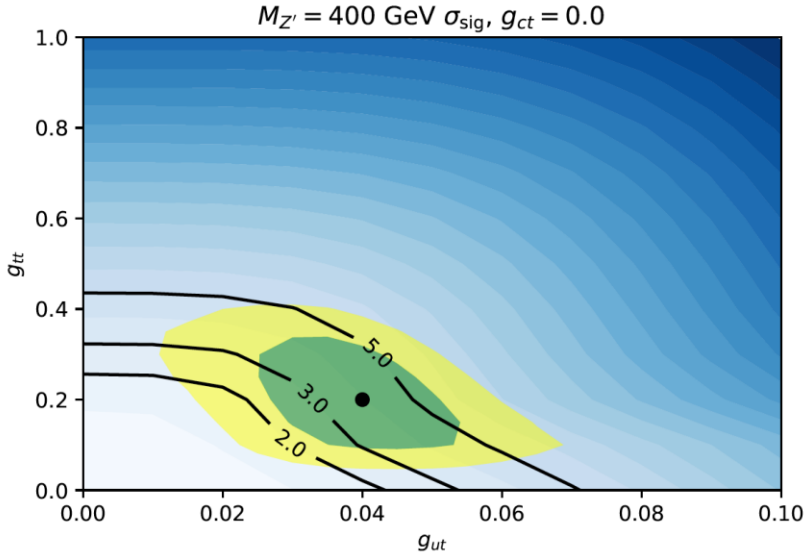
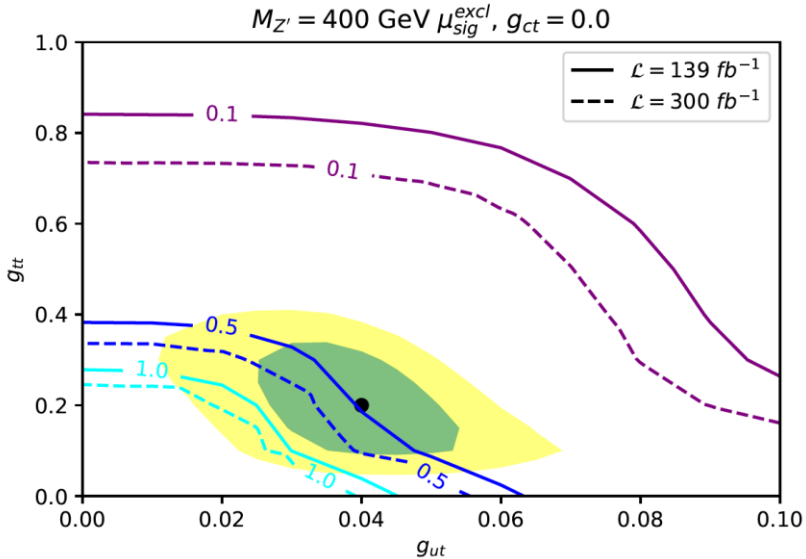
- Perform combined fit across all bins, including a sophisticated systematic model for the background.
  - With full Run 2 dataset can comfortably exclude best-fit point or have an excess with >3σ significance.
  - Potential for better performance exploiting more kinematic information.





Summary

- We have proposed a phenomenological FCNC Z' model that couples hierarchically to the up-type right-handed quarks to explain LHC discrepancies in multilepton+b-jets final states.
- We have found regions in parameter space that fit the data significantly better than the SM.
- We find that a sophisticated experimental search, along the lines of our proposed global analysis, could in the near future shed light on the existence of such a BSM scenario.
- If confirmed, it will be interesting to explore possible connections with other existing anomalies!

ttH analysis selections

$t\bar{t}H$	ATLAS		CMS	
	2LSS	3L	2LSS	3L
Total lepton charge	± 2	± 1	± 2	± 1
Lepton p_T [GeV]	20/20	15/15/10	25/15	25/15/10
Number of jets	≥ 2		≥ 3	≥ 2
Number of b-jets	≥ 1 (70% eff.)		≥ 1 (70% eff.) OR ≥ 2 (84% eff.)	
$\lvert m_{\ell\ell}\rvert$ (2LSS) or $\lvert m_{OSSF}\rvert$ (3L) [GeV]	> 12			
$\lvert m_{e^\pm e^\pm} - m_Z\rvert$ (2LSS) or $\lvert m_{OSSF} - m_Z\rvert$ (3L) [GeV]	-	> 10		
Other	-	$\lvert m_{\ell\ell\ell} - m_Z\rvert > 10$ GeV	Missing transverse momentum cuts	

4-top analysis selections

four-top-quarks	ATLAS		CMS	
	2LSS	$\geq$ 3L	2LSS	$\geq$ 3L
Total lepton charge	$\pm$2	-	$\pm$2	-
Lepton p_T [GeV]	28 (all ℓ)		25/20	25/20/20(/20)
Number of jets and b-jets	$\geq$ 6j $\geq$ 2bj (77% eff.)		$\geq$ 6j $\geq$ 2bj OR 5j $\geq$ 3bj (55-70% eff.)	$\geq$ 5j $\geq$ 2bj OR 4j $\geq$ 3bj (55-70% eff.)
H_T [GeV]	$>$ 500		$>$ 300	
$\lvert m_{e^\pm e^\pm}\rvert$ (2LSS) or $\lvert m_{OSSF}\rvert$ (3L) [GeV]	$>$ 15	-	$>$ 12	
$\lvert m_{e^\pm e^\pm} - m_Z\rvert$ (2LSS) or $\lvert m_{OSSF} - m_Z\rvert$ (3L) [GeV]	$>$ 10		-	$>$ 15
Other	-		Missing transverse momentum cuts	