An exploration of the anomalous *ttW* rate at the LHC

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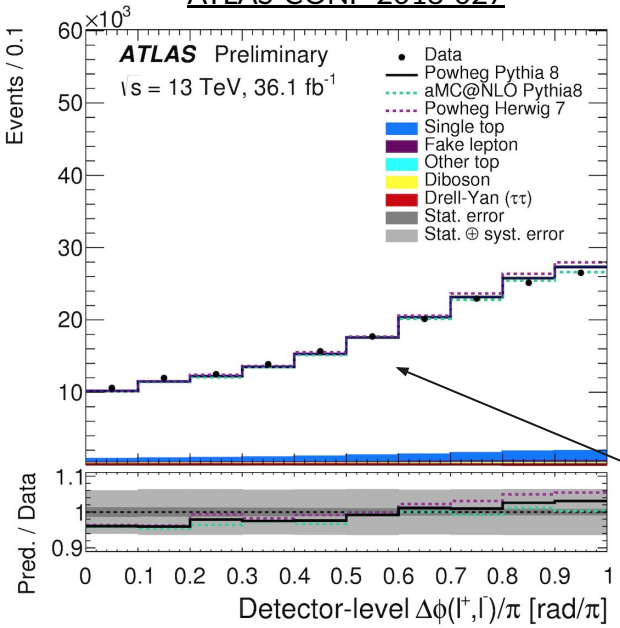
HEPP Workshop 2020

Multi-lepton anomalies at the LHC

… the 8σ conundrum… based on JHEP 1910 (2019) 157

Anomalous OS leptons

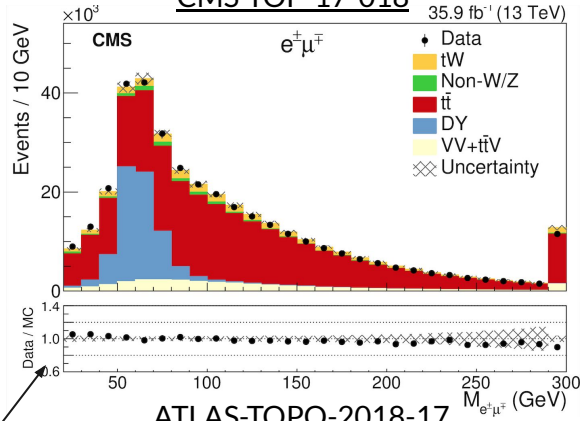
ATLAS-CONF-2018-027



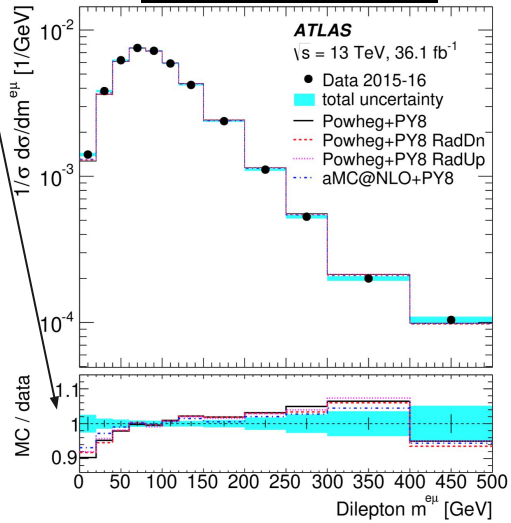
Enhancement of low di-lepton invariant mass

Distortion in di-lepton azimuthal angle

CMS-TOP-17-018



ATLAS-TOPQ-2018-17

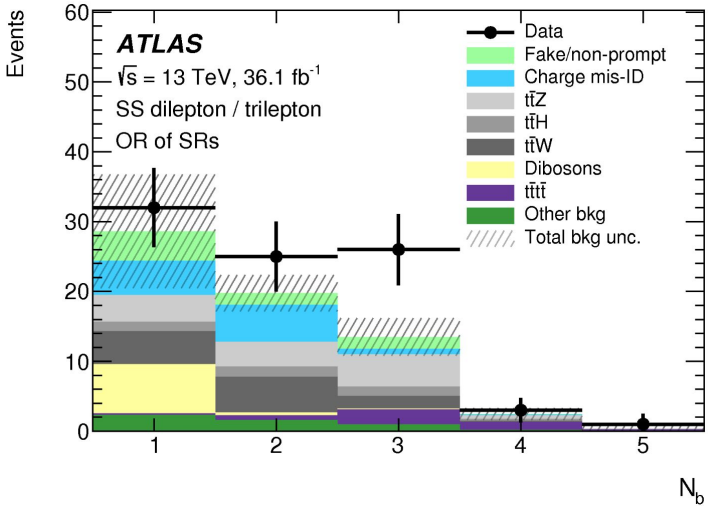


Anomalous SS leptons

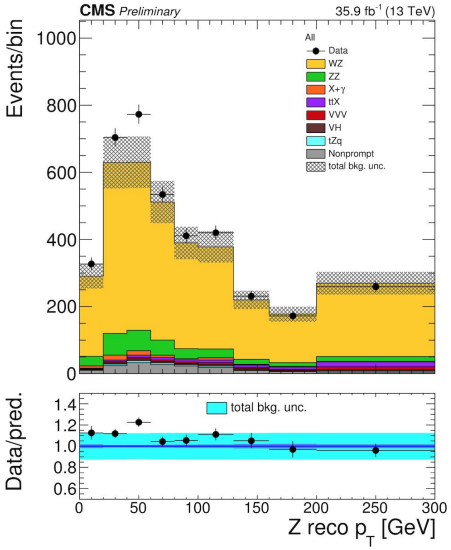
Hints of multiple SS leptons with additional *b*-jets.

In EW dominated processes too. Comes with low Z p_T.

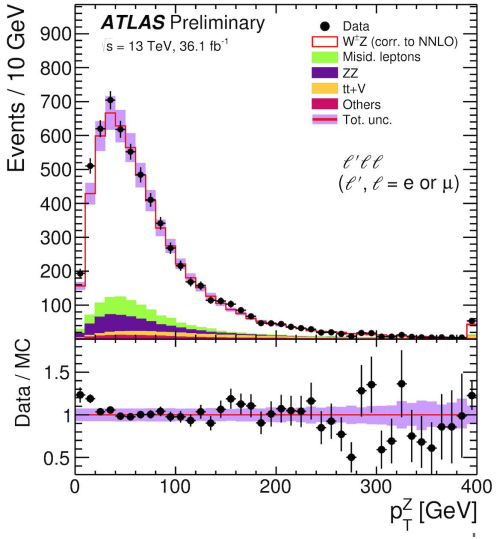
ATLAS-EXOT-2016-16



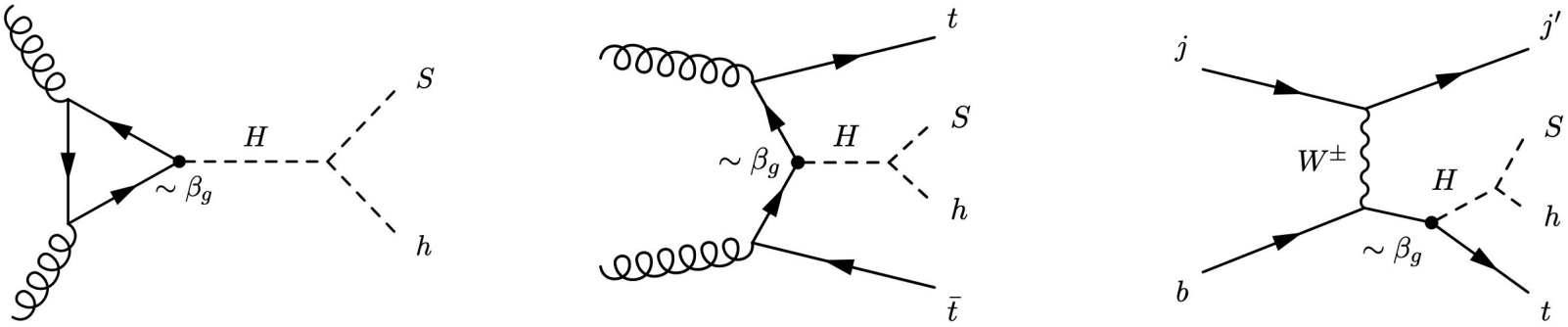
CMS-PAS-SMP-18-002



ATLAS-CONF-2018-034



The simplified new-physics model



Introduce 2 Higgs-like bosons: *S* and *H*

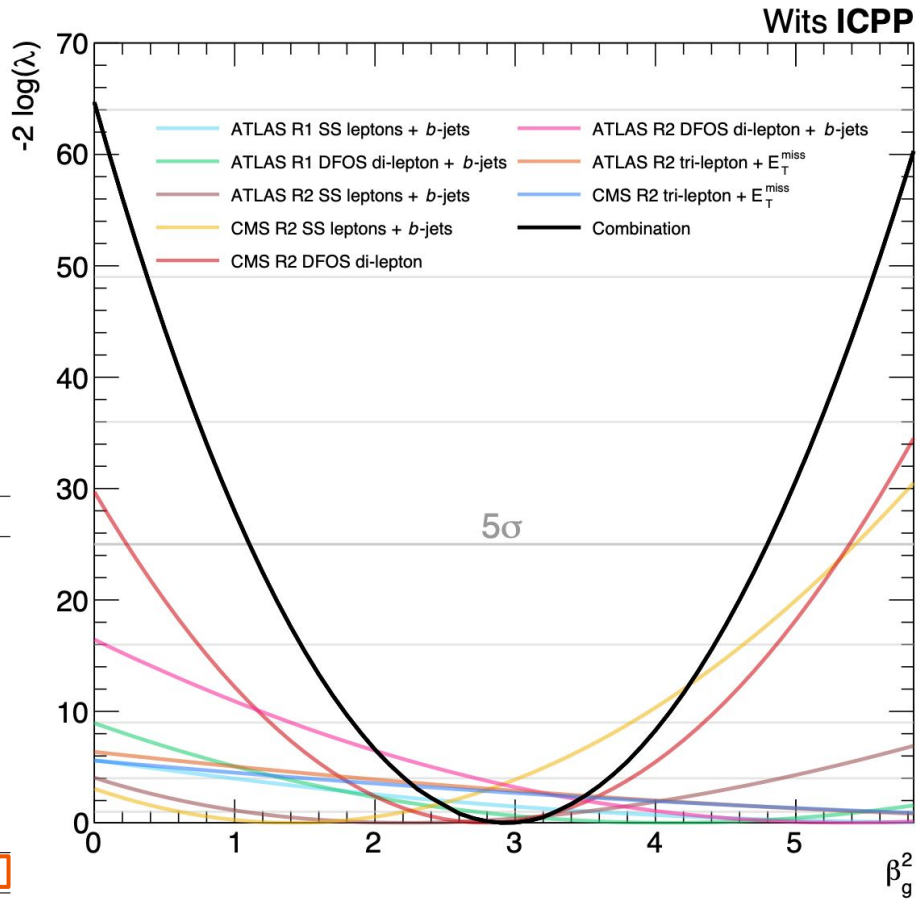
- Yukawa coupling is scaled by β_g (a free parameter)
- Masses are fixed *a priori*: *mH* = 270 GeV and *mS* = 150 GeV
- Decays are fixed *a priori*: BR ($H \rightarrow Sh$) = 100%, *S* has Higgs-like BRs

A source of multiple leptons and *b*-jets

Combining the anomalies

- Spread of best-fit β_g^2 values, may indicate that model is too simplified
  - However, results are all < 3σ compatible with each other

Selection	Best-fit β_g^2	Significance
ATLAS Run 1 SS leptons + b-jets	6.51 ± 2.99	2.37σ
ATLAS Run 1 DFOS di-lepton + b-jets	4.09 ± 1.37	2.99σ
ATLAS Run 2 SS leptons + b-jets	2.22 ± 1.19	2.01σ
CMS Run 2 SS leptons + b-jets	1.41 ± 0.80	1.75σ
CMS Run 2 DFOS di-lepton	2.79 ± 0.52	5.45σ
ATLAS Run 2 DFOS di-lepton + b-jets	5.42 ± 1.28	4.06σ
CMS Run 2 tri-lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$	9.70 ± 3.88	2.36σ
ATLAS Run 2 tri-lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$	9.05 ± 3.35	2.52σ
Combination	2.92 ± 0.35	8.04σ



The anomalous *ttW* rate

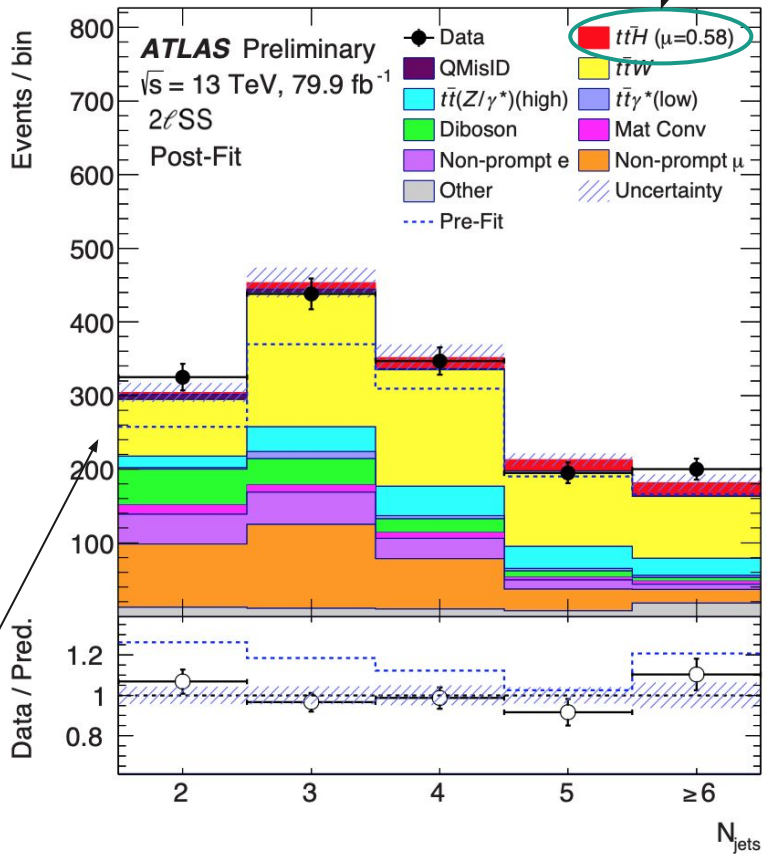
An earlier combination of multi-lepton *tth*: 1.92 ± 0.38 (arXiv:1706.02477)

The *ATLAS* multi-lepton *tth* search

- Basic selection: ≥ 2 SS leptons, ≥ 2 jets, ≥ 1 *b*-jets.
- Dominant background: *ttW*
  - Relatively difficult to reduce *ttW* background, since kinematics are similar to *tth*.
  - Employs a complex ML algorithm to analyse.
- ***ATLAS*** use an "updated" cross section for *ttW*
  - This is 727 fb (compared with ~600 fb in an aMC@NLO calculation).

Looks okay, right? Think again!

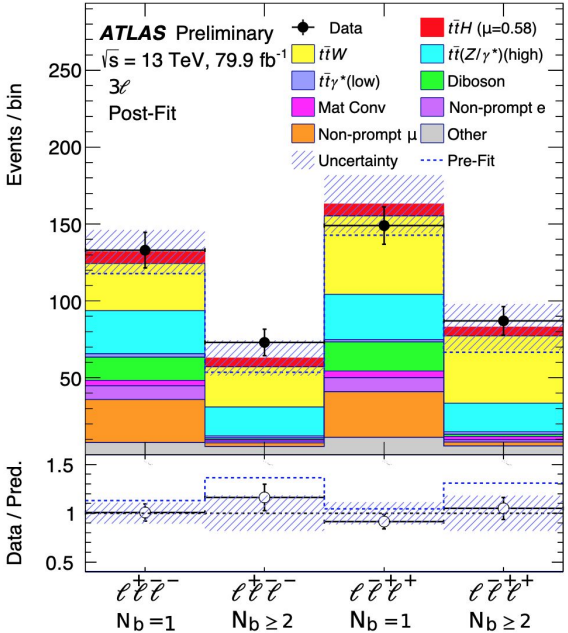
ATLAS-CONF-2019-045



The *ATLAS normalisation factors*

- The *ttW* prediction in these plots is "post-fit"
  - In the fit, the normalisation is unconstrained and uncorrelated between different channels.
- When looking at the ***ATLAS*** plots, focus on the dashed line ("pre-fit").
  - This includes all unscaled backgrounds *AND* the full Higgs signal.
- Thankfully, ***ATLAS*** provide the *normalisation factors* for the *ttW*:

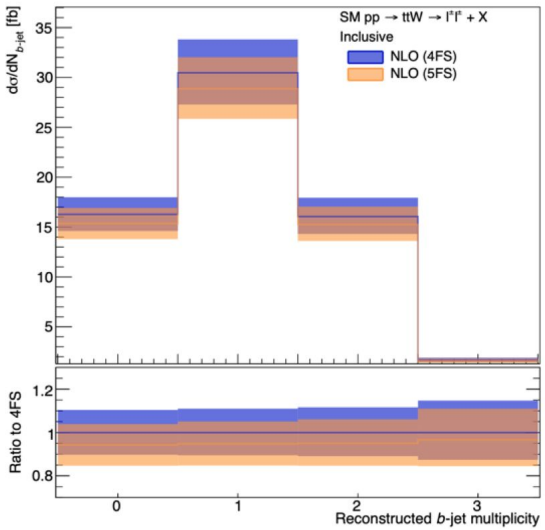
ATLAS-CONF-2019-045



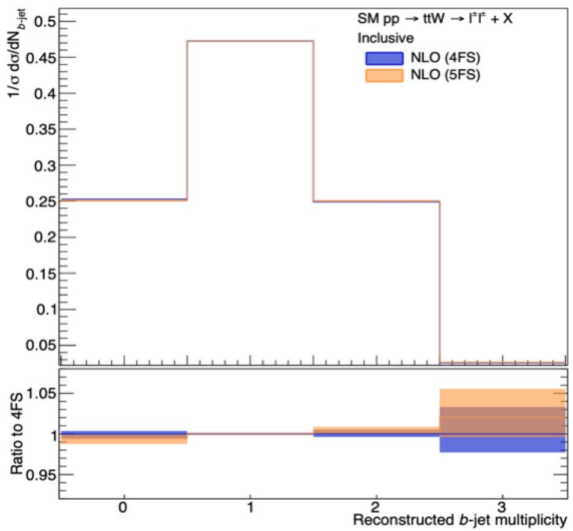
the LJ and HJ categories of the 2ℓSS channel, and one corresponding to the 3ℓ channel categories. The measured normalisation factors are: $\hat{\lambda}^{2\ell\mathrm{LJ}}_{t\bar{t}W} = 1.56^{+0.30}_{-0.28}$, $\hat{\lambda}^{2\ell\mathrm{HJ}}_{t\bar{t}W} = 1.26^{+0.19}_{-0.18}$, and $\hat{\lambda}^{3\ell}_{t\bar{t}W} = 1.68^{+0.30}_{-0.28}$. The agreement is improved after the application of the background corrections resulting from the likelihood fit,

What is the source of the high *ttW* rate?

- Using aMC@NLO, analysed with a detector simulation:
  - Overall uncertainty in 2 and 3 lepton categories: <12% (scale) and <2% (PDF)
- As a function of *b*-jet multiplicity, most of the uncertainty is "correlated"
- **It seems highly unlikely that additional quantum corrections can account for the extra 42%!**

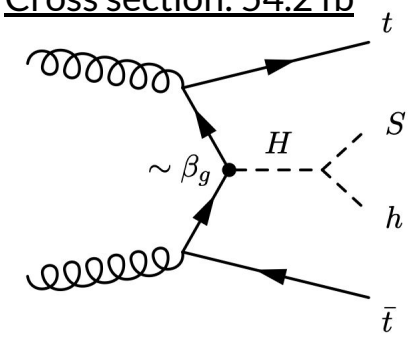


Normalise



Is it compatible with the established multi-lepton deviations?

Cross section: 54.2 fb



- This can be established using the simplified model in producing *ttH* and *tH*.

	2lSS Channel	3l Channel
Excess in the data	211 events	61.3 events
BSM (*tH*)	5.89	1.57
BSM (*ttH*)	8.92	3.67
Detector correction	0.873	1.34
Central value of β_g^2	**14.2**	**12.2**

Without systematics!

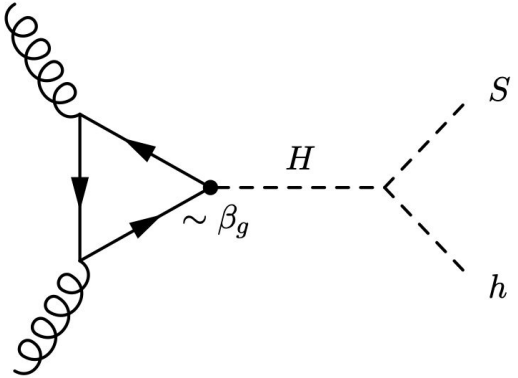
The original result:

Combination: $\beta_g^2 = 2.92 \pm 0.35$

SS only: $\beta_g^2 = 2.35 \pm 0.63$

Where are the missing events?

- Using just *ttH* and *tH*: $\beta_g^2 > 10$, where we would have expected something around **3**…
- Extra BSM events may come from the ggF production mode:



Decays to leptons via *WW*, *ZZ*, etc.

Typically decays to *bb*

- *B*-hadrons can radiate muons which can be reconstructed
- Small effect, but ggF has a large cross section (~10 pb)

- Given the large ggF cross section, this can contribute to the search!
  - Study ongoing… to fully understand requires a full simulation.

Summary and outlook

- It has been established that certain regions of the multi-lepton phase space is anomalous at the LHC.
- This has been corroborated by the recent ATLAS search for *tth* in a multi-lepton final state.
  - The need to re-scale *ttW* is unlikely to be explained using current SM tools.
- A simplified BSM model, with one degree of freedom, can explain the anomaly.

Still need to understand for the future:

1. What is the impact of the ggF production mode?
2. Need to quantify all theoretical sources of systematic uncertainties in the SM predictions.
3. Devise a set of observables to suggest for future searches.

FIN

Backup slides

An older combination of multi-lepton *tth*

arXiv:1706.02477

Reference	Channel	Measured μ_{tth}
CMS Run 1 [35]	Same-sign 2ℓ	$5.3^{+2.1}_{-1.8}$
	3ℓ	$3.1^{+2.4}_{-2.0}$
	4ℓ	$-4.7^{+5.0}_{-1.3}$
	Combination	$2.8^{+1.0}_{-0.9}$
ATLAS Run 1 [36]	$2\ell 0\tau_{\text{had}}$	$2.8^{+2.1}_{-1.9}$
	3ℓ	$2.8^{+2.2}_{-1.8}$
	$2\ell 1\tau_{\text{had}}$	$-0.9^{+3.1}_{-2.0}$
	4ℓ	$1.8^{+6.9}_{-2.0}$
	$1\ell 2\tau_{\text{had}}$	$-9.6^{+9.6}_{-9.7}$
	Combination	$2.1^{+1.4}_{-1.2}$
CMS Run 2 [37]	Same-sign 2ℓ	$1.7^{+0.6}_{-0.5}$
	3ℓ	$1.0^{+0.8}_{-0.7}$
	4ℓ	$0.9^{+2.3}_{-1.6}$
	Combination	$1.5^{+0.5}_{-0.5}$
ATLAS Run 2 [38]	$2\ell 0\tau_{\text{had}}$	$4.0^{+2.1}_{-1.7}$
	3ℓ	$0.5^{+1.7}_{-1.6}$
	$2\ell 1\tau_{\text{had}}$	$6.2^{+3.6}_{-2.7}$
	4ℓ	< 2.2
	Combination	$2.5^{+1.3}_{-1.1}$
Error weighted mean		1.92 ± 0.38

Table 3: The measured μ values for tth production in multileptonic analysis channels. A combination is estimated as the error weighted mean of each quoted combined result.