$t\bar{t}$ + γ / Z / W

Measurements of $t\bar{t}$ pairs produced in association with electroweak gauge bosons using the ATLAS detector

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on behalf of the ATLAS collaboration

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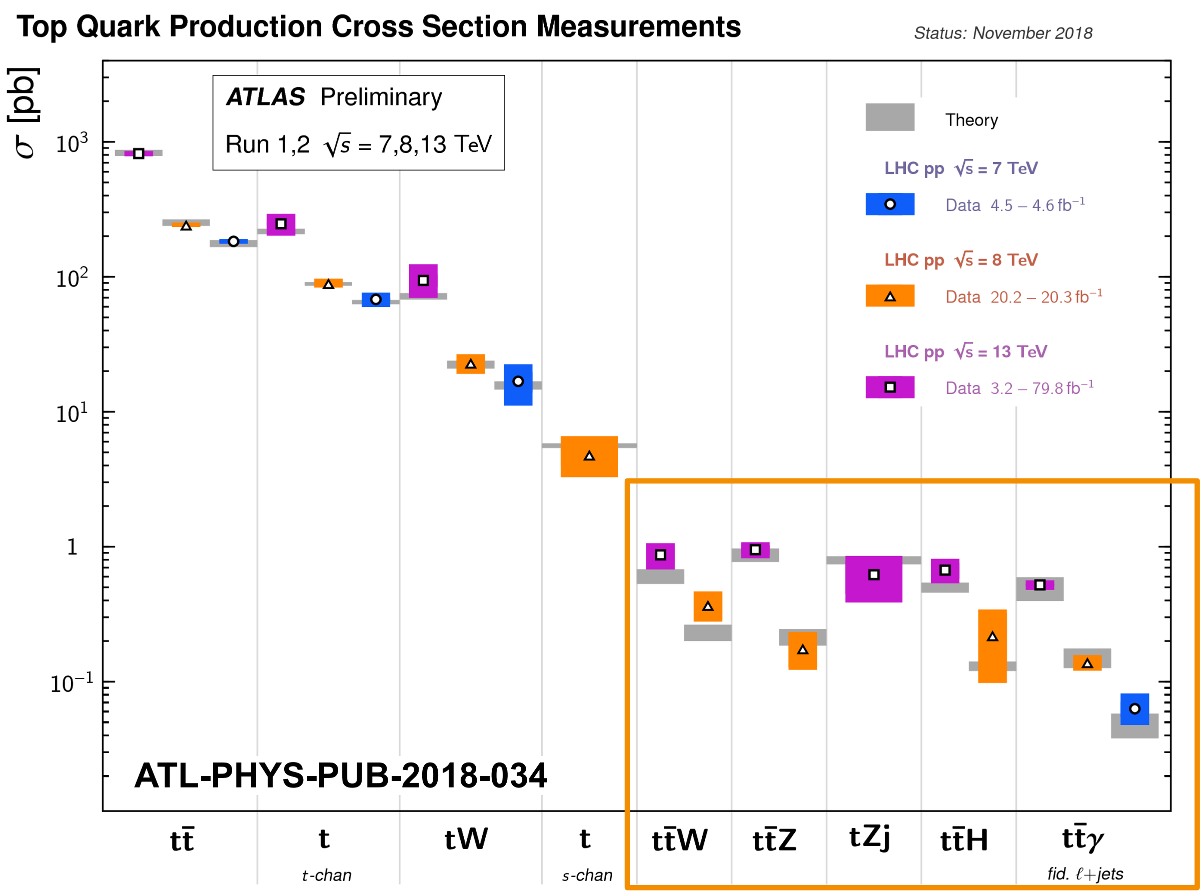
Introduction

> Large statistics and centre-of-mass energy allows us to explore the phase space of $t\bar{t}$ associated production with electroweak bosons at the LHC



Cross section measurements of rare production modes at 13 TeV, with 36 fb^{-1} data are shown:

- $t\bar{t} + W/Z$
- $t\bar{t} + \gamma$

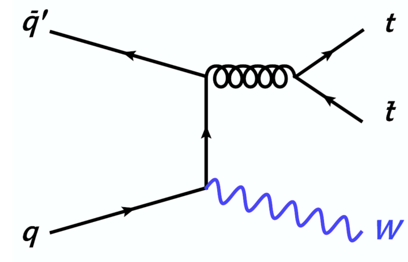
See talk by B. Stelzer on $t\bar{t} + H$

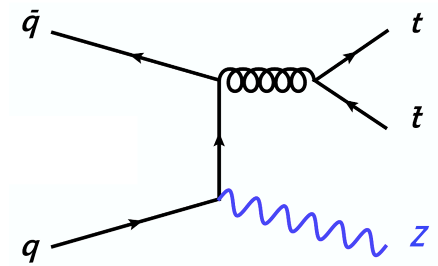
Predicted cross sections of order 1 pb

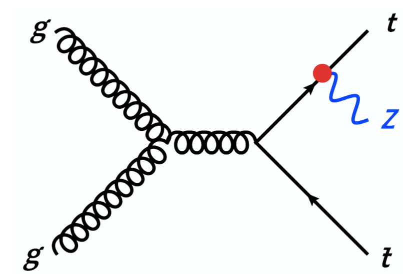
$\mathrm{t\bar{t}} + \mathrm{W/Z}$ overview

arXiv:1901.03584

- BSM models could enhance the $\mathrm{t\bar{t}} + \mathrm{W/Z}$ cross section
- Direct probe of tZ coupling in FSR
- Large irreducible background for searches including
  - Two-Higgs-Doublet models ATL-PHYS-PUB-2018-027
  - SUSY stop search JHEP 06 (2018) 108
  - Observation of ttH(H->multi-lepton final states) Phys. Rev. D 97 (2018) 072003







- Measurement divided into regions defined by lepton (ℓ) multiplicity and charge to enhance sensitivity

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

Same Sign (SS) or Opposite Sign (OS) 2ℓ.
Here ℓ = electron or muon.

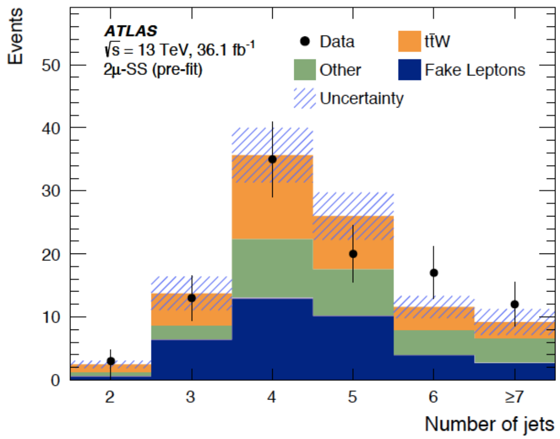
Yields low statistics, high purity selection.

$t\bar{t} + W/Z$ event selection

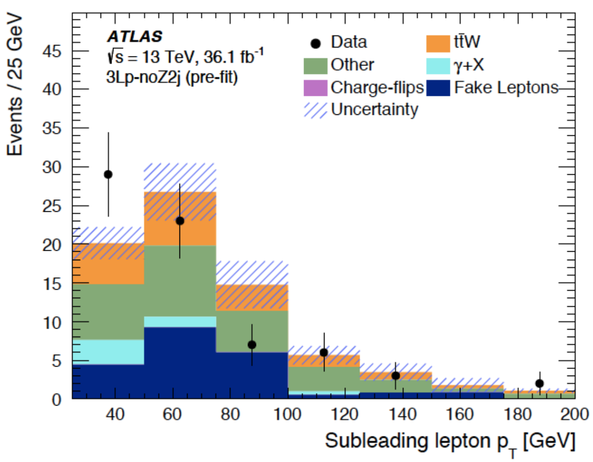
arXiv:1901.03584

- To enhance ttW and ttZ signals, the 2ℓ, 3ℓ or 4ℓ selections are split by:
  - Lepton charge, lepton flavour, $\ell\ell$ invariant mass, numbers of jets and b-tagged jets

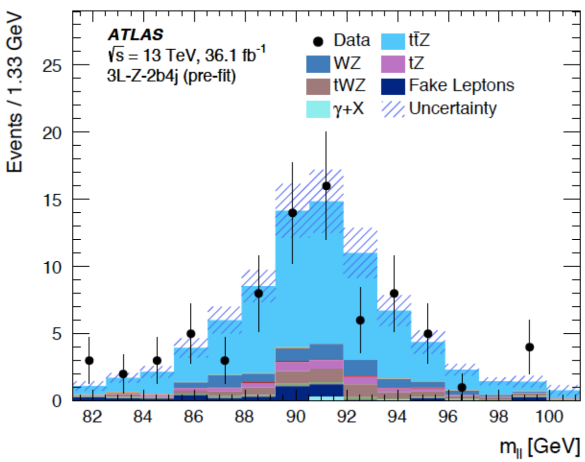
Examples:



2μ, SS, ≥2 b-jets, Z-veto



3ℓ, + charge sum, ≥2 b-jets, Z-veto



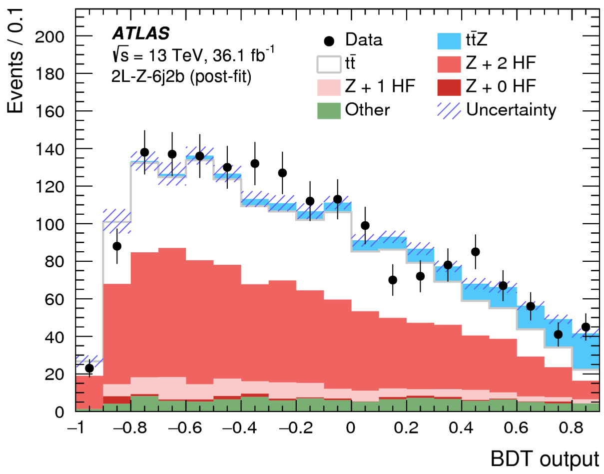
3ℓ, ≥2 b-jets, M_Z window

- fake lepton background from hadron decays, photon conversions or misidentified jets
- Reject by tight isolation and a multivariate discriminate to distinguish prompt from non-prompt leptons

$t\bar{t} + Z$ yields

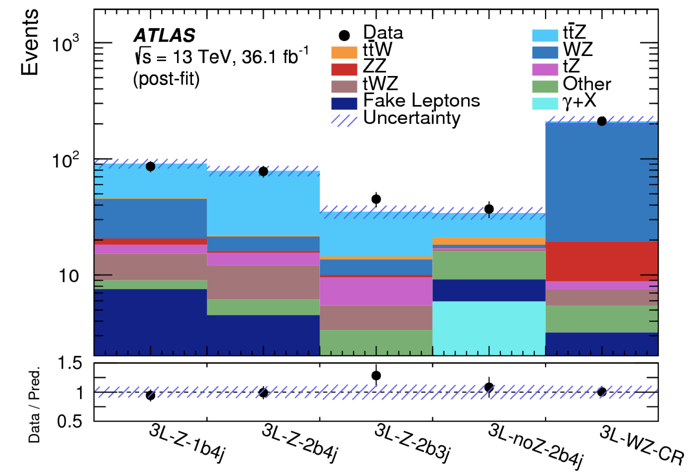
arXiv:1901.03584

2ℓ OS



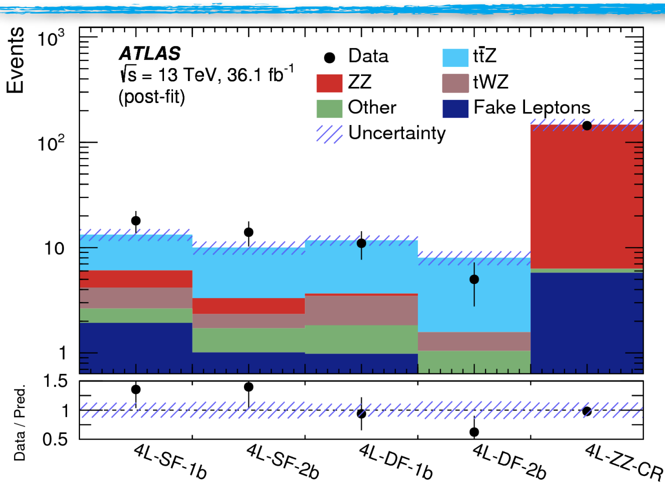
- fully hadronic top decays
- same flavour (SF) ℓ pair in M_Z window
- a BDT rejects larger tt and Z+jets bkg.

3ℓ



- semi-leptonic top decays
- one OS SF ℓ pair in M_Z window
- WZ+jets normalisation determined in Control Region, defined by b-jet veto

4ℓ



- fully leptonic final state
- 2 OS ℓ pairs, one forms Z candidate
- Flavour of 2nd OS ℓ pair and #b-jets define regions

- ZZ background rejected in SF by high E_T^{miss} selection and M_Z veto, ZZ normalisation from CR

$t\bar{t} + W$ yields

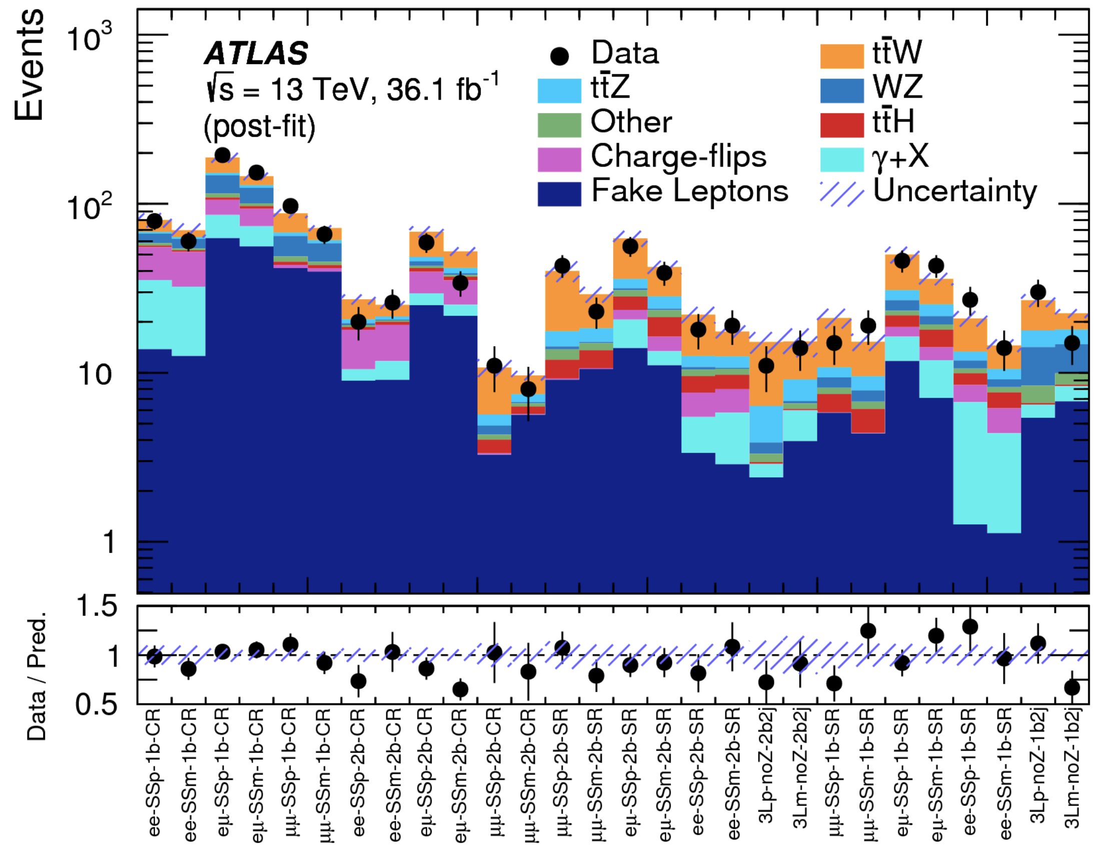
arXiv:1901.03584

12 regions in 2ℓ SS

- Select SS ℓ pair with M_Z veto
- Invert E_T^{miss} and $\Sigma_{jets,\ell}(p_T)$ conditions for Fake Lepton CRs
- Exploit charge asymmetric ttW signal (preference for positive) over charge symmetric backgrounds.
- misidentify electron charge leads to Charge-flips background

4 regions in 3ℓ

- Veto OS SF ℓ pair in M_Z window
- Require 2 or 3 jets.
- background from ttZ requires simultaneous measurement of σ_{ttZ} and σ_{ttW}



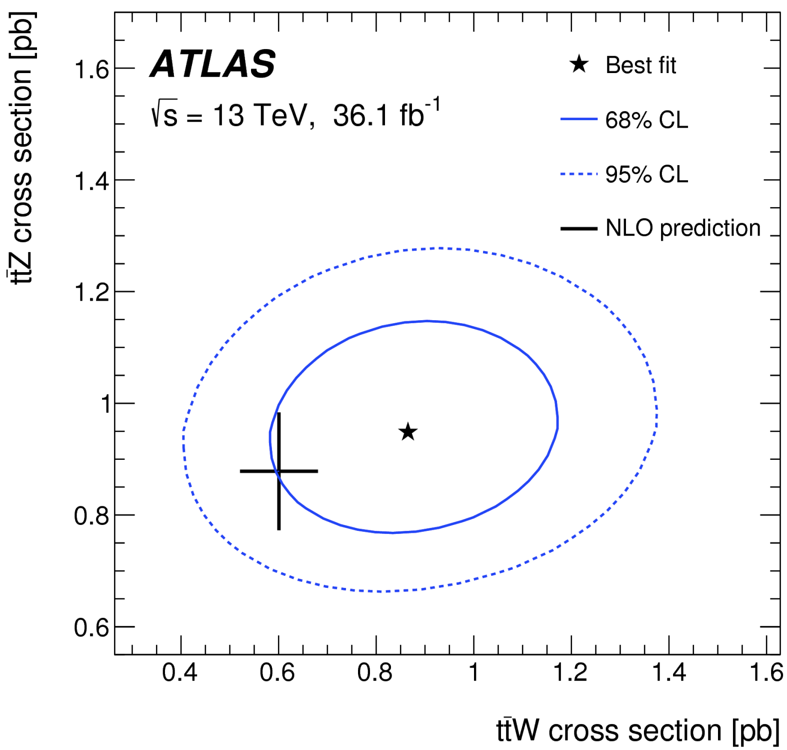
$t\bar{t} + Z/W$ cross section measurements

arXiv:1901.03584

- σ_{ttZ} and σ_{ttW} are evaluated simultaneously over all channels in a binned profile likelihood fit

$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08_{\text{stat.}} \pm 0.10_{\text{syst.}}\ \text{pb} = 0.95 \pm 0.13\ \text{pb}$$

$$\sigma_{t\bar{t}W} = 0.87 \pm 0.13_{\text{stat.}} \pm 0.14_{\text{syst.}}\ \text{pb} = 0.87 \pm 0.19\ \text{pb}$$



Excess over background only hypothesis:
- ttZ: observed and expected >5σ
- ttW: 4.3σ obs., 3.4σ exp.

WZ, ZZ and Z+jets backgrounds all compatible with SM.

The limiting systematic uncertainties arise from the signal and background modelling.

$t\bar{t} + W/Z$ BSM interpretation

arXiv:1901.03584

- Effective field theory (EFT) provides model independent parameterisation of deviations from the SM.
- 5 additional operators ($\mathcal{O}_i$) and corresponding coefficients on σ_{ttZ} (C_i) that are sensitive to the ttZ vertex are considered within a 6-dimension EFT
- $\sigma_i^{(1)}$and $\sigma_{ii}^{(2)}$ from NLO MG5_aMC+Py8
- EFT parameters are evaluated in a fit to ttZ rich regions, to determine the best-fit values of C_i.

$$\sigma_{\text{tot},i} = \sigma_{\text{SM}} + \frac{C_i}{(\Lambda/1\text{TeV})^2}\sigma_i^{(1)} + \frac{C_i^2}{(\Lambda/1\text{TeV})^4}\sigma_{ii}^{(2)}$$

Operator	Expression
$O_{\phi Q}^{(3)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi)(\bar{Q}\gamma^\mu \tau^I Q)$
$O_{\phi Q}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$
$O_{\phi t}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{t}\gamma^\mu t)$
O_{tW}	$(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W_{\mu\nu}^I$
O_{tB}	$(\bar{Q}\sigma^{\mu\nu} t)\tilde{\phi}B_{\mu\nu}$

- Measured constraints represent a notable improvement over previous findings:

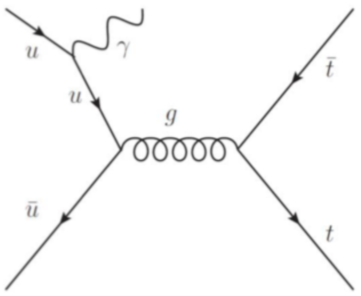
Coefficients	$C_{\phi Q}^{(3)}/\Lambda^2$	$C_{\phi t}/\Lambda^2$	C_{tB}/Λ^2	C_{tW}/Λ^2
Previous indirect constraints at 68% CL	[−4.7, 0.7]	[−0.1, 3.7]	[−0.5, 10]	[−1.6, 0.8]
Previous direct constraints at 95% CL	[−1.3, 1.3]	[−9.7, 8.3]	[−6.9, 4.6]	[−0.2, 0.7]
Expected limit at 68% CL	[−2.1, 1.9]	[−3.8, 2.7]	[−2.9, 3.0]	[−1.8, 1.9]
Expected limit at 95% CL	[−4.5, 3.6]	[−23, 4.9]	[−4.2, 4.3]	[−2.6, 2.6]
Observed limit at 68% CL	[−1.0, 2.7]	[−2.0, 3.5]	[−3.7, 3.5]	[−2.2, 2.1]
Observed limit at 95% CL	[−3.3, 4.2]	[−25, 5.5]	[−5.0, 5.0]	[−2.9, 2.9]
Expected limit at 68% CL (linear)	[−1.9, 2.0]	[−3.0, 3.2]	–	–
Expected limit at 95% CL (linear)	[−3.7, 4.0]	[−5.8, 6.3]	–	–
Observed limit at 68% CL (linear)	[−1.0, 2.9]	[−1.8, 4.4]	–	–
Observed limit at 95% CL (linear)	[−2.9, 4.9]	[−4.8, 7.5]	–	–

$t\bar{t} + \gamma$ motivation

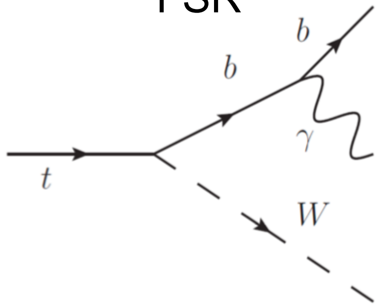
arXiv:1812.01697

- $t\bar{t} + \gamma$ inclusive and differential cross section measurements
- can probe electroweak $t\gamma$ couplings
  - Deviation in pT spectrum could hint at new physics, e.g. anomalous dipole moments of the top quark
  - Differential distributions sensitive to $t\bar{t}$ spin correlation and charge asymmetry
- Constrain EFT models
- Selection optimised to enhance top-radiated γ, but measurement includes all sources
  - large angular distance between γ and lepton to cut FSR

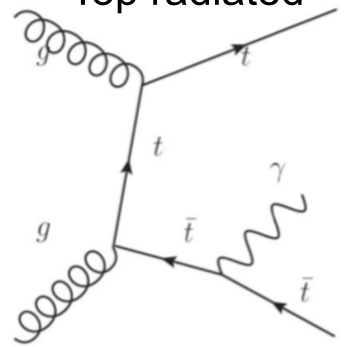
ISR



FSR



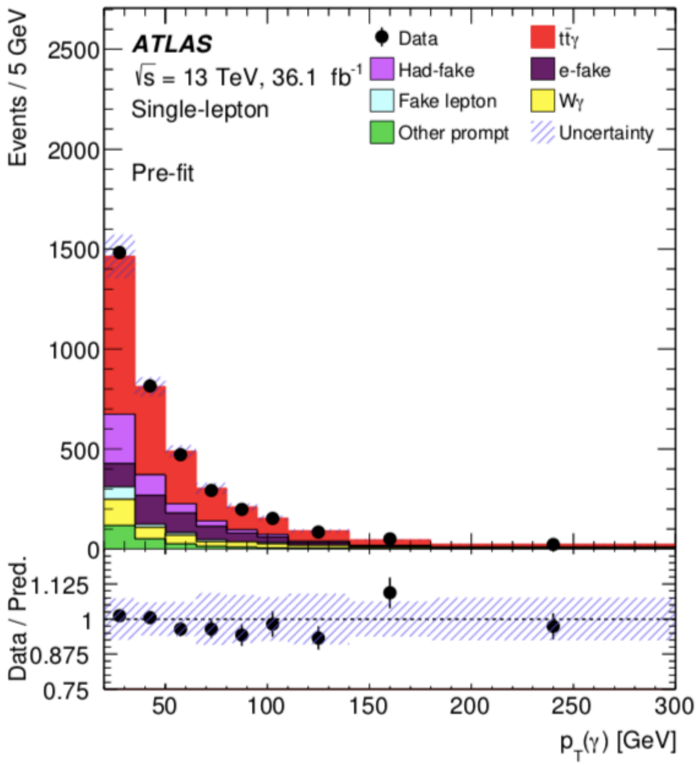
Top radiated



$t\bar{t} + \gamma$ overview

arXiv:1812.01697

- Considers Semi-leptonic and Di-leptonic $t\bar{t}$ decays
- Events selected using MVA
- Inclusive cross section from likelihood fit



- Fiducial differential cross sections are measured in the same fiducial volume without a likelihood fit, as a function of:
  - Photon transverse momentum $p_T(\gamma)$ and pseudorapidity $\eta(\gamma)$,
  - the angular difference the photon and nearest lepton $\Delta R(\gamma, \ell)$
  - the pseudorapidity difference $\Delta\eta(\ell, \ell)$ and opening angle $\Delta\phi(\ell, \ell)$ between two leptons

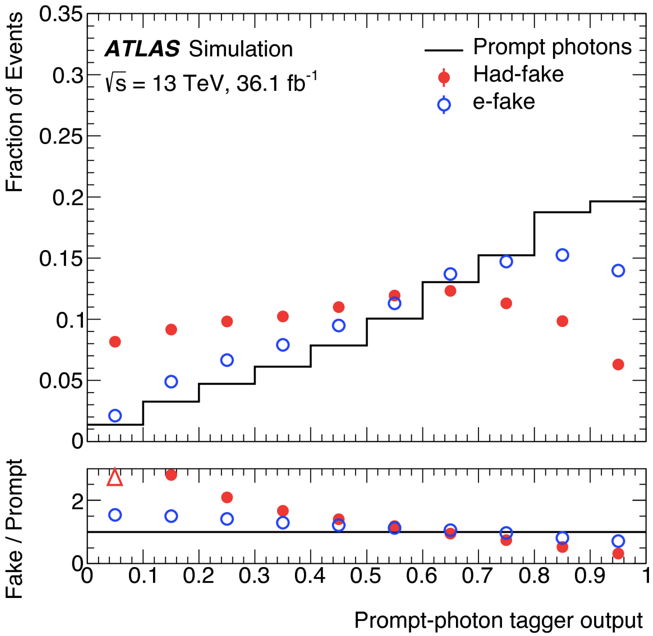
$t\bar{t} + \gamma$ backgrounds

arXiv:1812.01697

- Challenging estimate of 'fake' backgrounds, by object misidentification
- Contribution of fake sources cannot be estimated from Monte Carlo
  - Data-driven (or semi data-driven) methods needed

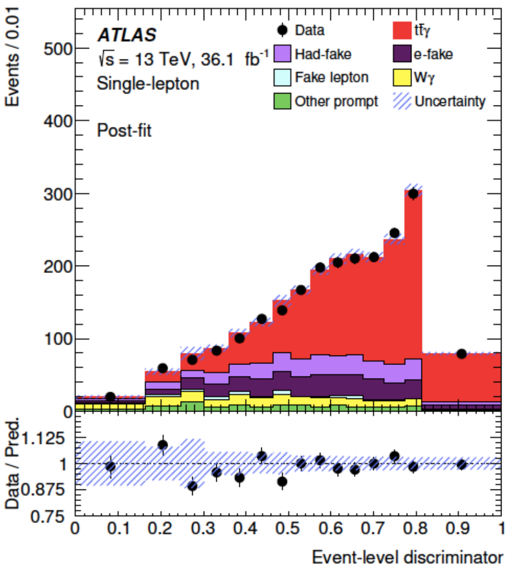
Hadronic Fake Photons and Electronic Fake Photons

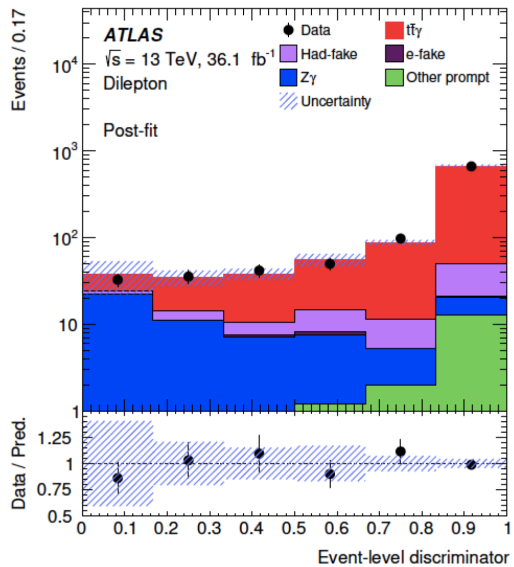
- Main source is $t\bar{t}$ when a final state jet is reconstructed as a photon, using ABCD method.
- Separation from prompt photon through neural network that feeds into final discriminator
- classification is achieved through shower shape variables and energy leakage fraction in the calorimeters

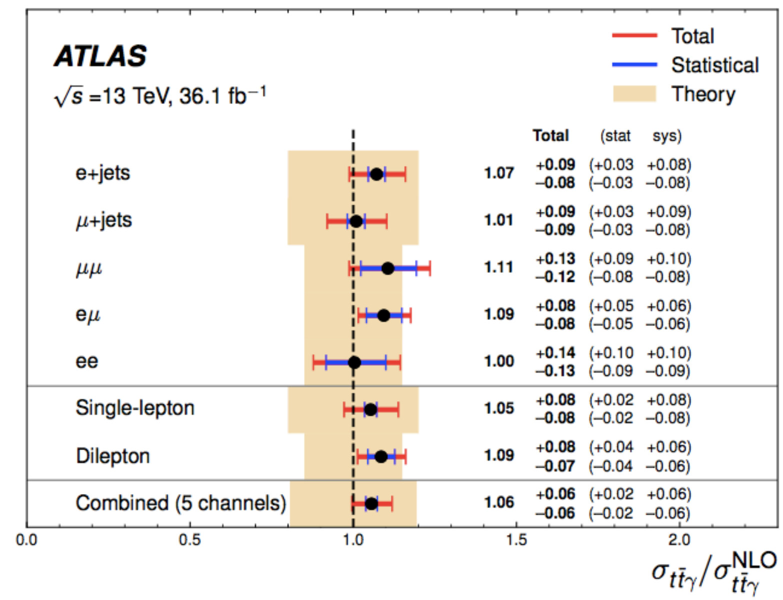


$t\bar{t}+\gamma$ Fiducial inclusive cross section

arXiv:1812.01697







- $t\bar{t}+\gamma$ cross section is obtained in likelihood fit of ELD spectrum in both channels
- Corrected to a fiducial volume
  - $p_T(\gamma)$ >20 GeV, $|\eta(\gamma)|$<2.37
  - Isolated γ

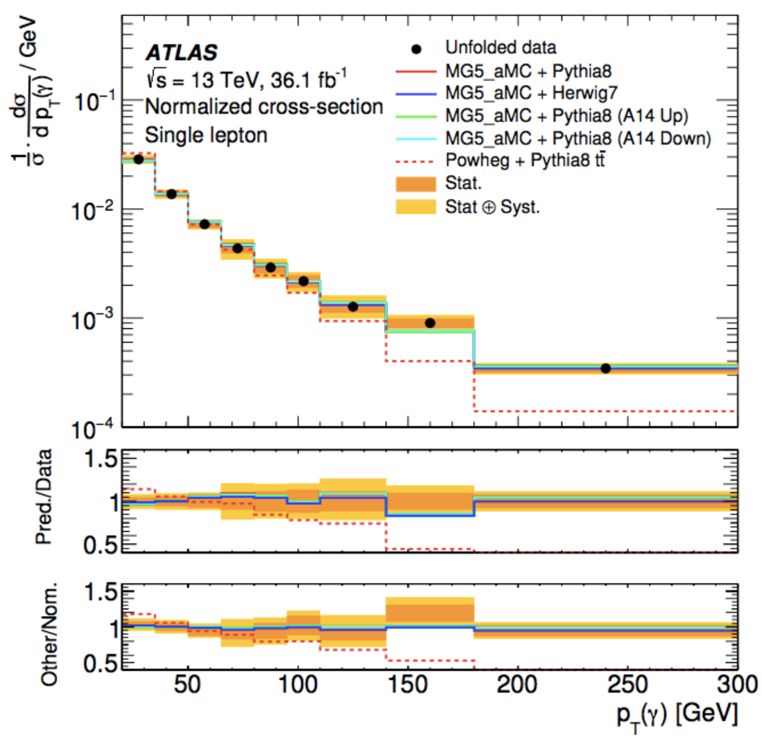
- Split by channels show consistent results
- Combined signal strength $\mu = 1.06 \pm 0.06$, in good agreement with the SM @NLO

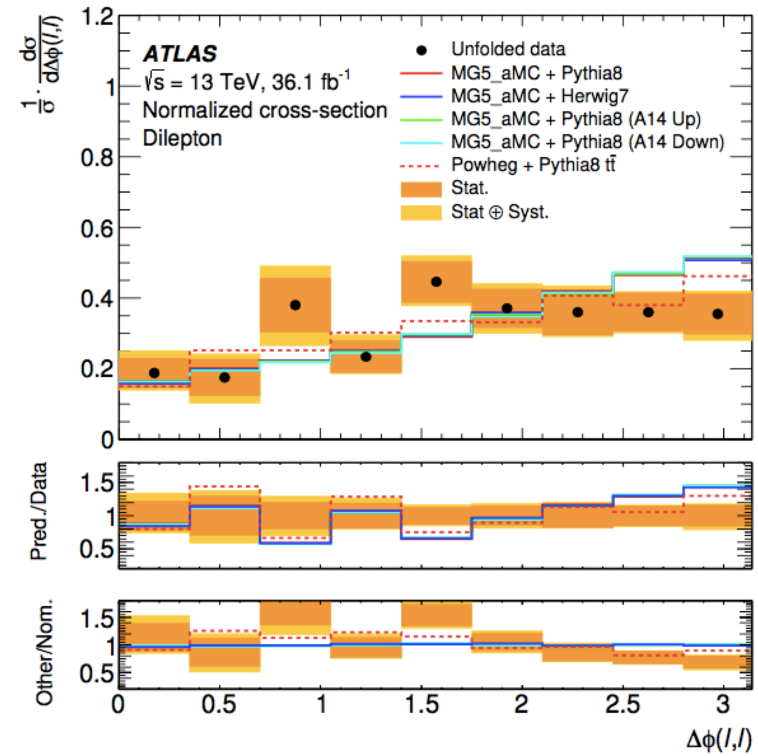
$$\sigma_{\text{fid}}^{\text{SL}} = 521 \pm 9(\text{stat.}) \pm 41(\text{sys.})\ \text{fb and}$$
$$\sigma_{\text{fid}}^{\text{DL}} = 69 \pm 3(\text{stat.}) \pm 4(\text{sys.})\ \text{fb},$$

$t\bar{t} + \gamma$ Fiducial differential cross sections

arXiv:1812.01697

- Iterative Bayesian Unfolding of differential distributions to fiducial volume, after background subtraction.
- Interesting examples are shown:





- Good agreement with $t\bar{t} + \gamma$ MG5_aMC@LO Py8
- (left) $p_T(\gamma)$ found to be softer in NLO tt PowHegPy8 (γ from parton shower).
- (right) small trend at large $\Delta\phi(\ell, \ell)$, as seen in tt events arXiv:1903.07570

Conclusion

- The latest measurements from ATLAS on production modes associated with a top quark pair were presented for the 36 fb^{-1}, 13 TeV dataset
  - tt+W and tt+Z inclusive cross sections were found to be consistent with the SM predictions and a BSM interpretation for tt+Z was performed
  - inclusive and differential, fiducial cross section measurements of tt+γ were also shown to be consistent with SM predictions
- Higher sensitivity over previous results not just due to increase in data statistics
  - Improvements also due to better signal/background separation through multivariate techniques and refined data-driven techniques to estimate fake backgrounds

Backup

$t\bar{t} + Z/W$ cross section measurements

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$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08_{stat.} \pm 0.10_{syst.}\ \text{pb} = 0.95 \pm 0.13\ \text{pb}$$

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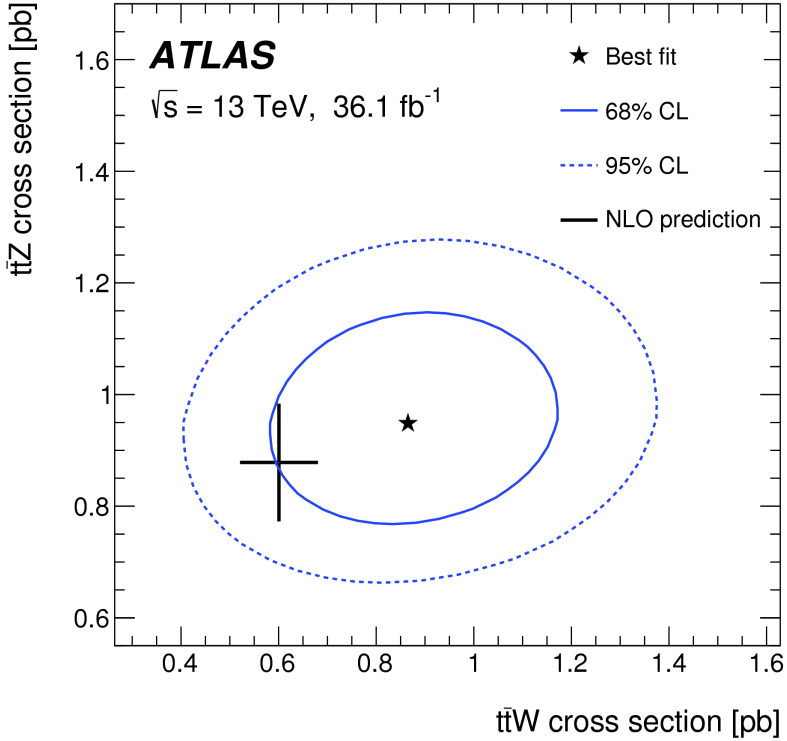

Signal strength μ as ratio to SM predictions:

Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	–
$3\ell\ t\bar{t}Z$	1.08 ± 0.18	–
2ℓ-SS and $3\ell\ t\bar{t}W$	–	1.41 ± 0.33
4ℓ	1.21 ± 0.29	–

SM NLO calculation includes renormalisation and factorisation scale uncertainties.