Top quark production measurements in ATLAS and CMS

SUSY 2018

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On behalf of the ATLAS and CMS Collaborations

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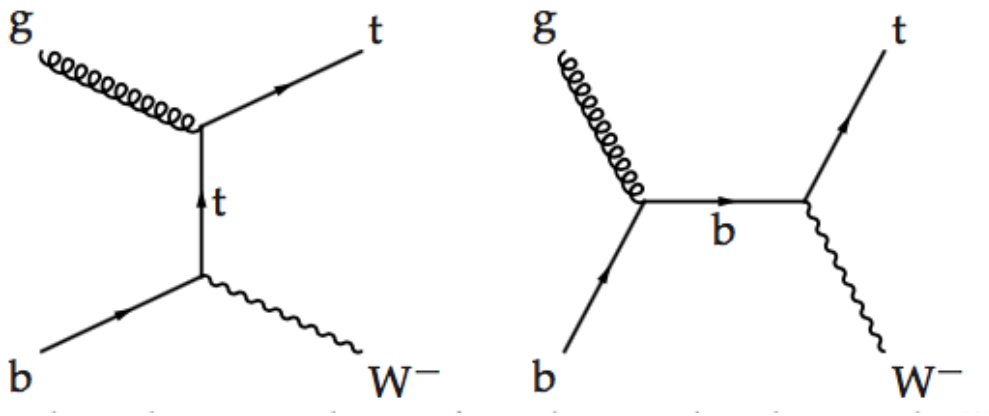
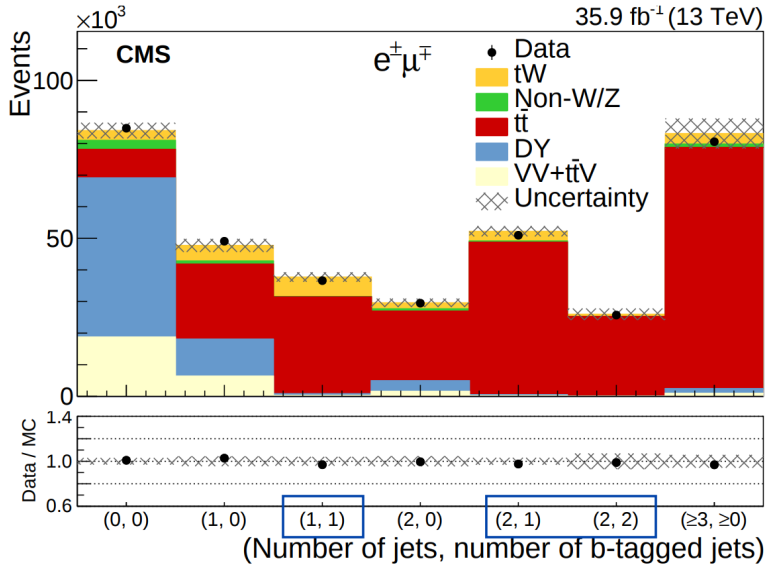
Outline

Presented measurements at 13 TeV

- tW production, including the interference with $t\bar{t}$
- Production in the t-channel
- $t\bar{t}Z$ and $t\bar{t}W$ production and constraints on effective operators
- $t\bar{t}b\bar{b}$ measurement
- tZq production
- FCNC constraints from $t \rightarrow Zq$ decays

tW measurement by CMS at 35.9 fb^{-1} (1)

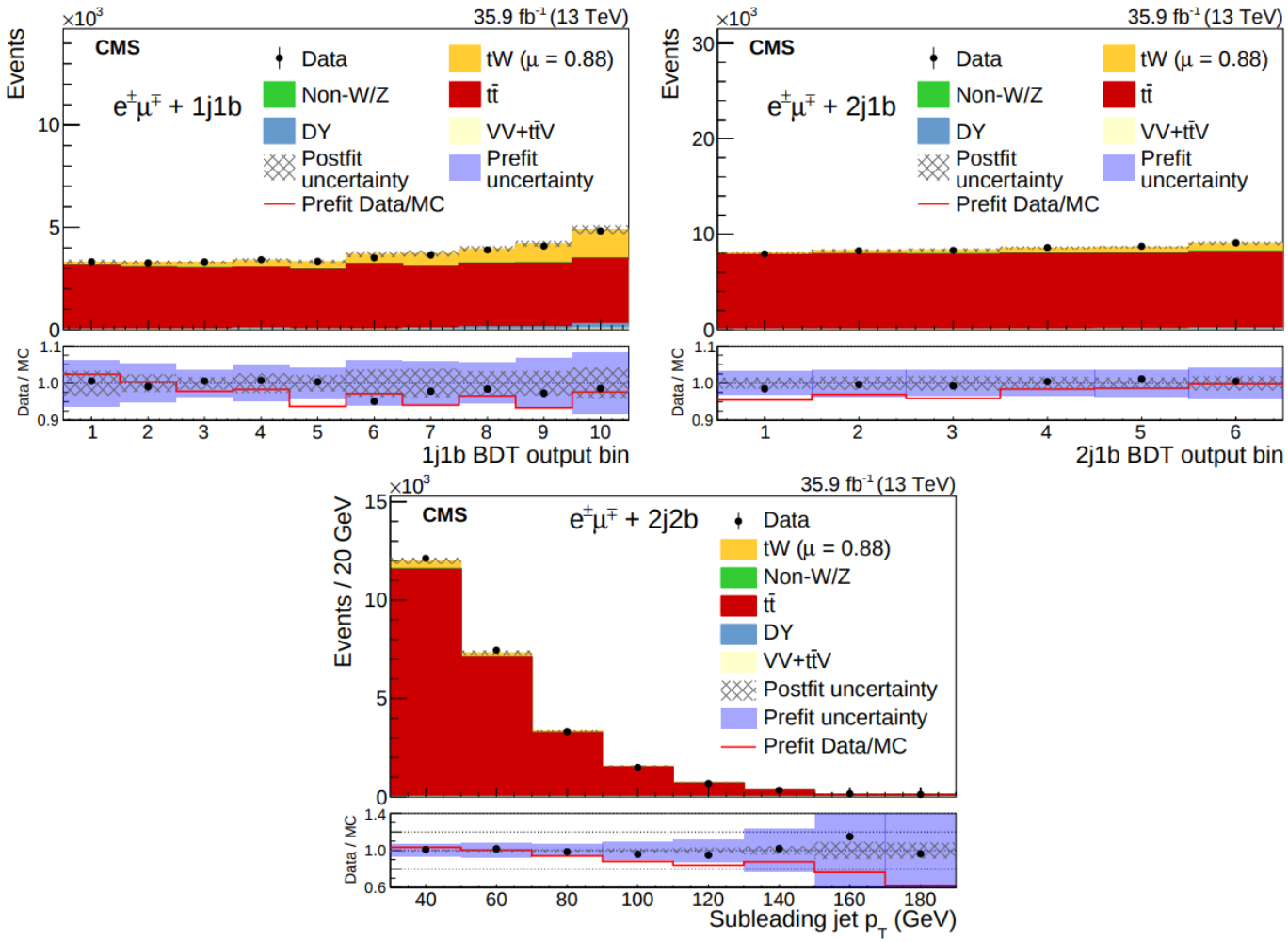




- Selection: opposite sign charge (OS) dilepton in the $e\mu$ channel.
- 3 categories: signal-enriched 1j1b; background-enriched 2j1b, 2j2b.
- Maximum likelihood fit performed to the distribution of BDT discriminants in 1j1b and 2j1b, and to the 2nd leading jet p_{T} in 2j2b.
- Main systematic uncertainties: luminosity, pileup, jet energy scale, lepton efficiencies.

▸ arXiv:1805.07399

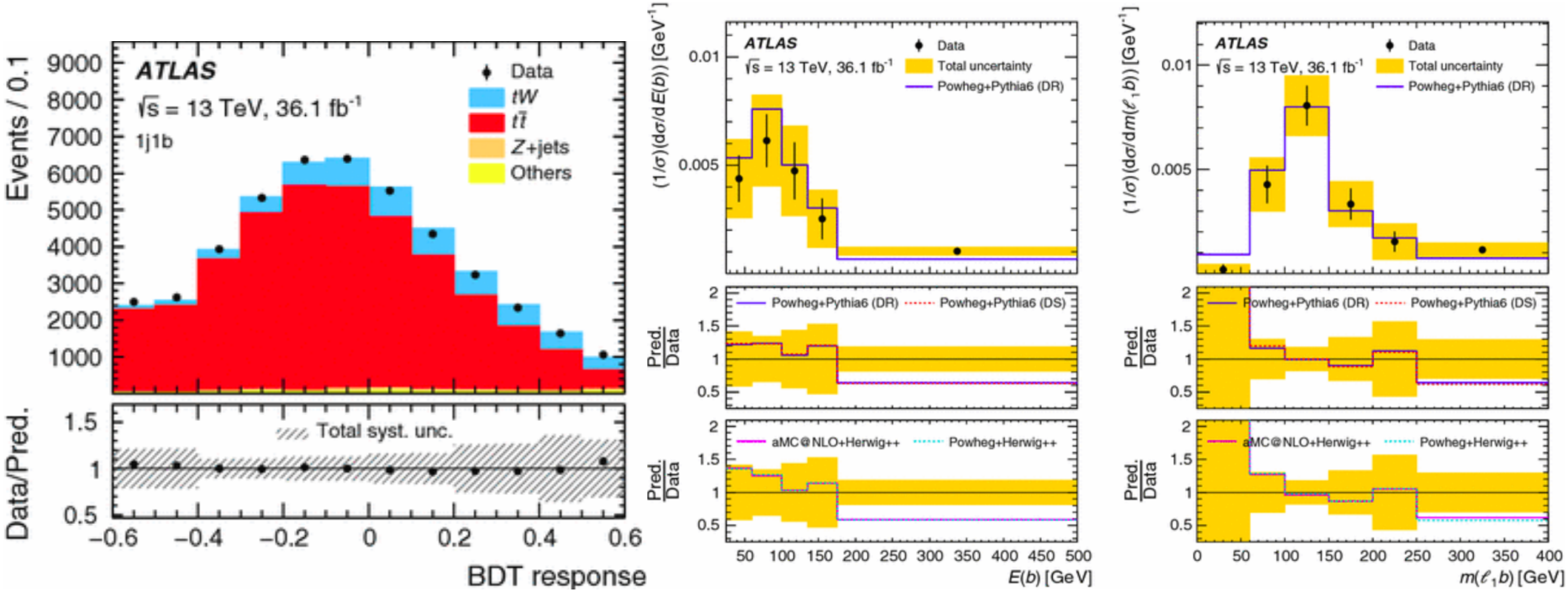
tW measurement by CMS at 35.9 fb^{-1} (2)



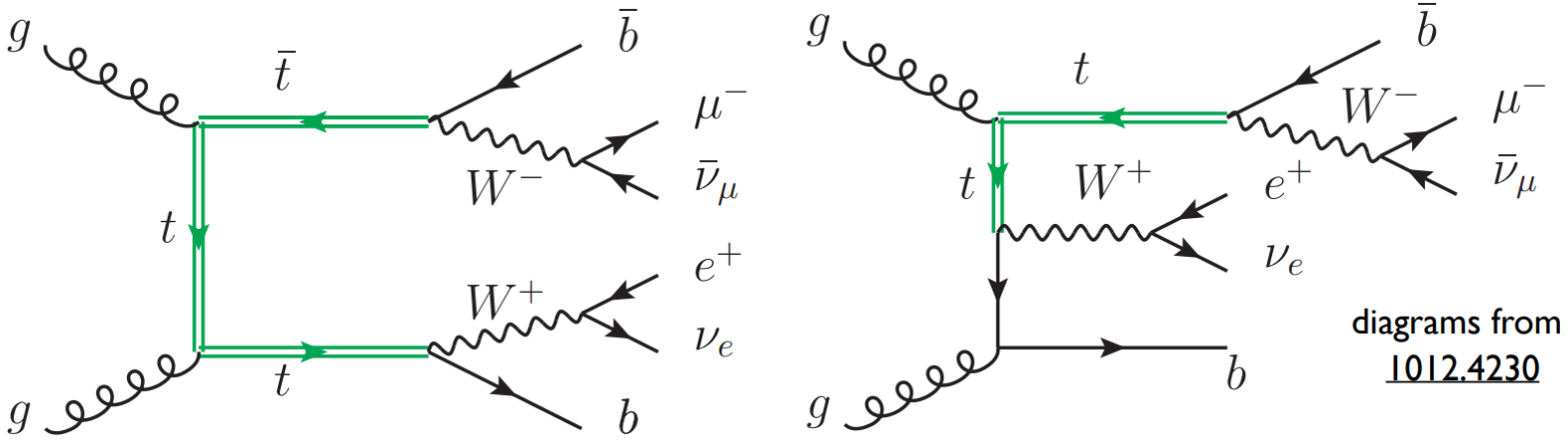
- $\sigma_{tW} = 63.1 \pm 1.8(\text{stat}) \pm 6.4(\text{syst}) \pm 2.1(\text{lumi})$ pb. Precision: 11 %.
- SM prediction: 71.7 ± 1.8 (scale) $\pm$ 3.4 (PDF) pb.

tW differential measurement by ATLAS, 36.1 fb^{-1}

- Selection: two OS leptons and **exactly one** b-tagged jet (1b1j).
- Cuts are imposed to reduce backgrounds, especially Z+jets.
- BDTs are trained and a cut on the BDT output (> 0.3) is applied to get a region enriched in tW.
  ▸ Eur. Phys. J. C 78 (2018) 186
- Six unfolded differential distributions are presented.
- The distributions are normalised to the fiducial cross section.
- Main uncertainties include statistical and the modelling of $t\bar{t}$ and tW.



tW-$t\bar{t}$ interference

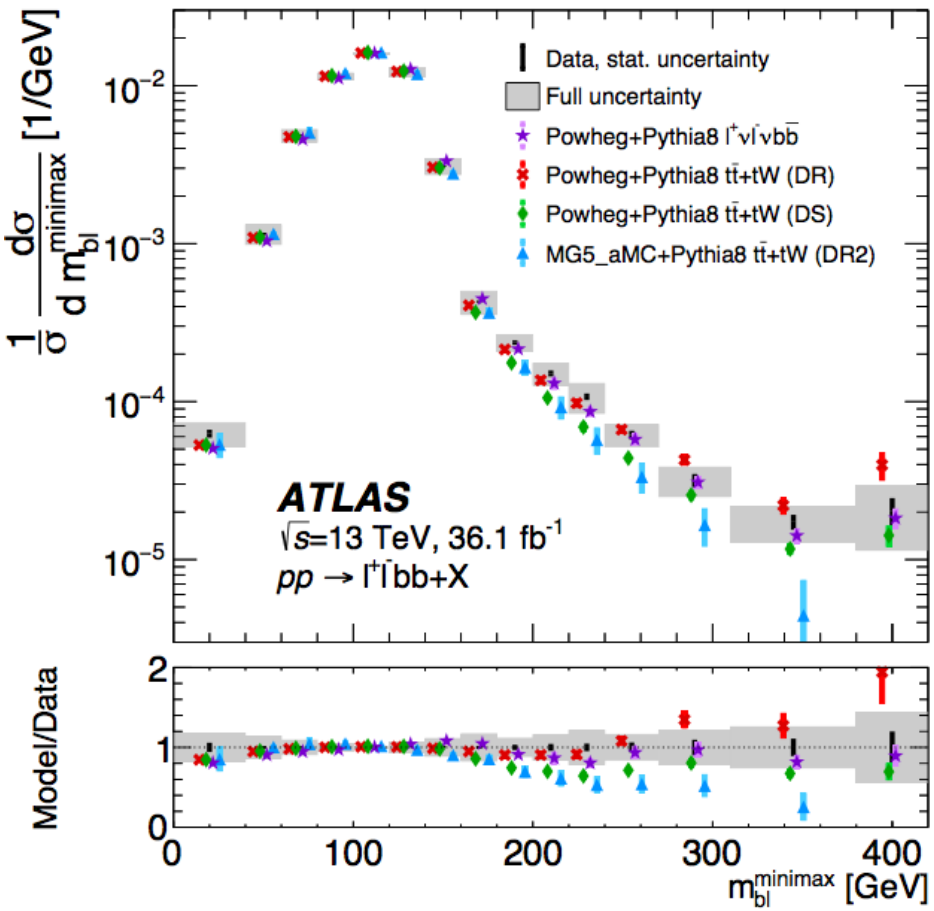


Ambiguity when modelling tW at NLO in QCD: overlap with $t\bar{t}$.

Methods for addressing overlap with $t\bar{t}$

- Diagram Removal (DR): remove overlapping diagrams completely.
- DR2: set the amplitudes squared of overlapping diagrams to zero. This retains an interference term with $t\bar{t}$.
- Diagram Subtraction (DS): subtract overlapping part at cross section level, using momentum reshuffling. Gauge invariant by construction.
- Abandon the distinction between $t\bar{t}$ and tW. Instead simulate (and measure) WbWb at NLO in QCD (implementation in Powheg).

tW-$t\bar{t}$ interference at ATLAS with 36.1 fb^{-1}

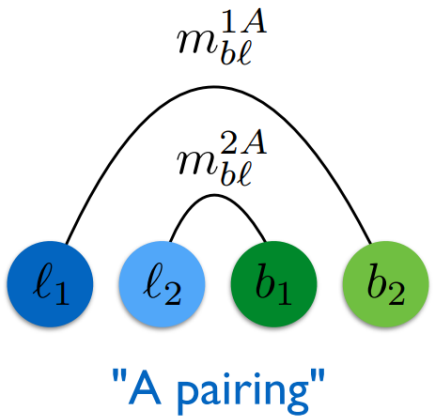


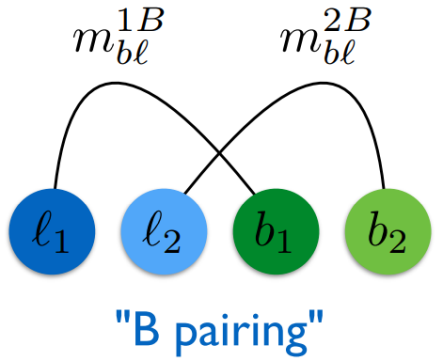
$m_{bl}^{minimax} = \min(\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1}))$

Designed to capture interference effects at high values.

arXiv:1806.04667

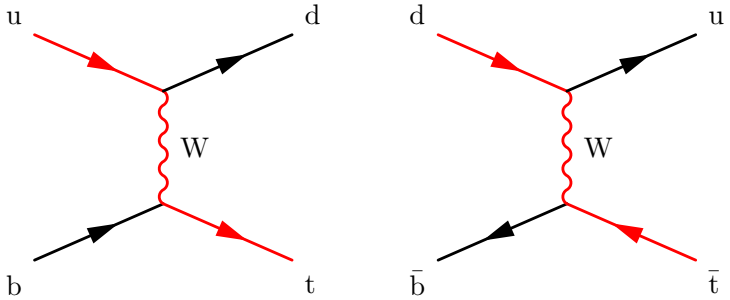
- The WbWb (bb4l) prediction has overall good agreement with data. Not available for all decay modes.
- DR prediction: nominal for single top analyses. DS: usually applied as a systematic variation.
- Further studies have been suggested for DR2, treating the top decays in different ways.





t channel production at CMS with 35.9 fb^{-1}

- Selection: one charged lepton and 2-3 jets. Split by # jets and b-jets.
- A multivariate discriminator for background reduction is applied.

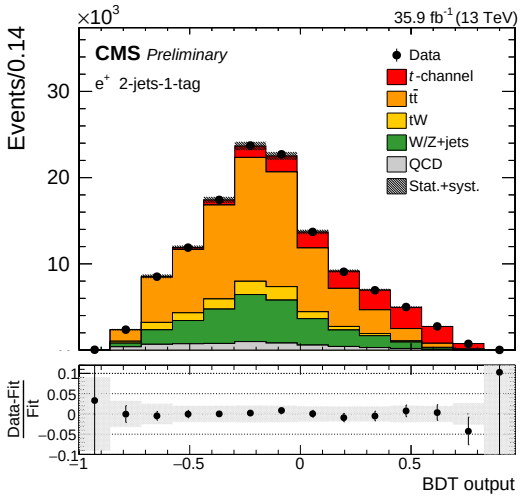


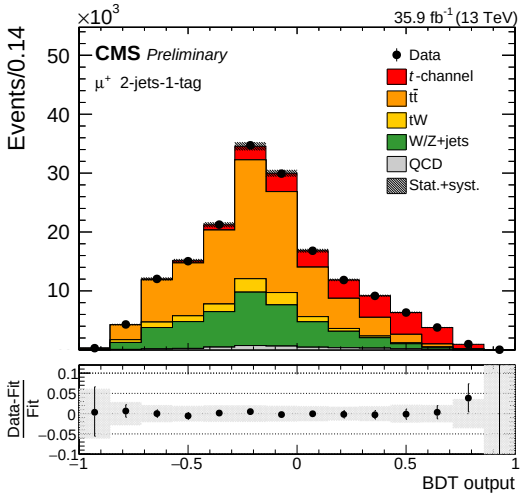
$\sigma_t^{th} = 136.0^{+4.1}_{-2.9}(\text{scale})\pm 3.5(\text{PDF}+\alpha_s)\text{pb}$, $\sigma_{\bar{t}}^{th} = 81.0^{+2.5}_{-1.7}(\text{stat})\pm 3.2(\text{PDF}+\alpha_s)\text{pb}$,
$R_{t\text{-ch}}^{th} = 1.661 \pm 0.026$.

Results

- $\sigma_t = 136.3 \pm 1.1(\text{stat})\pm 20.0(\text{syst})\text{pb}$ (15%),
  $\sigma_{\bar{t}} = 82.7 \pm 1.1(\text{stat})\pm 13.0(\text{syst})\text{pb}$ (16%).
- $R_{t\text{-ch}} = 1.65 \pm 0.02(\text{stat})\pm 0.04(\text{syst})$ (2.7 %).
- Good agreement found with most pdf sets.
- $|f_{LV}\,V_{tb}| = 1.00 \pm 0.05$ (exp) ± 0.02 (theo).
  f_{LV} is anomalous form factor (=1 in SM).
- Main uncertainty from PS-scale for σ_t, $\sigma_{\bar{t}}$.

▸ CMS PAS TOP-17-011





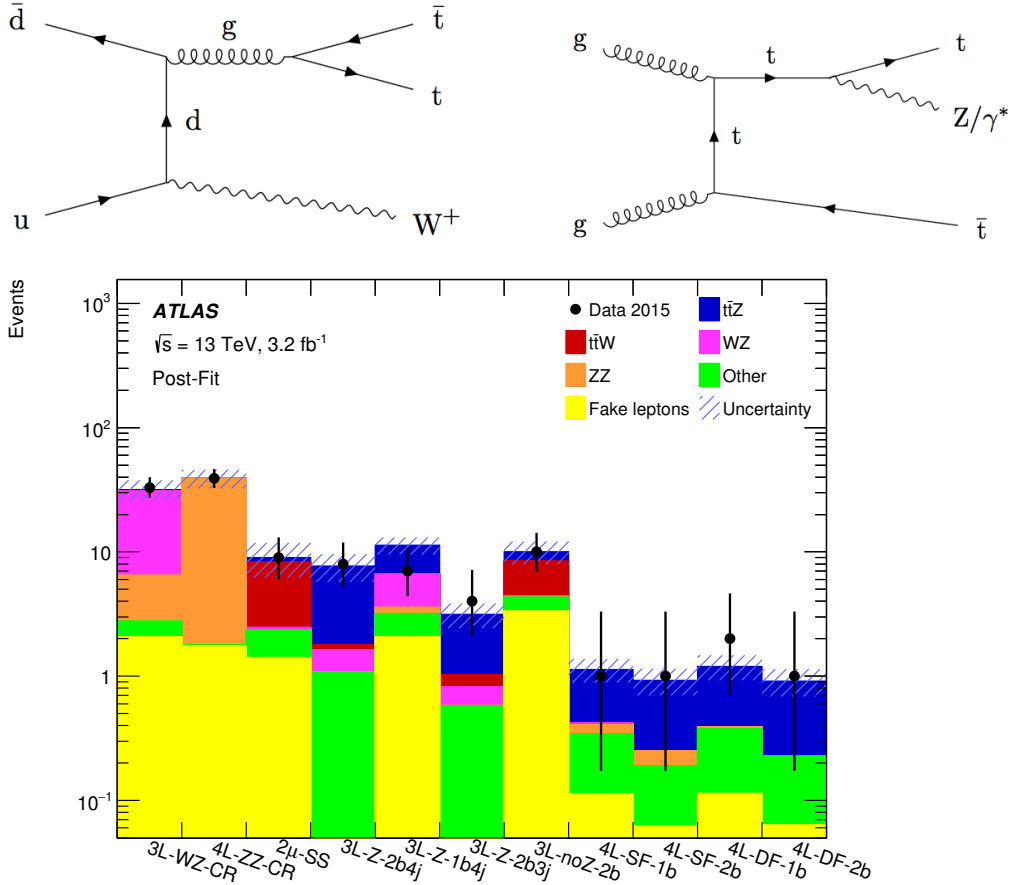
ttV measurement by ATLAS at 3.2 fb^{-1}

Motivation: study tZ coupling, constrain backgrounds to BSM searches.

- Selection: 2 leptons of same sign charge (SS, targeting $t\bar{t}W$), or 3 or 4 leptons (targeting $t\bar{t}Z$).
- Cuts imposed on number of jets and b-jets and on $m_{\ell^+\ell^-}$.
- Main backgrounds: fake leptons (2LSS), WZ (3L) and ZZ (4L).

▸ Eur. Phys. J. C77 (2017) 40

- $\sigma^{th}_{t\bar{t}Z} = 0.84$ pb$\pm$12%; 3.4σ.
- $\sigma^{th}_{t\bar{t}W} = 0.60$ pb$\pm$12%; 1.0σ.



Results

- $\sigma_{t\bar{t}Z} = 0.92 \pm 0.29(\text{stat.}) \pm 0.10(\text{syst.})$ pb; 3.9σ. Precision: 33%.
- $\sigma_{t\bar{t}W} = 1.50 \pm 0.72(\text{stat.}) \pm 0.33(\text{syst.})$ pb; 2.2σ. Precision: 53%.

ttV measurement by CMS at 35.9 fb^{-1} (1)

Targeting $t\bar{t}Z$:

- Signal regions: 3L, 4L. Split further by # jets and b-jets.
- $m_{\ell^+\ell^-} \sim m_Z$ is required.
- Main backgrounds: WZ and ZZ (simulated, verified in CRs).
- Main systematics: scale, trigger and b-tagging.

Targeting $t\bar{t}W$:

- Signal regions: SS. Split further by # jets and b-jets.
- Non-prompt lepton (NPL) background evaluated by data-driven method.
- MVA training employed.
- Main systematics: trigger, NPL, background $t(\bar{t}) + X$ modelling.

Results $t\bar{t}Z$

$\sigma_{t\bar{t}Z} = 0.99^{+0.09}_{-0.08}(\mathrm{st})^{+0.12}_{-0.10}(\mathrm{syst})\mathrm{pb}$,
$\mu = 1.17^{+0.11}_{-0.10}(\mathrm{st})^{+0.14}_{-0.12}(\mathrm{syst})^{+0.11}_{-0.12}(\mathrm{th})$.
Significance well above 5σ.
Precision: 15%.

Results $t\bar{t}W$

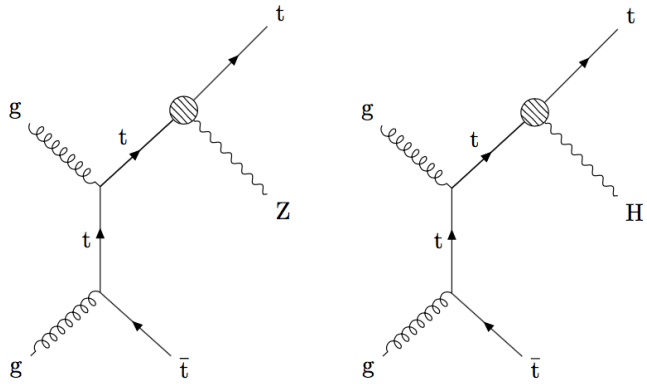
$\sigma_{t\bar{t}W} = 0.77^{+0.12}_{-0.11}(\mathrm{st})^{+0.13}_{-0.12}(\mathrm{syst})\mathrm{pb}$,
$\mu = 1.23^{+0.19}_{-0.18}(\mathrm{st})^{+0.20}_{-0.18}(\mathrm{syst})^{+0.13}_{-0.12}(\mathrm{th})$.
Significance: 5.3σ (4.5σ expected).
Precision: 23%.

▸ arXiv:1711.02547

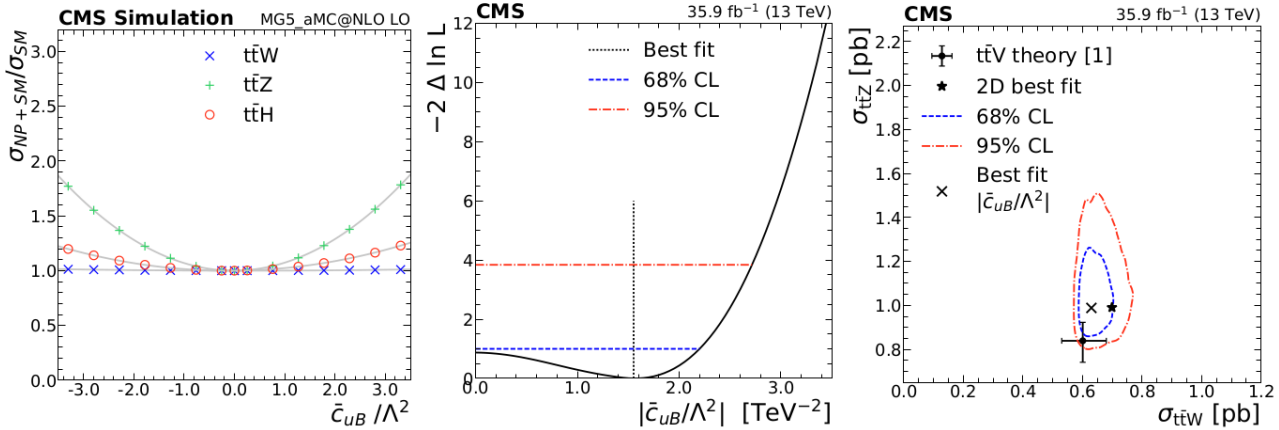
ttV measurement by CMS at 35.9 fb^{-1} (2)

Effective operators that affect $t\bar{t}Z$, $t\bar{t}W$ and $t\bar{t}H$ production are constrained.

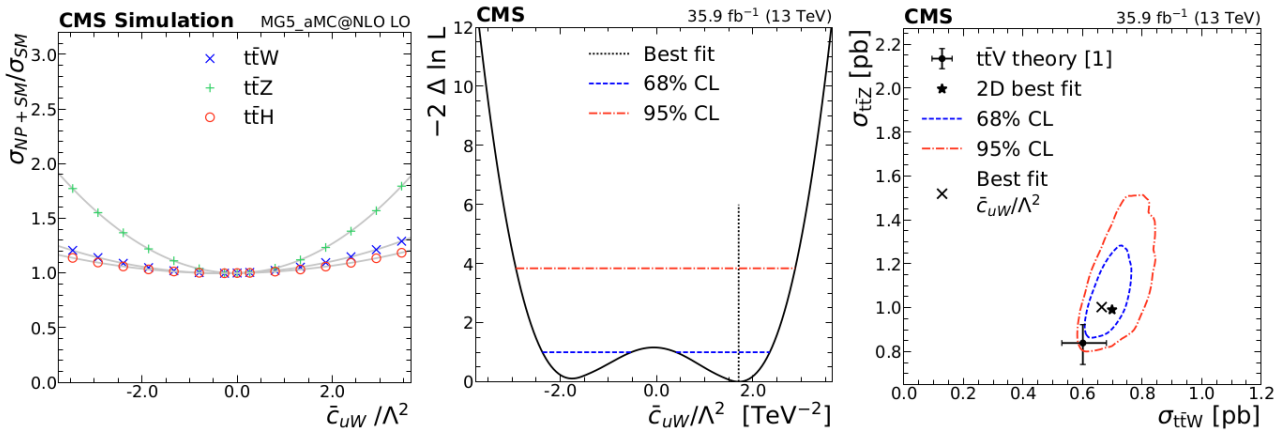
$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + ...$



$\mathcal{O}_{uB} = (\bar{q}_p \sigma^{\mu\nu} u_r)\tilde{\phi} B_{\mu\nu}$



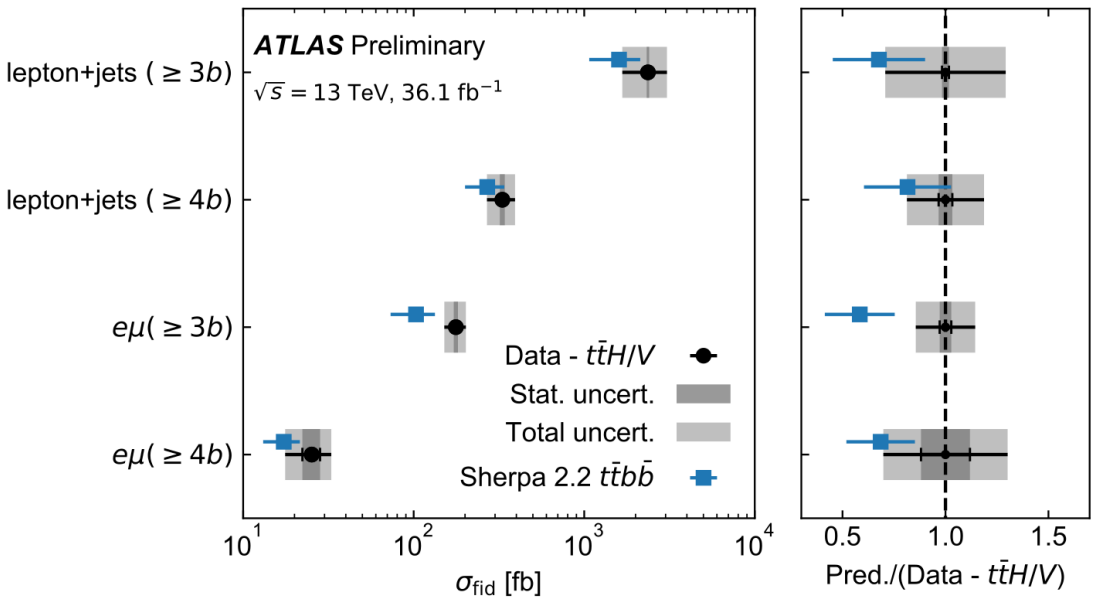
$\mathcal{O}_{uW} = (\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{\phi} W^I_{\mu\nu}$

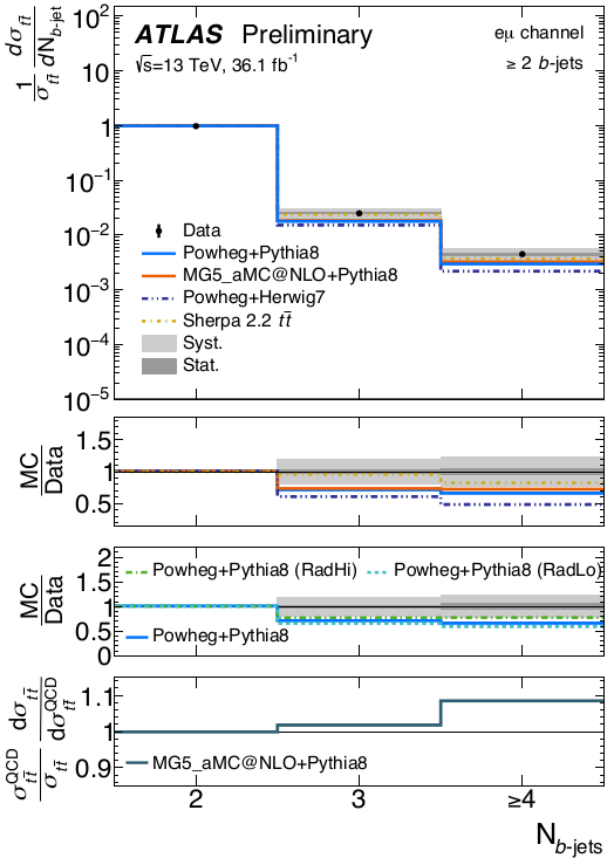


$t\bar{t}b\bar{b}$ measurement by ATLAS at 36.1 fb^{-1}

$t\bar{t}b\bar{b}$ is measured in $e^{\pm}\mu^{\mp}$ and lepton+jets SRs. Motivation: test QCD, understand background to $t\bar{t}H$.

▸ ATLAS-CONF-2018-029

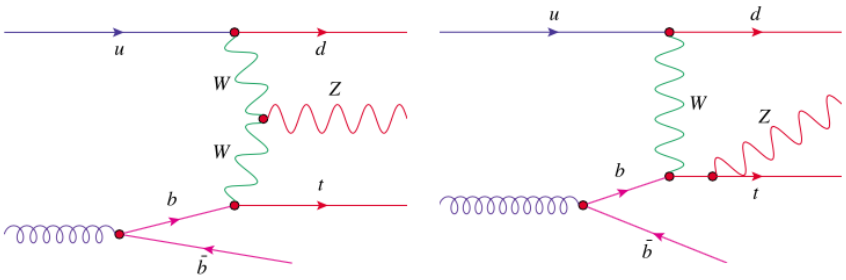




Results

- SHERPA 2.2 $t\bar{t}b\bar{b}$ NLO prediction is lower than data (but within unc).
- All predictions where additional b-jets come from PS undershoot the data. Only SHERPA 2.2 $t\bar{t}$ (NLO) desribes the $N_{b\text{-jets}}$ spectrum.
- Unfolded differential distributions are shown, precision: 10-30%.

tZq production at CMS, 35.9 fb^{-1} (1)



▸ Phys. Lett. B 779 (2018) 358

- tZq production sensitive to the tZ and the triple gauge couplings.
- BSM models with FCNCs could affect production through $t \to Zq$ decays.

Selection

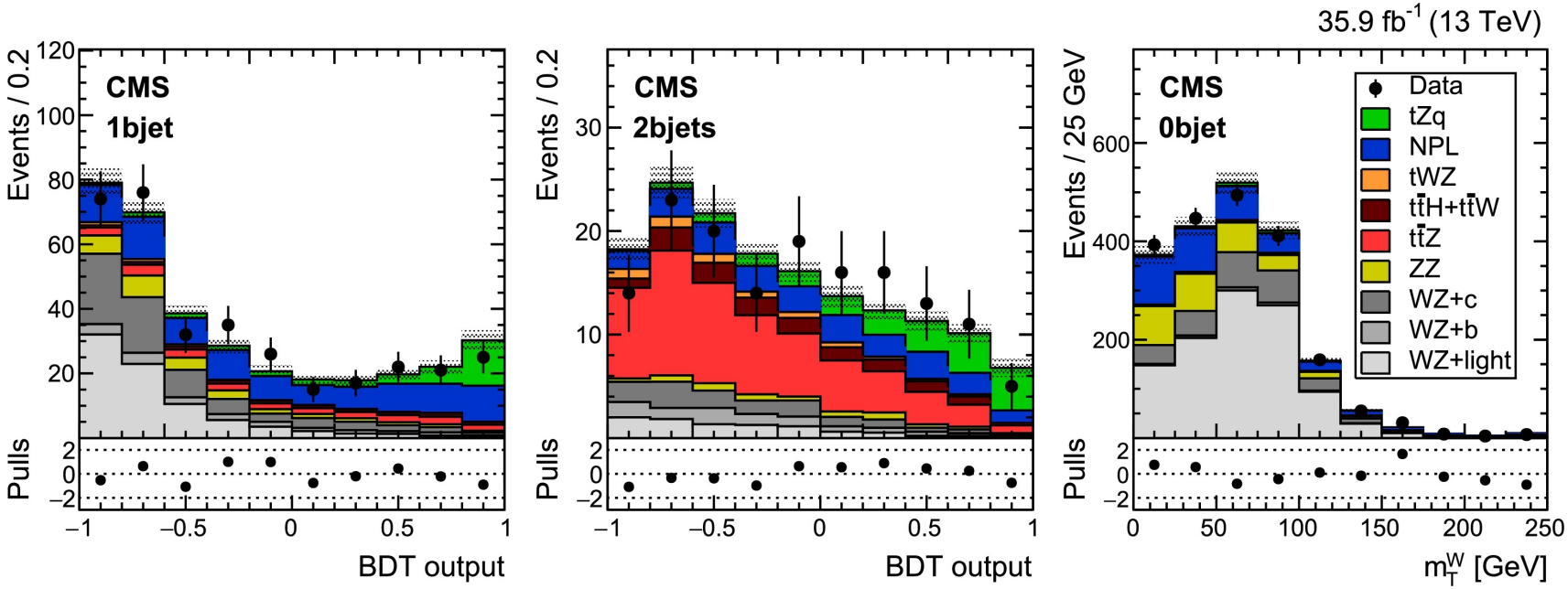
Preselection: 3 charged final state leptons, of which 2 are OS and same flavour (SF) with $|m_{\ell^+\ell^-} - m_Z| < 15\,\mathrm{GeV}$. Three regions:

- 1 b-jet signal region: targets tZq. **2-3 jets**, of which 1 b-tagged.
- CRs with 0 or ≥ 2 b-tagged jets, to constrain the WZ and $t\bar{t}Z$.

Fit strategy

- Binned maximum-likelihood fit to the distributions in the BDT discriminators in the 2 b-jets and 1 b-jet regions.
- Fit to the m_T^W distribution in the 0 b-jet region.
- MEM info included in training $\to$ 20% higher expected significance.

tZq production at CMS, 35.9 fb^{-1} (2)



The NPL background is not part of the BDT training.

$\sigma^{theo,NLO}_{tq\ell^+\ell^-} = 94.2 \pm 3.1$ fb, $(m_{\ell^+\ell^-} > 30\,\mathrm{GeV})$.

Results

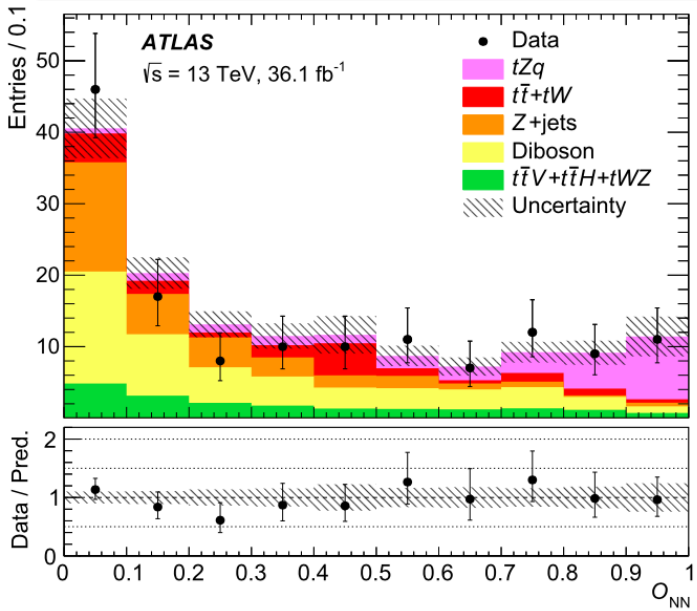
- $\sigma_{tq\ell^+\ell^-} = 123^{+33}_{-31}(\mathrm{stat})^{+29}_{-23}(\mathrm{syst})$ fb. Precision: 36 %.
- Evidence for tZq production at 3.7 σ (3.1 σ expected).
- $\mu = 1.31^{+0.35}_{-0.33}(\mathrm{stat})^{+0.31}_{-0.25}(\mathrm{syst})$.

tZq production at ATLAS, 36.1 fb^{-1}

- SR: 3 charged leptons, one b-tagged jet, an additional jet, $|m_{\ell^+\ell^-} - m_Z| < 10\,\mathrm{GeV}$, $m_T(\ell,\nu) > 20\,\mathrm{GeV}$. CRs for $t\bar{t}$ and diboson.
- Signal generated at LO, scaled to NLO, $\sigma^{th}_{tZq} = 800^{+6.1\%}_{-7.4\%}$ fb.
- A NN is trained. Main variables: $|\eta|$ and p_{T} of the untagged jet, m_t.

Results

- $\sigma_{tZq} = 600 \pm 170(\mathrm{stat.}) \pm 140\ (\mathrm{syst.})$ fb. Precision: 37 %.
- Evidence for tZq production with significance: 4.2σ, expected: 5.4σ.



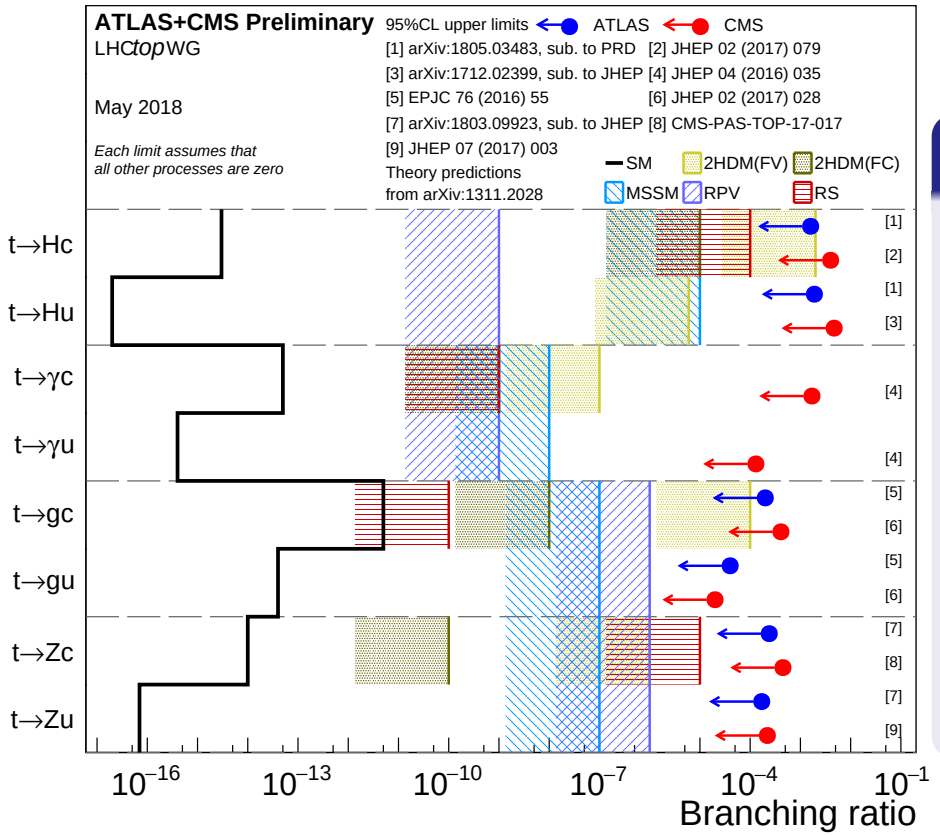
Source	Uncertainty [%]
tZq radiation	±10.8
Jets	±4.6
b-tagging	±2.9
MC statistics	±2.8
tZq PDF	±2.2
Luminosity	±2.1
Leptons	±2.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	±0.3

▸ Physics Letters B 780 (2018) p 557

FCNC

Flavour changing neutral currents

- Not present at tree level in the Standard Model.
- Suppressed in loop processes by the unitarity of the CKM matrix.
- SM top FCNC decays are experimentally unobservable.



FCNCs from BSM

- At tree level: two higgs-doublet models, heavy vector-like quarks.
- Loop-induced enhancements: two-Higgs-doublet models, MSSM, R-parity-violating SUSY, warped extra dimensions, composite Higgs.

FCNC $t \to Zq$ search by ATLAS, 36.1 fb^{-1}

arXiV:1803.09923

- $t\bar{t}$ production followed by $t \to Zq$ of one of the tops.
- Selection: 3 charged leptons, $\geq$2 jets, of which $\geq$1 is b-tagged and $E_T^{\mathrm{miss}} > 20\,\mathrm{GeV}$.
- Main backgrounds: diboson, $t\bar{t}Z$ and tZ.
- Event reconstruction performed using χ^2 minimisation.
- Main uncertainties on signal yields: event modelling and jets.

Results

- $\mathcal{B}(t \to Zc) < 2.4 \cdot 10^{-4}$, expected $3.2 \cdot 10^{-4}$.
- $\mathcal{B}(t \to Zu) < 1.7 \cdot 10^{-4}$, expected $2.4 \cdot 10^{-4}$.
- These are the most stringent limits to date.

Table 1: Maximum allowed FCNC $t \to qZ$ ($q = u, c$) branching ratios predicted by several models [3–10].

Model:	SM	QS	2HDM	FC 2HDM	MSSM	RPV SUSY	RS	EMF
$\mathcal{B}(t \to qZ)$:	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}	10^{-6}

Summary and conclusions

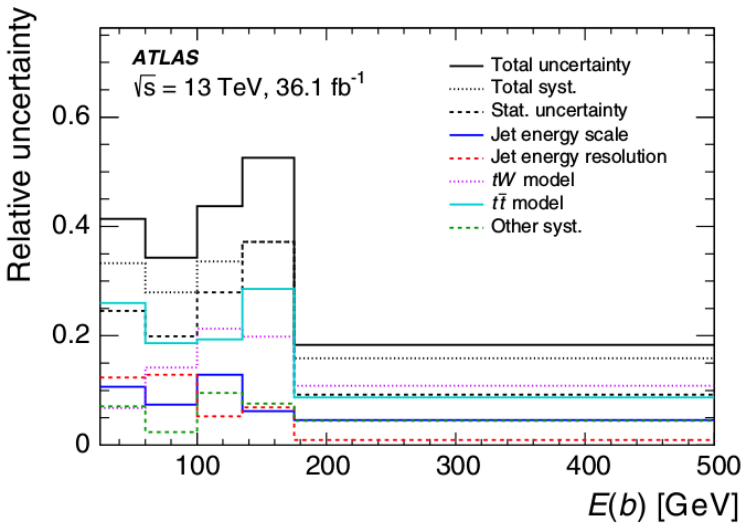
- Some recent highlights ATLAS and CMS top quark production measurements have been shown.
- The SM predictions for signle top production in the tW and t channels have been tested. From $R_{t\text{-ch}}$, pdfs are constrained.
- Background processes for SUSY and other BSM searches have been measured.
- Limits on EFT coefficients have been placed using $t\bar{t}V$ measurements.
- Systematical uncertainties limit the precision of several analyses.
- $t\bar{t}b\bar{b}$ has been measured, putting QCD predictions to a test.
- Measurements of single top production in association with a Z boson have been performed and used to place limits on FCNCs.
- All measurements presented here are in agreement with the SM.
- The $t\bar{t}b\bar{b}$ measurement suggests that improvements can be made to the modelling of the of the b-jets.

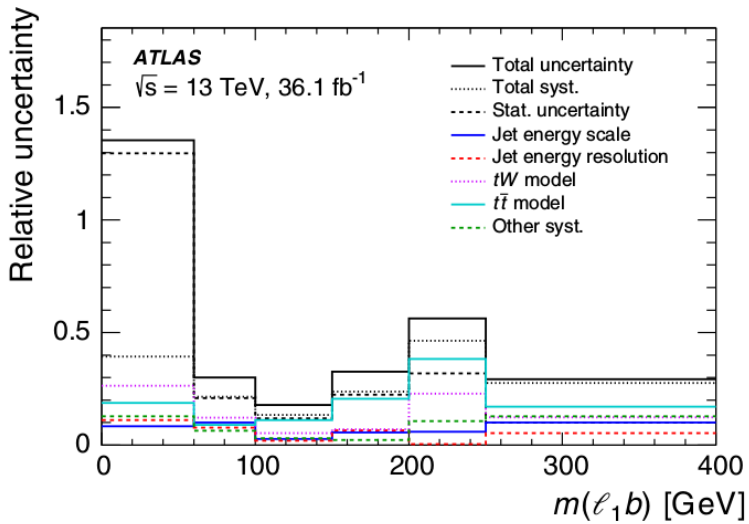
Backup

Uncertainties for ATLAS tW differential analysis

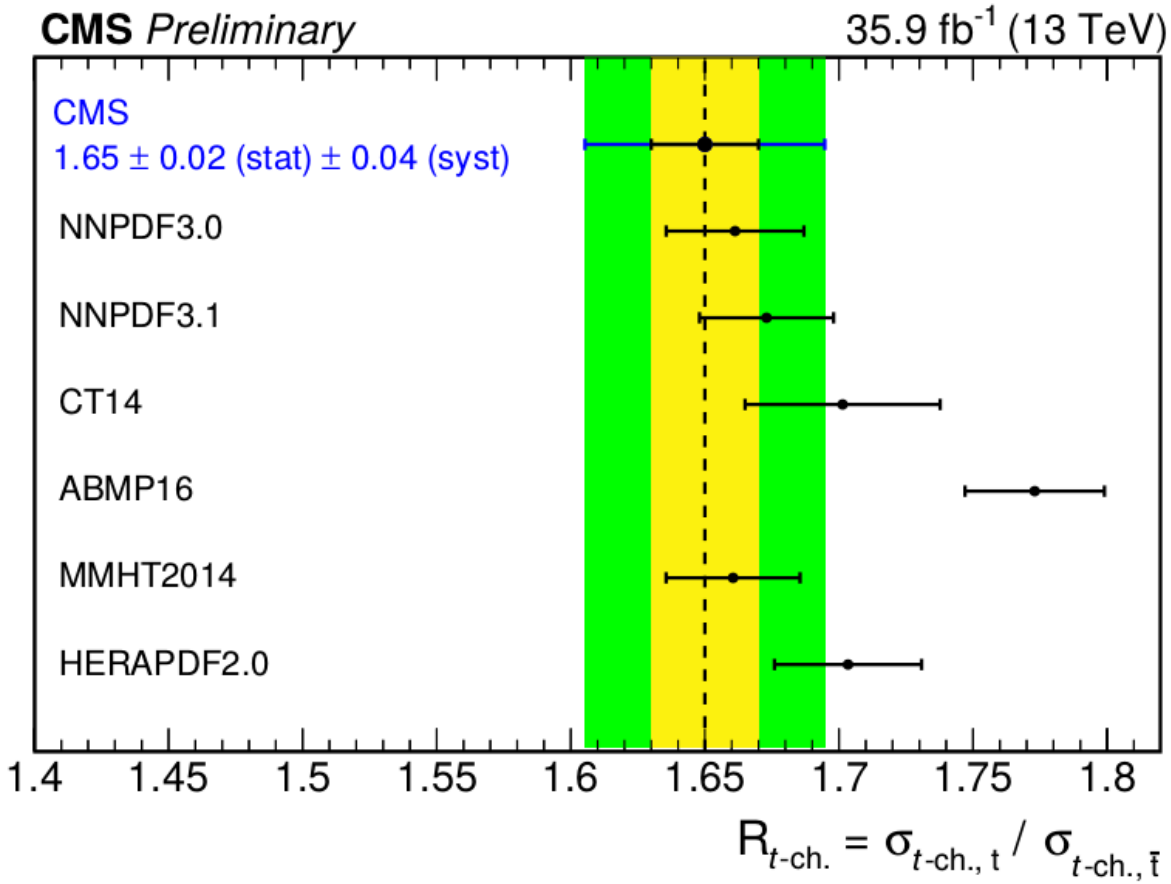
$E(b)$ bin [GeV]	[25, 60]	[60, 100]	[100, 135]	[135, 175]	[175, 500]
$(1/\sigma)\ d\sigma/dx$ [GeV^{-1}]	0.00438	0.00613	0.00474	0.00252	0.00103
Stat. uncertainty	25	20	28	37	9.3
Total syst. uncertainty	33	28	34	37	16
Total uncertainty	41	34	44	53	18

$m(\ell_1 b)$ bin [GeV]	[0, 60]	[60, 100]	[100, 150]	[150, 200]	[200, 250]	[250, 400]
$(1/\sigma)\ d\sigma/dx$ [GeV^{-1}]	0.000191	0.00428	0.00806	0.00333	0.00153	0.00114
Stat. uncertainty	130	21	12	22	32	10
Total syst. uncertainty	39	22	13	24	46	28
Total uncertainty	140	30	18	33	56	29





Constraints on pdfs from CMS t-channel measurement



EFT limits from the CMS $t\bar{t}V$ measurement

Wilson coefficient	Best fit [TeV^{-2}]	68% CL [TeV^{-2}]	95% CL [TeV^{-2}]
$\bar{c}_{uW}/\Lambda^2$	1.7	$[-2.4,-0.5]$ and $[0.4,2.4]$	$[-2.9,2.9]$
$\lvert\bar{c}_H/\Lambda^2 - 16.8\ \text{TeV}^{-2}\rvert$	15.6	$[0,23.0]$	$[0,28.5]$
$\lvert\widetilde{c}_{3G}/\Lambda^2\rvert$	0.5	$[0,0.7]$	$[0,0.9]$
$\bar{c}_{3G}/\Lambda^2$	-0.4	$[-0.6,0.1]$ and $[0.4,0.7]$	$[-0.7,1.0]$
$\bar{c}_{uG}/\Lambda^2$	0.2	$[0,0.3]$	$[-1.0,-0.9]$ and $[-0.3,0.4]$
$\lvert\bar{c}_{uB}/\Lambda^2\rvert$	1.6	$[0,2.2]$	$[0,2.7]$
$\bar{c}_{Hu}/\Lambda^2$	-9.3	$[-10.3,-8.0]$ and $[0,2.1]$	$[-11.1,-6.5]$ and $[-1.6,3.0]$
$\bar{c}_{2G}/\Lambda^2$	0.4	$[-0.9,-0.3]$ and $[-0.1,0.6]$	$[-1.1,0.8]$

Uncertainties on the $t\bar{t}b\bar{b}$ inclusive measurements

Channel	analysis	measured cross-section [fb]
lepton + jets	$\sigma_{tt+\geq 1b}$	2450 ± 40 (stat) $\pm$ 690 (syst)
lepton + jets	$\sigma_{tt+\geq 2b}$	359 ± 11 (stat) $\pm$ 61 (syst)
$e\mu$	$\sigma_{tt+\geq 1b}$	181 ± 5 (stat) $\pm$ 24 (syst)
$e\mu$	$\sigma_{tt+\geq 2b}$	27 ± 3 (stat) $\pm$ 7 (syst)

Source	Fiducial cross-section phase space			
	$e\mu$		lepton + jets	
	$\geq 3b$ unc. (%)	$\geq 4b$ unc. (%)	$\geq 5j, \geq 3b$ unc. (%)	$\geq 6j, \geq 4b$ unc. (%)
Data statistics	2.7	9.0	1.7	3.0
Luminosity	2.1	2.1	2.3	2.3
Jet	2.6	4.3	3.6	7.2
b-tagging	4.5	5.2	17	8.6
Lepton	0.9	0.8	0.8	0.9
Pileup	2.1	3.5	1.6	1.3
$t\bar{t}c$ fit variation	5.9	11	-	-
Non-$t\bar{t}$ bkg	0.8	2.0	1.7	1.8
Detector+background total syst.	8.5	14	18	12
Parton shower	9.0	6.5	12	6.3
Generator	0.2	18	16	8.7
ISR/FSR	4.0	3.9	6.2	2.9
PDF	0.6	0.4	0.3	0.1
$t\bar{t}V/t\bar{t}H$	0.7	1.4	2.2	0.3
MC sample statistics	1.8	5.3	1.2	4.3
$t\bar{t}$ modelling total syst.	10	20	21	12
Total syst.	13	24	28	17
Total	13	26	28	17