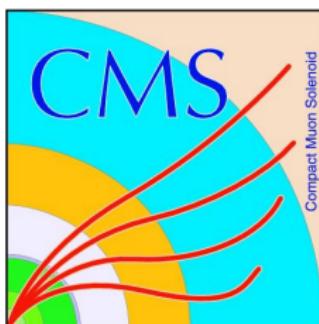


$t\bar{t}V(V = W, Z)$ measurements at ATLAS and CMS

Didar Dobur (Ghent University), Kerim Suruliz (University of Sussex)

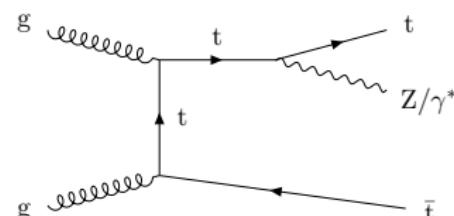
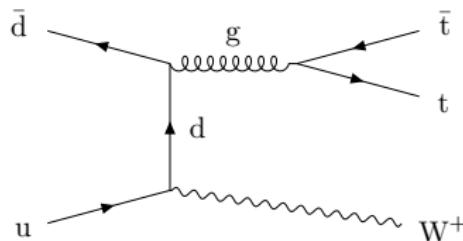
November 20, 2018



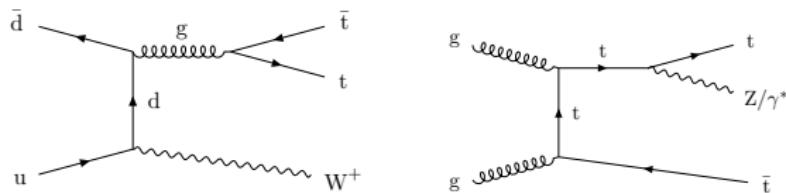
Introduction

Top pair production in association with a Z or W :

- Rare SM processes - provide an important test of the SM
- Important backgrounds to SM measurements in **multilepton final states** (in particular $t\bar{t}H(\rightarrow VV)$) as well as BSM searches
- $t\bar{t}Z/t\bar{t}W$ measurements provide a window to electroweak couplings of the top



$t\bar{t}V$ production at the LHC



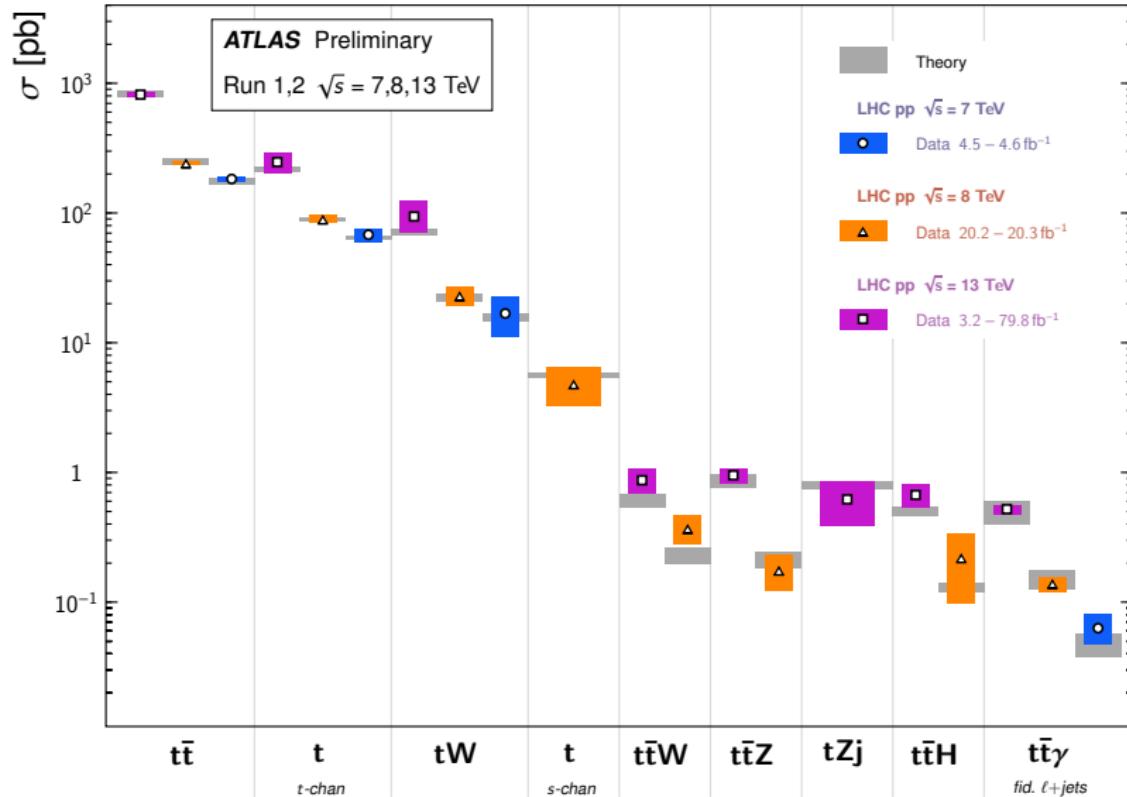
Cross sections computed to NLO in α_s ($= \mathcal{O}(\alpha_s^3 \alpha)$).

- $\mathcal{O}(\alpha_s \alpha^2), \mathcal{O}(\alpha_s^2 \alpha^2)$ electroweak corrections also known (Frixione et al, [arXiv:1504.03446](https://arxiv.org/abs/1504.03446))
- $\sigma_{t\bar{t}Z} = 0.88 \text{ pb}$ (0.84 pb) in ATLAS (CMS). Difference due to Z/γ^* interference and m_{ll} cuts in generation - $> 5 \text{ GeV}$ ($> 10 \text{ GeV}$), respectively
- $\sigma_{t\bar{t}W} = 0.60 \text{ pb}$
- Uncertainty for both processes $\sim 12\%$ (scale variations + PDF)
- The LO \rightarrow NLO k -factors are significant: 1.4-1.5

$t\bar{t}V$ production at the LHC: cross sections

Top Quark Production Cross Section Measurements

Status: November 2018



ATLAS and CMS $t\bar{t}V$ measurements

CMS paper (JHEP 08 (2018) 011) and ATLAS preliminary result both based on the full 2015+2016 dataset of 13 TeV collisions (36 fb^{-1}).

Many possible final states, with differing S/B and dominant backgrounds.

Process	$t\bar{t}$ decay	Boson decay	Channel	Main backgrounds
$t\bar{t}W$	$(\ell^\pm \nu b)(q\bar{q}b)$ $(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\ell^\pm \nu$ $\ell^\pm \nu$	SS dilepton Trilepton	Non-prompt Non-prompt, $t\bar{t}X$
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$ $(\ell^\pm \nu b)(q\bar{q}b)$ $(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\ell^+ \ell^-$ $\ell^+ \ell^-$ $\ell^+ \ell^-$	OS dilepton Trilepton Tetralepton	$Z + \text{jets}, t\bar{t}$ $WZ + \text{jets}, \text{ rare}$ $ZZ + \text{jets}, \text{ rare}$

ATLAS uses all of these; CMS doesn't consider the $t\bar{t}Z$ OS dilepton and $t\bar{t}W$ trilepton channels.

- Both ATLAS and CMS use $\ell = e, \mu$ only
- Non-prompt ('fake') lepton and charge flip backgrounds are very important in $t\bar{t}W$ measurement

ATLAS and CMS measurements: object definitions

CMS

- **Leptons:** $p_T > 10 \text{ GeV}$; $|\eta| < 2.5$ (2.4) for e (μ)
- Relative track isolation $I_{\text{rel}} < 0.1$ for electrons in all channels; $I_{\text{rel}} < 0.25$ for muons in $3l$ and $4l$ channels
 - Tighter isolation on muons in SS dilepton channel: $I_{\text{rel}} < 0.10$
- **Jets:** $p_T > 30 \text{ GeV}$, $|\eta| < 2.4$; b -tagging using a 70% efficiency operating point

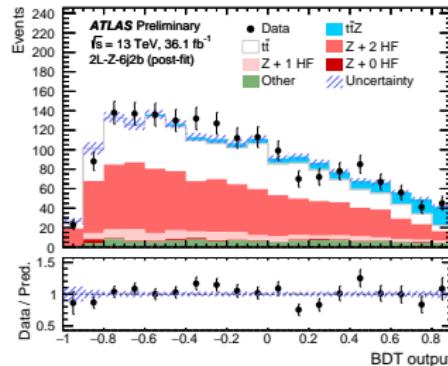
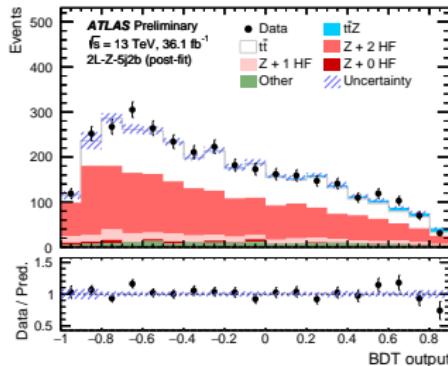
ATLAS

- **Leptons:** $p_T > 7 \text{ GeV}$; $|\eta| < 2.47$ (2.5) for e (μ)
 - In the channels targeting $t\bar{t}Z$, use track and calorimeter based isolation
 - Tighter isolation used in $2lSS$ and $3l$ dilepton channels targeting $t\bar{t}W$.
MVA discriminant used to suppress leptons from **heavy flavour decays**
 - rejection factor ~ 20 with an 80-95% signal lepton efficiency.
 - Another MVA discriminant used to suppress charge flip contribution for **electrons** in $2lSS$ channels
- **Jets:** $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$; b -tagging using a 77% efficiency operating point

ATLAS measurement: OS channel

Overwhelming $Z + \text{jets}$ and $t\bar{t}$ backgrounds \implies use a BDT to increase sensitivity.

- Three signal regions with different S/B : $2\ell-Z-6j1b, 2\ell-Z-5j2b, 2\ell-Z-6j2b$
- Data-driven estimate of $t\bar{t}$ from an $e\mu$ control region
- $Z + \text{heavy flavour}$ normalisation from data (low BDT values)



SS dilepton channel

Targets $t\bar{t}W \rightarrow (bjj)(bl^\pm\nu)l^\pm\nu$.

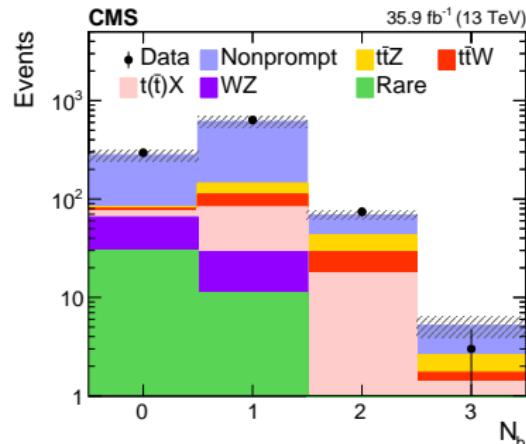
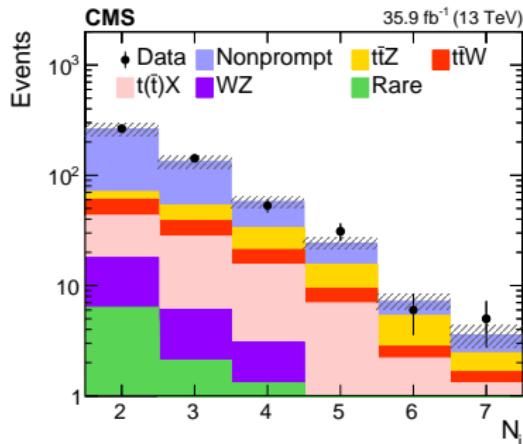
Common elements to ATLAS and CMS approaches:

- Two SS leptons with high p_T : ($> 25, > 25$) GeV
- Signal regions split by charge (++) and (--) and number of b -jets ($= 1$ and ≥ 2)
 - $t\bar{t}W$ production charge asymmetric: more + than -, due to u vs d PDF difference
 - Backgrounds largely charge symmetric (e.g. fake leptons)
- Dominant backgrounds - **non-prompt leptons** and **charge flips** - estimated using data-driven methods
- Z veto used to suppress charge flip contribution in SRs

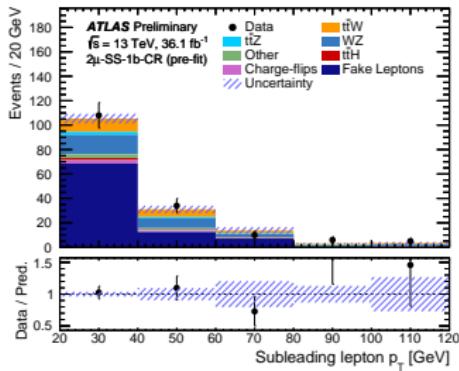
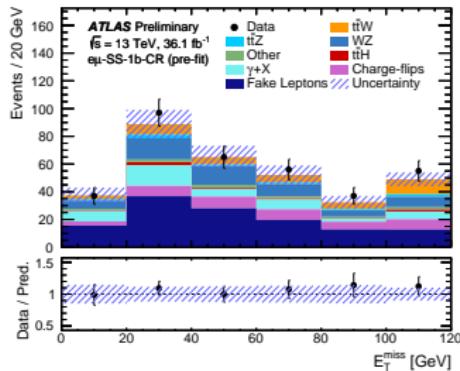
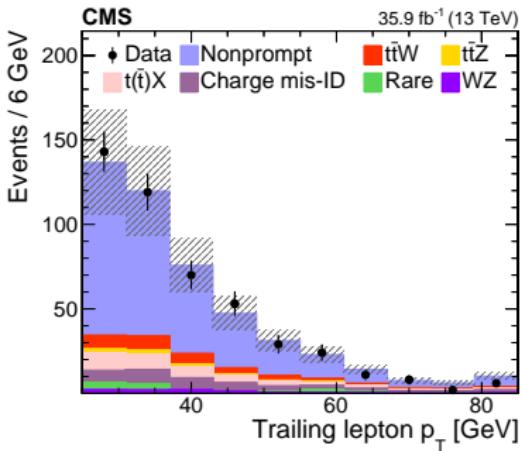
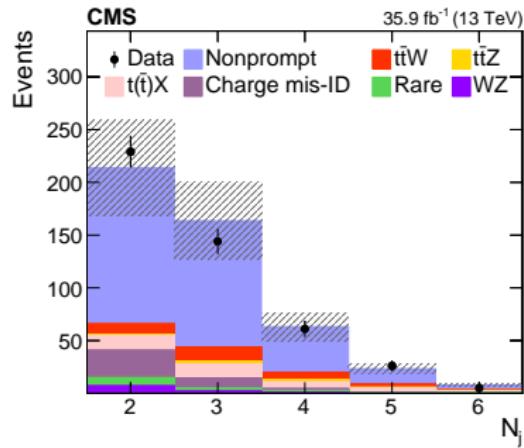
ATLAS and CMS: fake lepton background estimation

Fake lepton background estimated using “loose” leptons with a looser isolation requirement.

- CMS extracts the tight-to-loose ratios in QCD-enriched $1l$ region
- ATLAS extracts the ratios using SS regions orthogonal to the $t\bar{t}W$ SRs; these are also included in the fit used to extract the $t\bar{t}W$ signal
- CMS uses fake lepton enriched SS regions and $3l$ regions with events failing the Z -window requirement to validate the fake lepton estimate



Fake lepton background validation

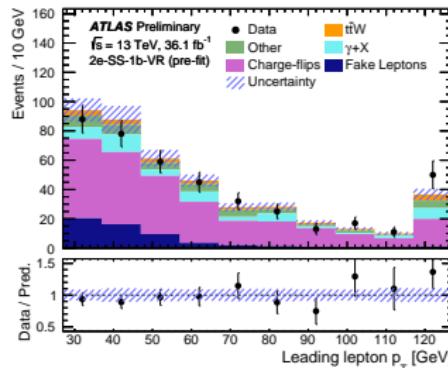
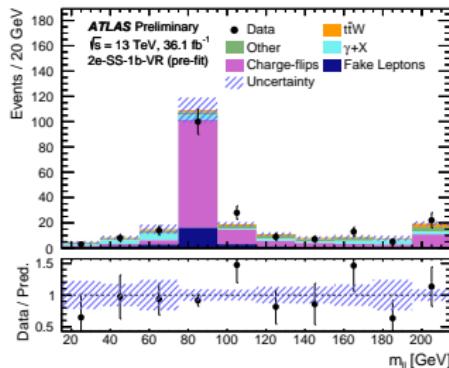


ATLAS: SS dilepton channel

Cut-and-count approach.

2l-SS signal regions

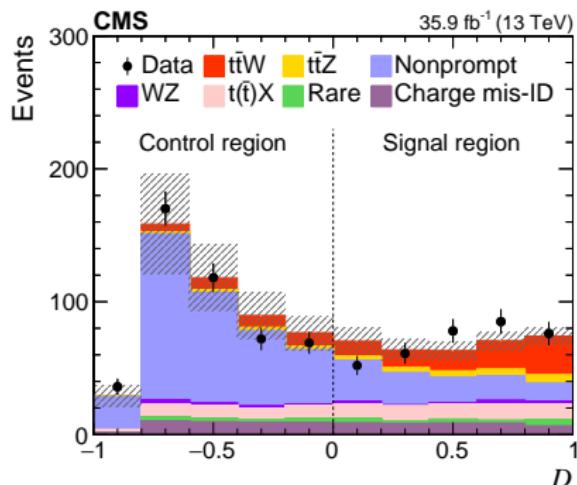
- Two SS leptons with $p_T > 25$ GeV, $H_T > 240$ GeV (with $H_T = \sum_{\text{jets}} p_T$)
- SRs split by flavour [$2e, e\mu, 2\mu$], charge and number of b -jets \implies 12 regions in total
- Charge flip probabilities extracted in Z -like SS events.
 - Applied to SR-like OS events to get charge flip yields in SRs



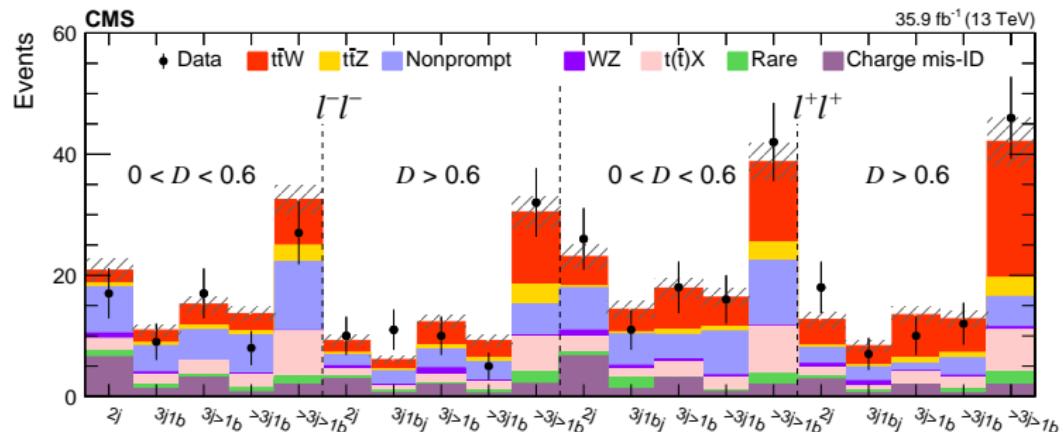
CMS: SS dilepton channel

A BDT is used to separate signal from background, using N_{jets} , $N_{\text{b-jets}}$, H_T , p_T^{miss} , M_T and other variables.

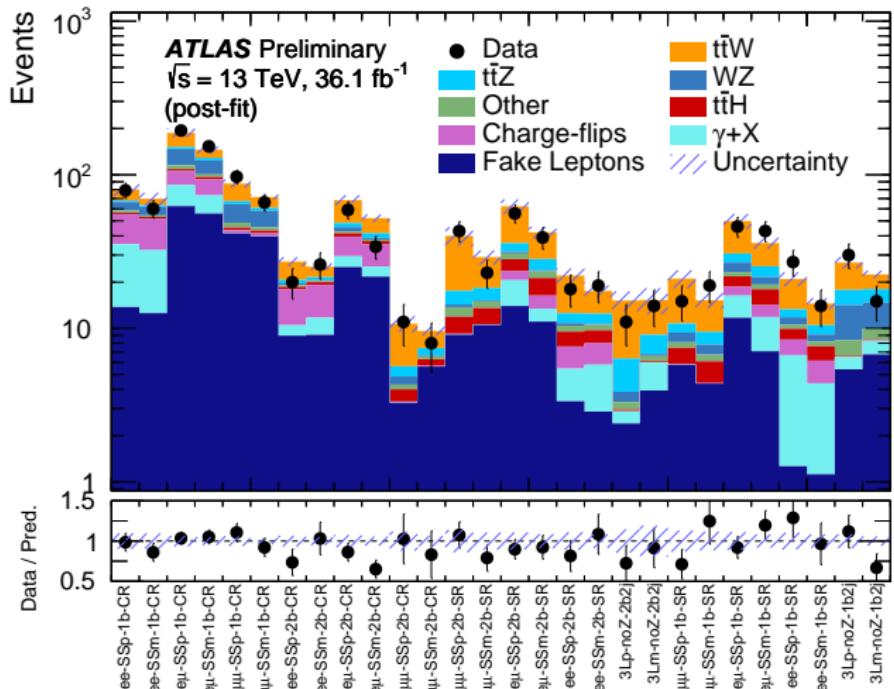
- Regions split by N_{jets} , $N_{\text{b-jets}}$ and the value of the BDT discriminant: $D \in [0, 0.6]$, $D > 0.6$, and lepton charge (++ and --) $\implies 20$ in total
- $D < 0$ regions also used, to constrain fake lepton background



SS dilepton channel results: CMS



SS dilepton channel results: ATLAS



Also includes the $3l$ regions targeting $t\bar{t}W$.

3l channel

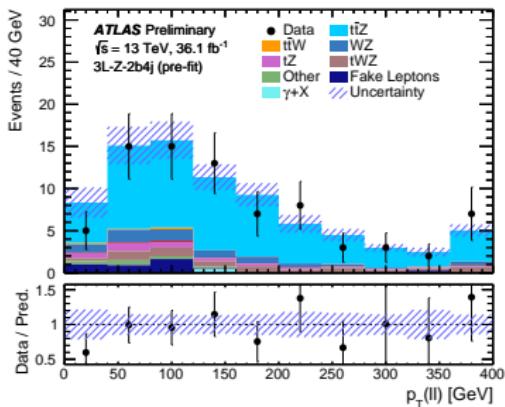
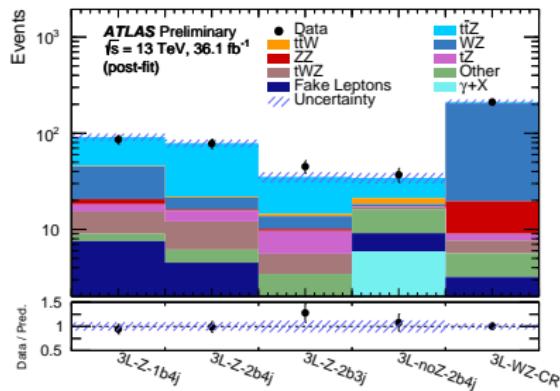
Most sensitive regions for $t\bar{t}Z$; some sensitivity to $t\bar{t}W$ (only considered in ATLAS).

- Both ATLAS and CMS categorise in N_{jets} and $N_{\text{b-jets}}$
- Dominant backgrounds: $WZ+\text{jets}$, non-prompt leptons and **rare SM processes**: tZ , tWZ , $t\bar{t}H$, etc.
- Dedicated control regions for $WZ+\text{jets}$ in both measurements

ATLAS: 3l channel ($t\bar{t}Z$)

Three leptons with p_T ($> 27, > 20, > 20$) GeV.

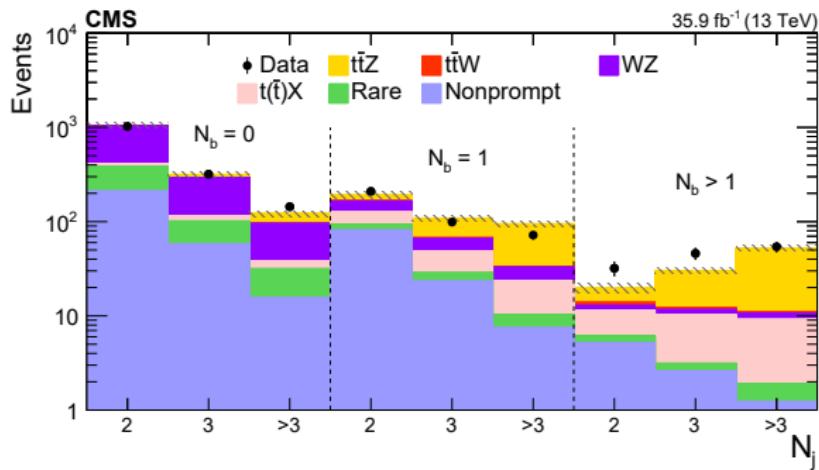
- Four signal regions, 3ℓ -Z-1b4j, 3ℓ -Z-2b3j, 3ℓ -Z-2b4j, 3ℓ -noZ-2b4j
- Control region for $WZ + \text{jets}$ defined using ≥ 3 jets and ≤ 0 b -tags
- Additional uncertainties included for $WZ + \text{HF}$ and extrapolation to the SR



CMS: 3l channel ($t\bar{t}Z$)

Three leptons with p_T ($> 40, > 20, > 10$) GeV.

- All regions require an OSSF pair with $|M(ll) - M(Z)| < 10$ GeV
- Nine signal regions with $N_{\text{jets}} \in [2, 3, > 3]$ and $N_{b-\text{jets}} \in [0, 1, > 1]$
- Control region for $WZ + \text{jets}$ defined using < 2 jets and $= 0$ b -tags



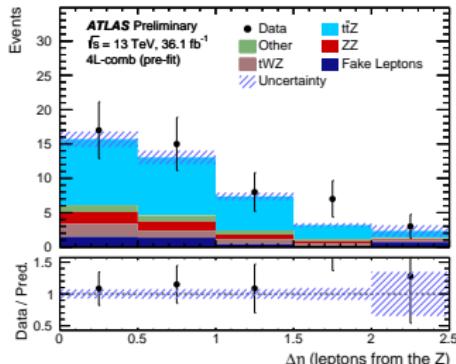
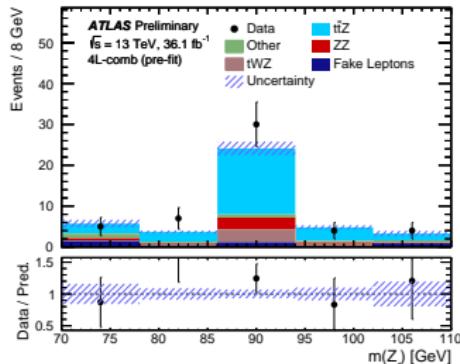
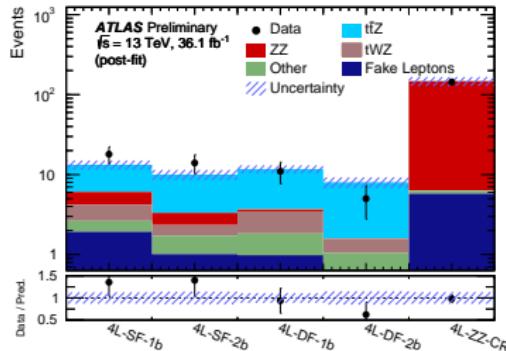
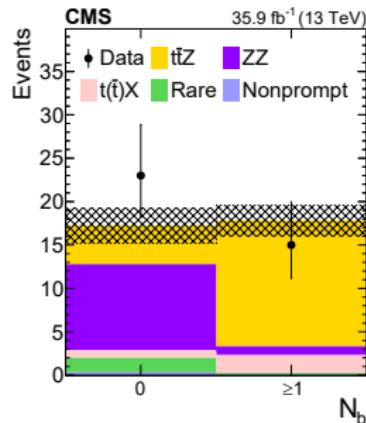
Mild excess in the $N_{b-jets} > 1$ regions extensively studied; consistent with a fluctuation (details in backup).

4l channel

$t\bar{t}Z$ -sensitive regions with excellent S/B , but relatively low yields due to small BR.

- Always require a Z -like OSSF pair
- **ATLAS** has four SRs, depending on the whether the other two flavours are the same ("SF") or different ("DF") and the number of b -jets (1 or ≥ 2) 4ℓ -DF-1b, 4ℓ -DF-2b, 4ℓ -SF-1b, 4ℓ -SF-2b
- **CMS** has one combined SR
- Dominant backgrounds are $ZZ + \text{jets}$ and rare SM processes ($tWZ, t\bar{t}X$)
- Dedicated control regions for $ZZ + \text{jets}$, where two OSSF pairs consistent with a Z boson are required

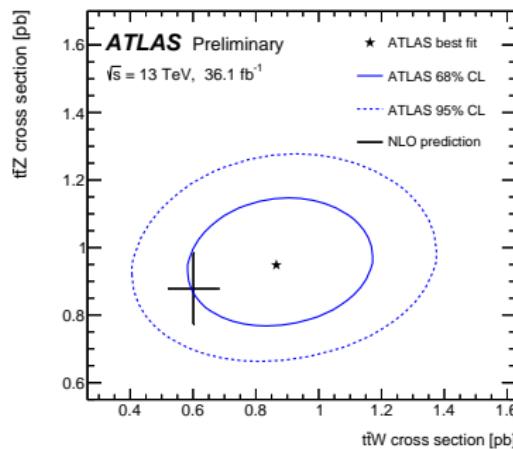
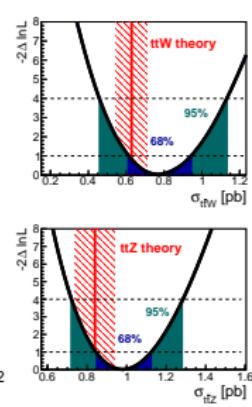
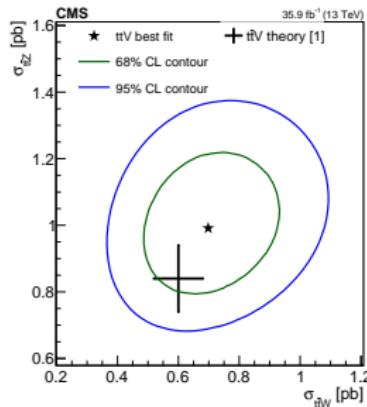
4l channel results



Combined fits

Both ATLAS and CMS extract the $t\bar{t}Z$ and $t\bar{t}W$ cross sections simultaneously.

- All SS dilepton, $3l$ and $4l$ signal regions used
- Both experiments also include fake lepton enriched regions in the fit
- ATLAS also includes the $WZ/ZZ+jets$ CRs



Measured cross sections

	CMS	ATLAS
$\sigma_{t\bar{t}Z}$	$0.99^{+0.09}_{-0.08}(\text{stat.})^{+0.12}_{-0.10}(\text{syst.}) \text{ pb}$	$0.95 \pm 0.08_{\text{stat.}} \pm 0.10_{\text{syst.}} \text{ pb}$
$\sigma_{t\bar{t}W}$	$0.77^{+0.12}_{-0.11}(\text{stat.})^{+0.13}_{-0.12}(\text{syst.}) \text{ pb}$	$0.87 \pm 0.13_{\text{stat.}} \pm 0.14_{\text{syst.}} \text{ pb}$

- Theory predictions $\sigma_{t\bar{t}Z} = 0.88 \text{ pb}$ and $\sigma_{t\bar{t}W} = 0.60 \text{ pb}$
- The sensitivity is comparable between the two experiments
- All values consistent with the SM

Uncertainties: CMS

Source	Uncertainty from each source (%)	Impact on the measured $t\bar{t}W$ cross section (%)	Impact on the measured $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	4	3
Jet energy scale and resolution	2–5	3	3
Trigger	2–4	4–5	5
B tagging	1–5	2–5	4–5
PU modeling	1	1	1
Lepton ID efficiency	2–7	3	6–7
Choice in μ_R and μ_F	1	<1	1
PDF	1	<1	1
Nonprompt background	30	4	<2
WZ cross section	10–20	<1	2
ZZ cross section	20	—	1
Charge misidentification	20	3	—
Rare SM background	50	2	2
$t(\bar{t})X$ background	10–15	4	3
Stat. unc. in nonprompt background	5–50	4	2
Stat. unc. in rare SM backgrounds	20–100	1	<1
Total systematic uncertainty	—	14	12

- $t\bar{t}Z$: 9% (stat) + 11% (syst)
 - Dominated by lepton ID efficiency, b -tagging and trigger uncertainties
- $t\bar{t}W$: 14% (stat) + 14% (syst)
 - Non-prompt/ $t(\bar{t})X$ background, trigger and b -tagging uncertainties

Uncertainties: ATLAS

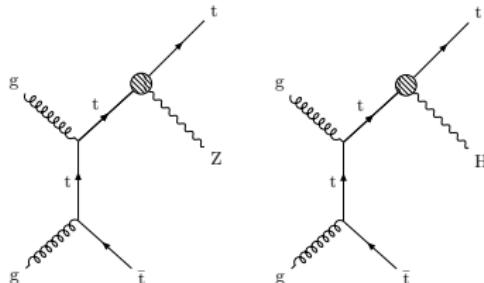
Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
CR and simulated sample statistics	1.8%	7.6%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	2.4%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10%	16%
Statistical	8.4%	15%
Total	13%	22%

- $t\bar{t}Z$: 8.4% (stat) + 10% (syst)
 - Dominated by signal & background modelling and b -tagging
- $t\bar{t}W$: 15% (stat) + 16% (syst)
 - Dominated by signal modelling, fake lepton background modelling and CR statistics

EFT interpretation

The measurements are sensitive to a number of EFT couplings.

- CMS considers 8 operators affecting $t\bar{t}Z$, $t\bar{t}W$ and $t\bar{t}H$ and uses the LO UFO model of [arXiv:1404.3667](#)
 - Some of these, e.g. $\mathcal{O}_{tG} \equiv y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$, can be constrained more precisely from other measurements (e.g. $t\bar{t}$ cross section)
 - $t\bar{t}H$ relevant since it's a major background to $t\bar{t}W$
- ATLAS focuses on 5 operators affecting $t\bar{t}Z$ only and uses the NLO model of [arXiv:1601.08193](#) - the effect on the background small and not considered
- Both use aMC@NLO to perform EFT computation

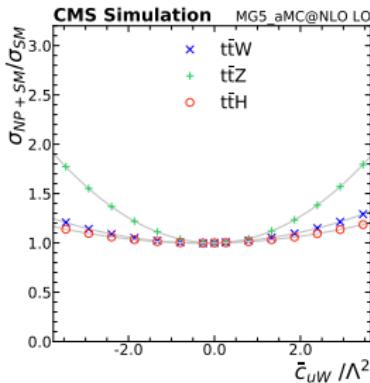
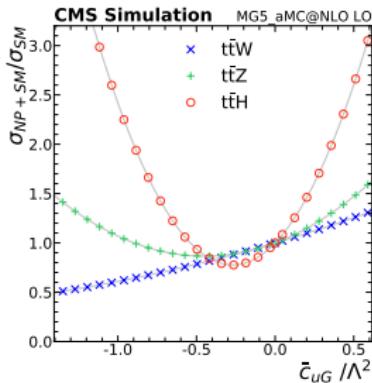
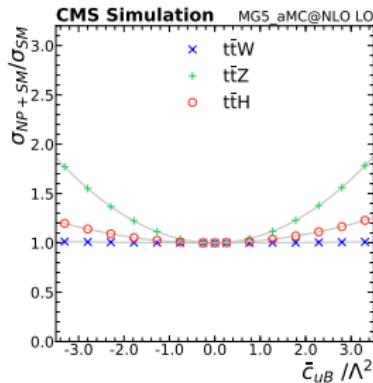


Operator	Expression
$\mathcal{O}_{\phi Q}^{(3)}$	$i \frac{1}{2} (\phi^\dagger \overset{\leftrightarrow}{D}_\mu \phi) (\bar{Q} \gamma^\mu \tau^I Q)$
$\mathcal{O}_{\phi Q}^{(1)}$	$i \frac{1}{2} (\phi^\dagger \overset{\leftrightarrow}{D}_\mu \phi) (\bar{Q} \gamma^\mu Q)$
$\mathcal{O}_{\phi t}$	$i \frac{1}{2} (\phi^\dagger \overset{\leftrightarrow}{D}_\mu \phi) (\bar{t} \gamma^\mu t)$
\mathcal{O}_{tW}	$y_t g_w (\bar{Q} \sigma^{\mu\nu} \tau^I t) \tilde{\phi} W_{\mu\nu}^I$
\mathcal{O}_{tB}	$y_t g_Y (\bar{Q} \sigma^{\mu\nu} t) \tilde{\phi} B_{\mu\nu}$

EFT interpretation: fit strategy

In both measurements, limits extracted by setting all operators except one to 0.

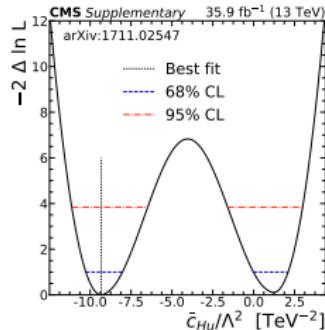
- Cross section parametrised as $\sigma_{\text{SM+NP}}(c_i) = s_0 + s_{1i}c_i + s_{2i}c_i^2$
- CMS uses the global effect on the cross section
- ATLAS performs the parametrisation for each signal region individually



EFT interpretation: results

NB: CMS and ATLAS operator definitions are not identical so limits cannot be directly compared.

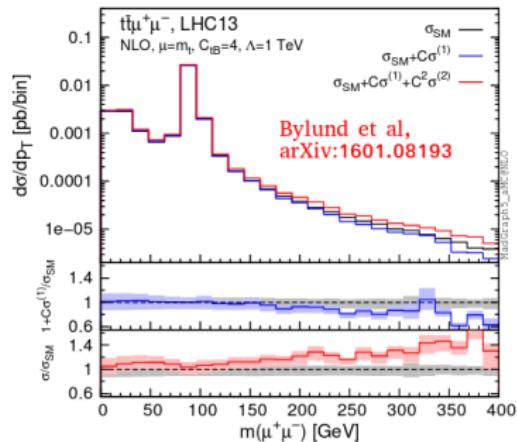
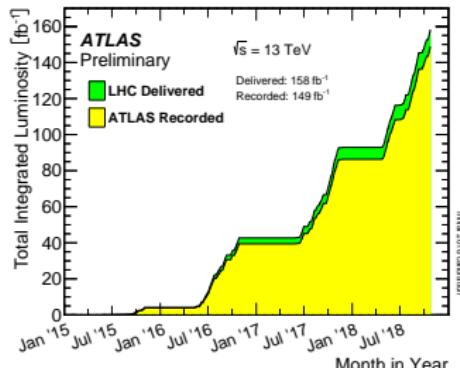
Wilson coefficient	Best fit [TeV ⁻²]	68% CL [TeV ⁻²]	95% CL [TeV ⁻²]
\bar{c}_{uW}/Λ^2	1.7	[-2.4, -0.5] and [0.4, 2.4]	[-2.9, 2.9]
$ \bar{c}_H/\Lambda^2 - 16.8 \text{ TeV}^{-2} $	15.6	[0, 23.0]	[0, 28.5]
$ \bar{c}_{3G}/\Lambda^2 $	0.5	[0, 0.7]	[0, 0.9]
\bar{c}_{3G}/Λ^2	-0.4	[-0.6, 0.1] and [0.4, 0.7]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



Coefficient	Expected limits at 68% and 95 % CL	Observed limits at 68% and 95 % CL	Previous constraints at 95 % CL
$(\mathcal{C}_{\phi Q}^{(3)} - \mathcal{C}_{\phi Q}^{(1)})/\Lambda^2$	[-2.1, 1.9], [-4.6, 3.7]	[-1.0, 2.7], [-3.4, 4.3]	[-3.4, 7.5]
$\mathcal{C}_{\phi t}/\Lambda^2$	[-3.8, 2.8], [-23, 5.0]	[-2.0, 3.6], [-27, 5.7]	[-2.0, 5.7]
$\mathcal{C}_{tB}/\Lambda^2$	[-8.3, 8.6], [-12, 13]	[-11, 10], [-15, 15]	[-16, 43]
$\mathcal{C}_{tW}/\Lambda^2$	[-2.8, 2.8], [-4.0, 4.1]	[-2.2, 2.5], [-3.6, 3.8]	[-0.15, 1.9]

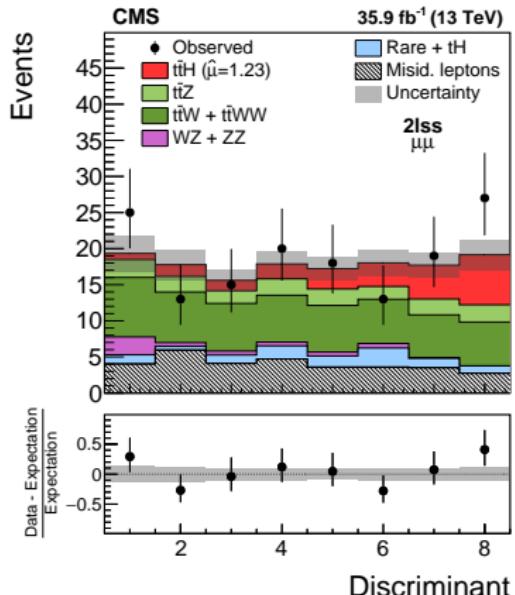
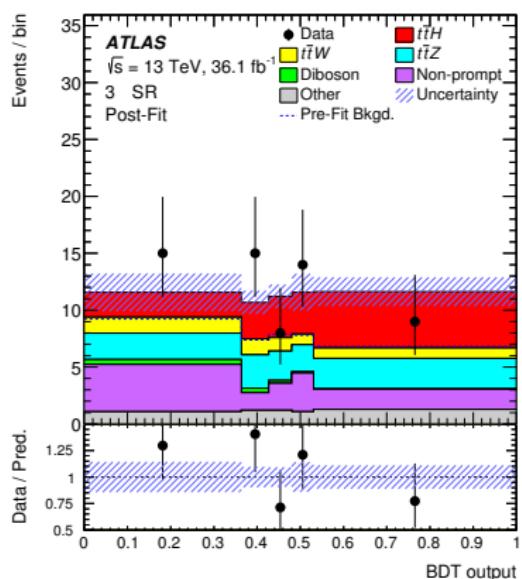
Conclusion and future directions

- We are entering the era of precision $t\bar{t}Z$ and $t\bar{t}W$ measurements
- New possibilities open up with the full Run 2 dataset
- systematics dominated \implies rare SM backgrounds ($tZ, tWZ, t\bar{t}H, VVV$ etc) and signal modelling need to be understood better
- Additional sensitivity to EFT operators from tails in differential distributions
- Combinations with other measurements sensitive to the same couplings (e.g. $t\bar{t}H, t\bar{t}\gamma$)



BACKUP

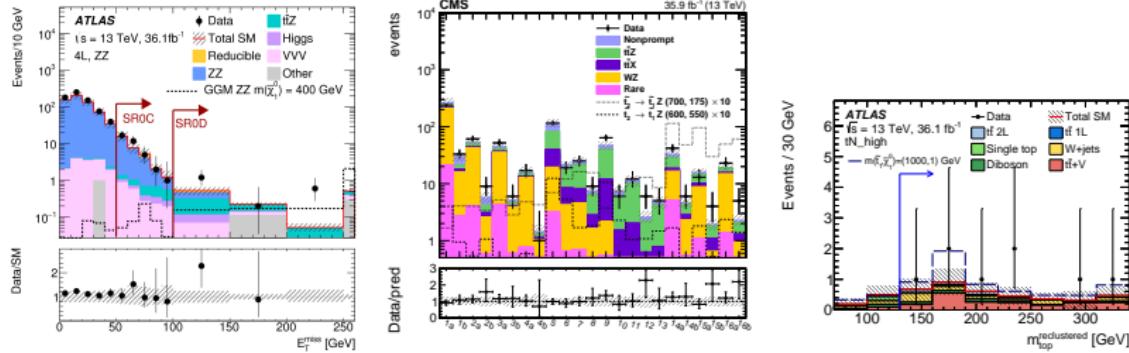
$t\bar{t}V$ as a background: $t\bar{t}H$



$t\bar{t}Z$ and $t\bar{t}W$ are among the dominant backgrounds in the measurement of $t\bar{t}H$ production in multilepton final states.

- All three processes are closely related
- MVA techniques used by both ATLAS and CMS to distinguish $t\bar{t}W/t\bar{t}Z$ from $t\bar{t}H$

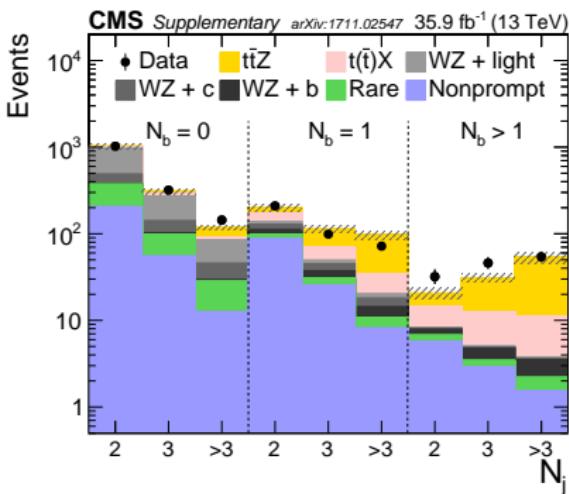
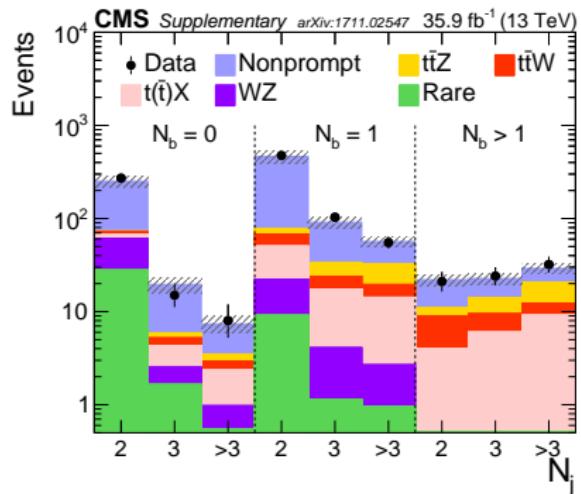
$t\bar{t}V$ as a background: searches



Important backgrounds to BSM physics searches in various final states:

- stop pair production ($t\bar{t}$ +MET final state)
- electroweak production giving 3/4 real leptons in the final state, same-charge dilepton searches
- ...and many others

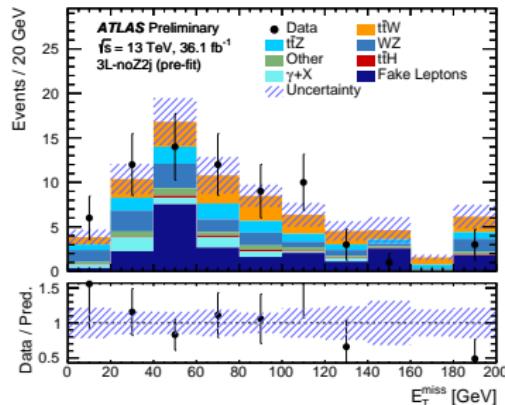
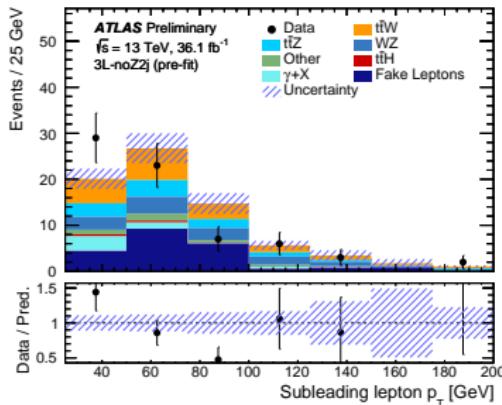
CMS: WZ and fake lepton backgrounds



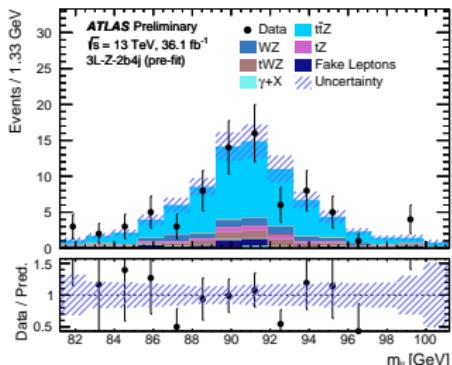
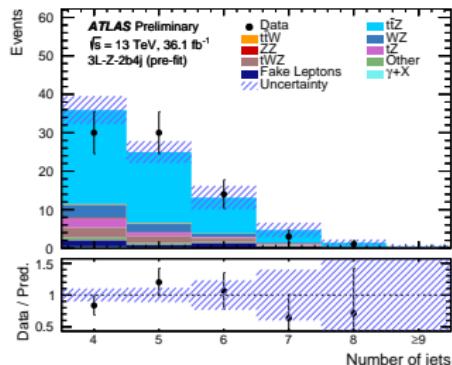
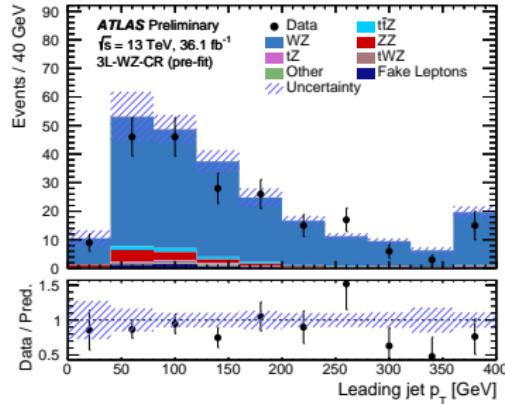
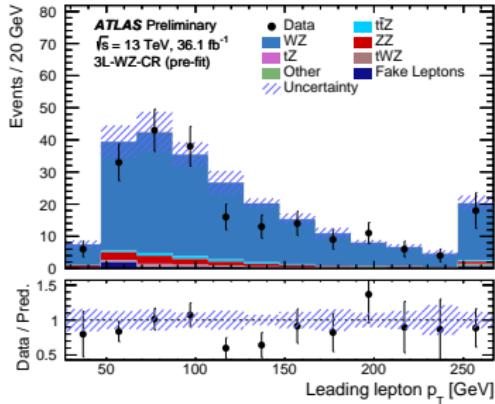
ATLAS: 3l channel ($t\bar{t}W$)

Only considered in ATLAS.

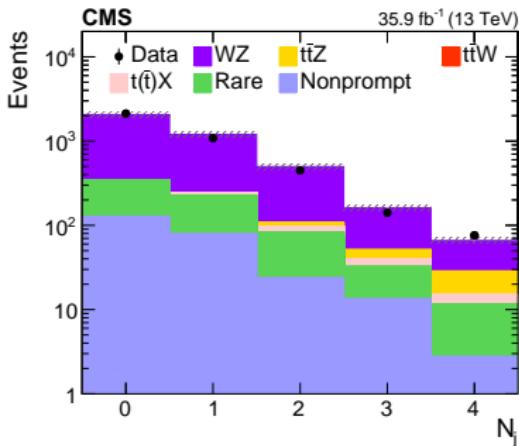
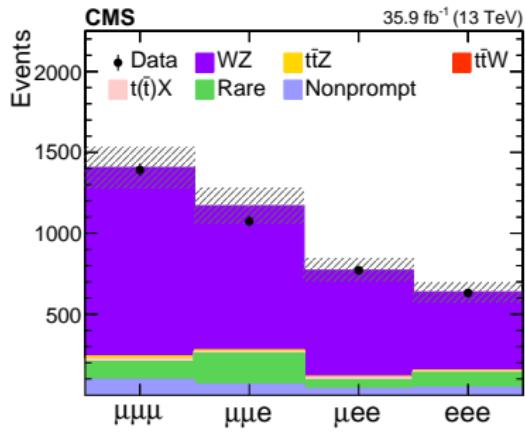
- Z -veto, $N_{\text{jets}} \in [2, 3]$; categories by non- Z lepton charge and $N_{\text{b-jets}}$
 \implies 4 regions in total
- Dominant background from fake leptons followed by $t\bar{t}Z$



ATLAS: 3l channel ($t\bar{t}Z$)

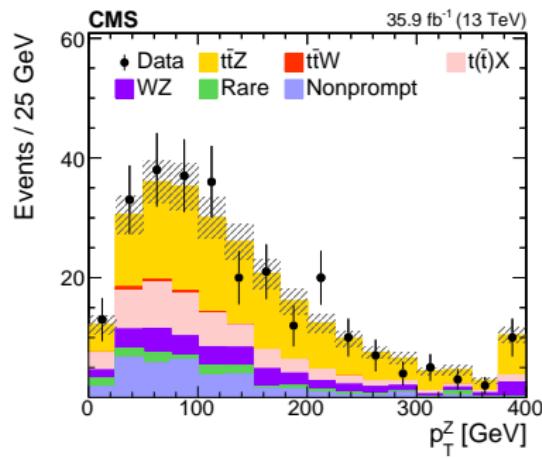
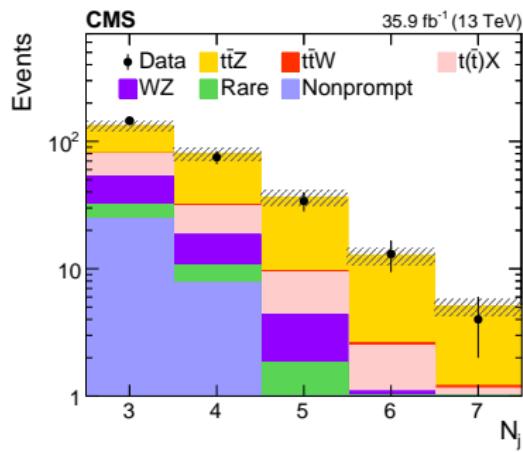


CMS: 3l channel - WZ CR



CMS: 3l channel ($t\bar{t}Z$)

Using combined regions with $N_{\text{jets}} \geq 3$ and $N_{\text{b-jets}} \geq 1$:



4l channel: $ZZ + \text{jets}$ background validation

