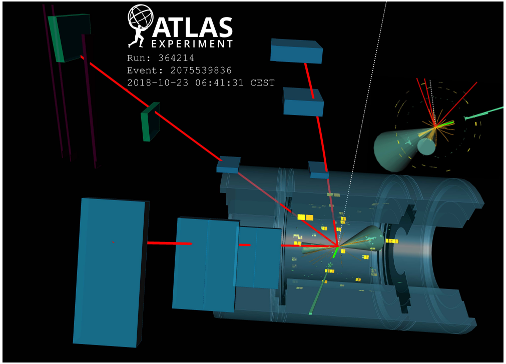
Top-quark production in association with γ, W, Z



4-lepton $t\bar{t}Z$ candidate

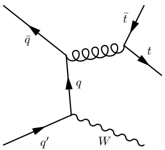
Rustem Ospanov, on behalf of the ATLAS and CMS Collaborations

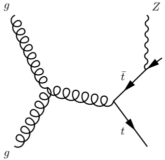
13th International Workshop on Top-Quark Physics

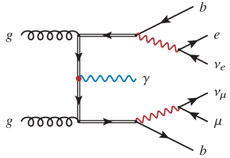
September 15th, 2020

Introduction

- LHC is the abundant source of top-quarks
  - Excellent performance of LHC and ATLAS and CMS experiments allows to record large datasets with high efficiency
  - About 140 fb^{-1} of data recorded by ATLAS/CMS each $\rightarrow$ allows differential measurements of very rare processes
- Top-quark production in association with γ, W, Z - rare processes that test couplings to gauge bosons
  - $t\bar{t}Z$ and tqZ - probe tZ coupling, also sensitive to details of the electroweak symmetry breaking mechanism
  - $t\bar{t}\gamma$ - probes $t\gamma$ coupling and anomalous dipole moment of top-quark
  - $t\bar{t}W$ - probes tW coupling, also important background for $t\bar{t}H$ analysis

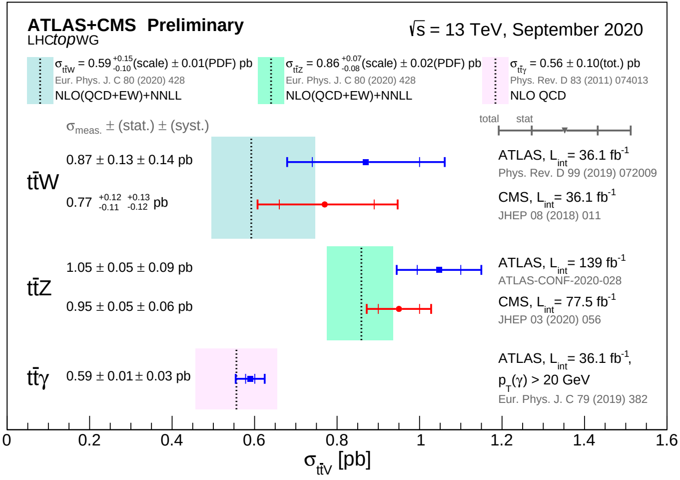






- Key experimental and theoretical requirements
  - Efficient identification of electrons, muons, and b-jets; machine learning techniques to suppress backgrounds
  - Precise predictions for signal and background processes

ATL-PHYS-PUB-2020-022



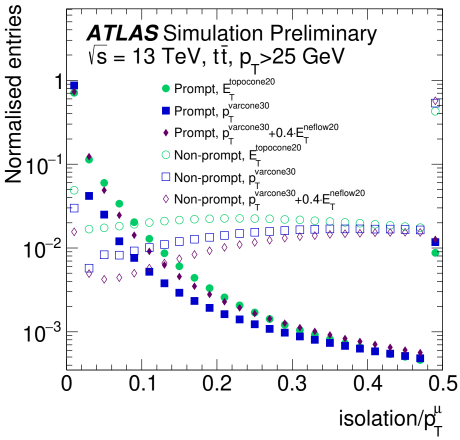
Outline of this talk:

- $t\bar{t}Z$ results:
  - CMS JHEP 03 (2020) 056
  - ATLAS ATLAS-CONF-2020-028
  - YSF talk by Florian Fischer about ATLAS $t\bar{t}Z$ results
- tqZ results:
  - CMS PRL 122 (2019) 132003
  - ATLAS JHEP 07 (2020) 124
- $t\bar{t}\gamma$ results
  - ATLAS JHEP 09 (2020) 049

Electron and muon isolation working points (WPs)

- Select prompt e/μ from W/Z decays and reject non-prompt e/μ produced in hadronic processes
  - e/μ produced in decays of b/c hadrons, typically embedded in the jet of light flavour hadrons
  - Decays of π/K contribute only at low muon p_T
  - Jets and conversions are additional sources of e fakes
- Select isolated e/μ with inner tracker and calorimeters:
  - Scalar sum of p_T of ID tracks within $\Delta R \lesssim 0.3$
  - Sum of E_T of topological clusters within $\Delta R \lesssim 0.3$
  - Particle-flow isolation matches ID tracks with calorimeter clusters to remove contributions from other collisions
- "Cut-based" isolation:
  - "Cut" criteria defined using ratios of track and calorimeter isolation sums over $p_T^{e/\mu}$ (often using p_T dependent cone)
- Multi-variate isolation:
  - Isolation and impact parameter measurements are combined using Boosted Decision Tree algorithm (BDT)
  - Also include properties of the closest jet

ATLAS-CONF-2020-030



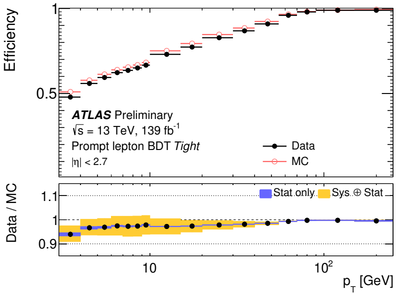
ATLAS isolation working points

- ATLAS uses "cut-based" and "PromptLepton BDT" working points for selecting isolated e/μ
  - e/μ isolation identification and isolation are summarised in EPJC 79 (2019) 639 and ATLAS-CONF-2020-030
- "PromptLepton BDT" working points developed for $t\bar{t}H$ and $t\bar{t}W$ analyses (and SUSY searches)

ATLAS muon isolation WPs

Working point	$3 < p_T < 5$ GeV		$5 < p_T < 20$ GeV		$20 < p_T < 100$ GeV		$p_T > 100$ GeV	
	ϵ_μ[%]	ϵ_{HF}[%]	ϵ_μ[%]	ϵ_{HF}[%]	ϵ_μ[%]	ϵ_{HF}[%]	ϵ_μ[%]	ϵ_{HF}[%]
Loose	63	14.3	86	7.2	97	6.1	99	12.7
Tight	53	11.9	70	4.2	89	1.0	98	1.6
PflowLoose	62	12.9	86	6.8	97	5.0	99	9.1
PflowTight	45	8.5	63	3.1	87	0.9	97	0.8
HighPtTrackOnly	92	35.9	92	17.2	92	4.5	92	0.6
TightTrackOnly	80	19.9	81	7.0	94	3.2	99	3.3
PLBDTLoose	81	17.4	83	5.1	93	1.3	98	1.7
PLBDTTight	57	9.6	69	2.7	87	0.5	98	1.7

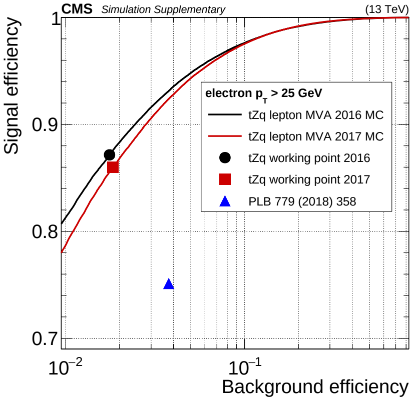
Efficiency of "PromptLepton BDT" for prompt μ



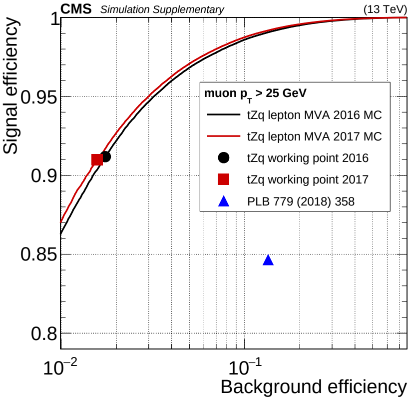
CMS BDT-based isolation working point

- CMS defined new isolation WPs that significantly suppresses non-prompt e/μ with better prompt efficiency
- These WPs allow lowering $p_T^{e/\mu}$ to 10 GeV, without significantly increasing non-prompt e/μ background

CMS electron BDT isolation WP

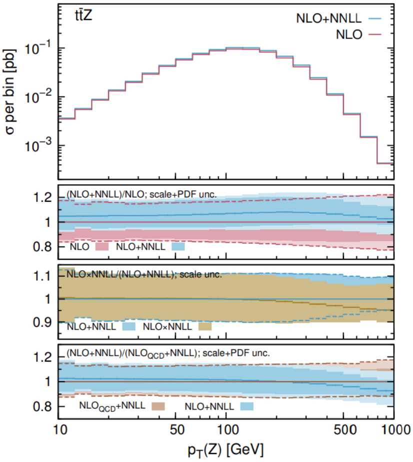


CMS muon BDT isolation WP



$t\bar{t}Z$ production at LHC

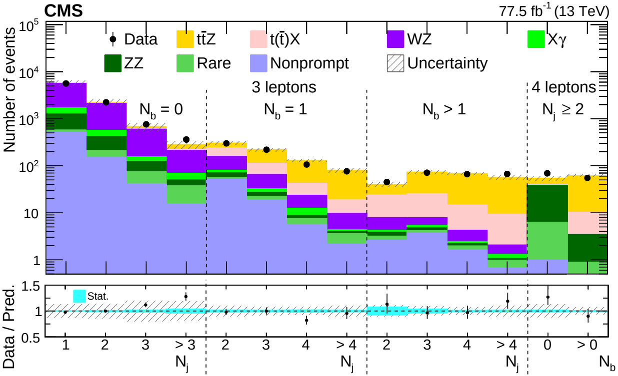
arXiv:1907.04343



- $t\bar{t}Z$ cross-section is computed at NLO+NNL with EW corrections
  - arXiv:1812.08622 and arXiv:1907.04343
  - Total cross section is $811^{+11\%}_{-10\%}$ (scale) $\pm$ 2.4% (PDF) fb
  - From LO to NLO: about +60% cross-section increase
  - From NLO to NLO+NNLL: about +8% cross-section increase
- Reporting latest ATLAS and CMS $t\bar{t}Z$ results:
  - CMS measurements using 77.5 fb^{-1} JHEP 03 (2020) 056
  - ATLAS measurements using 139 fb^{-1} ATLAS-CONF-2020-028
- Model $t\bar{t}Z$ with MadGraph5_aMC@NLO at NLO in QCD
  - Scale, α_S and PDF uncertainties
  - ATLAS: difference between HERWIG 7 and PYTHIA 8 included as modelling uncertainty

$t\bar{t}Z$ signal selection

- Select $Z \to e^+e^-/\mu^+\mu^-$ and $t\bar{t} \to bbl\nu l\nu/bbl\nu jj$ decays
- Signal and control regions are defined using multiplicity of leptons, jets, and b-jets:
  - 3-lepton signal regions: $= 1$ or ≥ 2 b-jet and $N_{\text{jet}} \geq 4$
  - 4-lepton signal regions: ≥ 1 b-jet and $N_{\text{jet}} \geq 2$



CMS

- 70% b-jet efficiency
- Multi-variate e/μ identification/isolation (BDT) $\to$ +15% prompt e/μ efficiency with a factor 2 to 4 better non-prompt rejection
- $|m_{ll} - m_Z| < 10$ (20) GeV for 3l (4l)

3l lepton $p_T > 40, 20, 10$ GeV

4l lepton $p_T > 40, 10, 10, 10$ GeV

ATLAS

- 60/70 (85)% b-jet efficiency for 3l (4l)
- *Medium* e/μ identification and standard ("cut-based") isolation
- $|m_{ll} - m_Z| < 10$ GeV for 3l and 4l

3l lepton $p_T > 27, 20, 20$ GeV

4l lepton $p_T > 27, 20, 10, 7$ GeV

4l $E_T^{\text{miss}} > 50(100)$ GeV for 1(2) Z

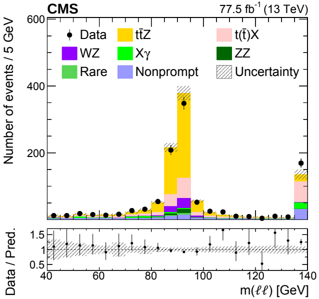
$t\bar{t}Z$ signal regions for inclusive cross-section measurement

- ATLAS: 2 SR for 3l, 4 SR for 4l, 2 CR for WZ and ZZ
- CMS: 8 SR+CR for 3l, 6 SR+CR for 4l
- CMS: lower p_T thresholds and e/μ BDT $\rightarrow$ 20 to 30% higher acceptance

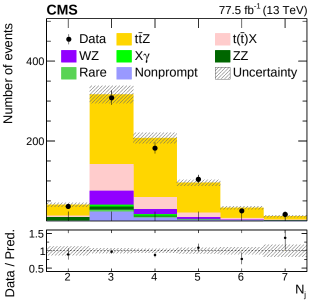
Post-fit event yields in the combined 3l and 4l SR

	$t\bar{t}Z$	$t(\bar{t})X$	WZ	non-prompt	data	$\int \mathcal{L}$
CMS	455	105	54	33	660	77.5 fb^{-1}
ATLAS	518	114	46	37	732	139 fb^{-1}

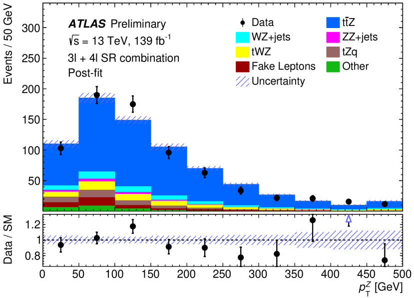
CMS m_Z



CMS N_{jet}



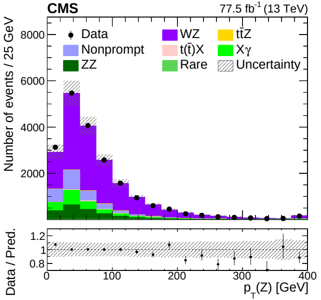
ATLAS Z p_T



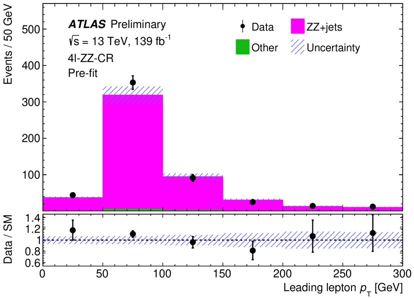
$t\bar{t}Z$ background processes

- Data control regions (CRs) used to normalise WZ and ZZ background processes
  - WZ + light flavour jet : 3l CR with zero b-jet or low jet multiplicity
  - ZZ + jets : 4l CR with zero b-jet
- MC simulation used to estimate other prompt 3l/4l processes:
  - WZ + heavy flavour jet - about 20 (50)% normalisation uncertainty for CMS (ATLAS)
  - $t(\bar{t})X$: $t\bar{t}W$, $t\bar{t}H$, tqZ, tWq - about 10-15% normalisation uncertainty
- Non-prompt/fake leptons are estimated from CRs with about 30 (50)% uncertainty for CMS (ATLAS)

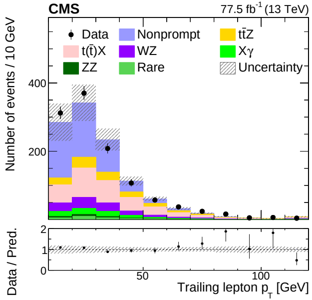
3l WZ CR



4l ZZ CR



Non-prompt lepton CR



$t\bar{t}Z$ total cross-section measurements

- Total $\sigma(\text{pp} \to t\bar{t}Z)$ cross-section is measured in $t\bar{t}Z$ phase space with 3l and 4l:
  - ATLAS: 1.05 ± 0.05 (stat.) ± 0.09 (syst.) fb
  - CMS: 0.95 ± 0.05 (stat.) ± 0.06 (syst.) fb $\to$ more precise than the theory prediction
  - NLO+NLL theory: $0.863^{+0.07}_{-0.09}$(scale) ± 0.03 (PDF $+ \alpha_S$) fb
  - *Measured total cross-sections are consistent between two experiments and with the theory*
- Leading sources of systematic uncertainty for ATLAS are not included in the CMS analysis:
  - Difference between Herwig 7 and Pythia 8 $\to$ 3.1% impact on cross-section
  - Different diagram removal schemes for interference between $t\bar{t}Z$ and tWZ $\to$ 2.9% impact on cross-section
  - Earlier talk by Simone Amoroso about definitions of modelling uncertainties by two experiments

CMS total σ per channel

Lepton requirement	Measured cross section
3ℓ	$0.97 \pm 0.06\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{pb}$
4ℓ	$0.91 \pm 0.14\,(\text{stat}) \pm 0.08\,(\text{syst})\,\text{pb}$
Total	$0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{pb}$

ATLAS signal strength per channel (relative NLO in QCD cross-section)

Fit configuration	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$
Combined	$1.19 \pm 0.06\,(\text{stat.}) \pm 0.10\,(\text{syst.})$

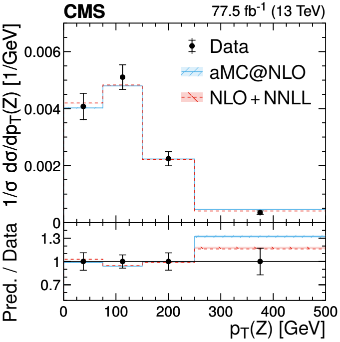
$t\bar{t}Z$ differential cross-sections

- ATLAS and CMS report absolute and normalised differential cross-sections:
  - Parton level: $p_T(Z)$, $cos\theta^*_Z$ and $|y^Z|$ cross-sections (combined 3l+4l, after QCD/electroweak radiation)
  - ATLAS also reports differential cross-sections at particle level:

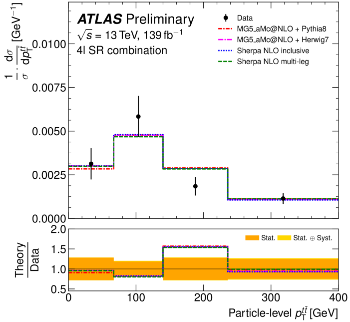
    3l N_{jet}, $p_{\mathrm{T}}^{l,\text{non-Z}}$, $\Delta\phi$ and Δy between Z and t decaying leptonically

    4l N_{jet}, $p_{\mathrm{T}}^{t\bar{t}}$, $\Delta\phi$ between Z and $t\bar{t}$, $\Delta\phi(ll)$ for $t\bar{t} \rightarrow ll$

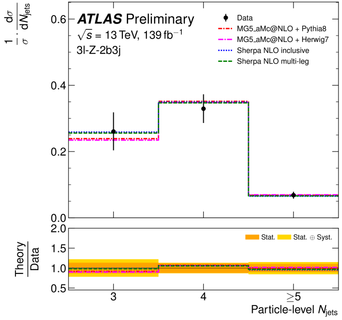
Normalised $p_T(Z)$



Normalised $p_{\mathrm{T}}^{t\bar{t}}$



Normalised 3l N_{jet}



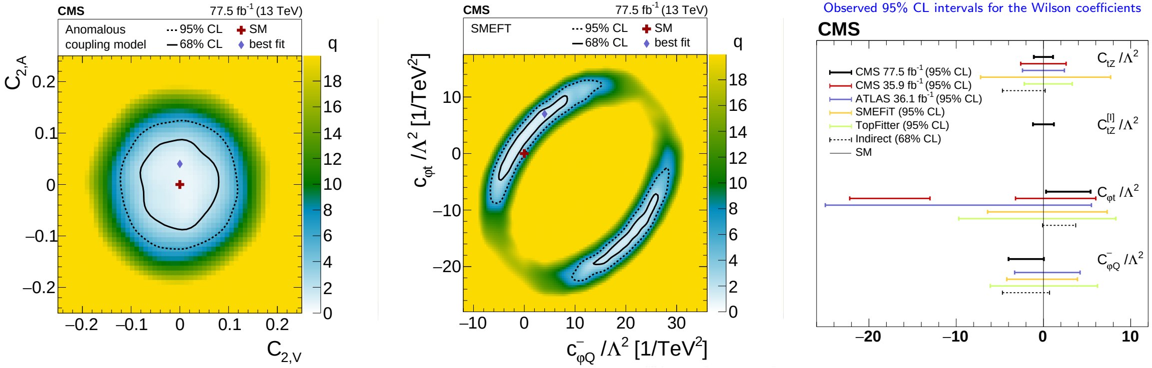
$t\bar{t}Z$ anomalous coupling and EFT limits

- CMS set limits on anomalous couplings and EFT interpretation
  - Define 15 SRs and 15 CRs split into $p_T(Z)$ and $cos\theta_Z^*$ bins separately for 3l/4l
  - Test for anomalous axial-vector and vector current couplings and dipole moments (four parameters)
  - Test for four EFT operators that induce anomalous interactions of top-quark with Z/γ

Scan in the electroweak dipole moment plane

EFT test for anomalous neutral current interactions

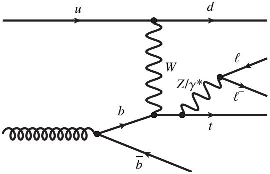
Observed 95% CL intervals for the Wilson coefficients



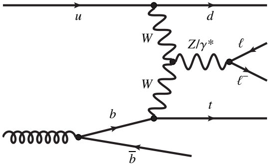
tqZ production at LHC

- tqZ process is sensitive to several couplings: WWZ, ttZ, tbW
  - Sensitive to coupling modifications that otherwise preserve $t\bar{t}Z$ and single top-quark production
  - Sensitive to the presence of flavour changing neutral currents
- CMS and ATLAS published observations of tqZ production:
  - CMS PRL 122 (2019) 132003 using 77.4 fb^{-1} and ATLAS JHEP 07 (2020) 124 using 139 fb^{-1}
- tqZ is identified by $t \to bl\nu$ decays and $Z \to e^+e^-/\mu^+\mu^-$, with the recoiling (forward) jet
  - Require 3 e/μ with $p_T > 28, 20, 20$ GeV for ATLAS and $p_T > 25, 15, 10$ GeV for CMS
  - CMS used BDT based e/μ identification/isolation $\to$ 8 to 12% higher prompt e/μ efficiency while rejecting a factor 2 to 8 more non-prompt e/μ compared to the previous analysis
  - Both experiments employed machine learning techniques to identify the tqZ signal

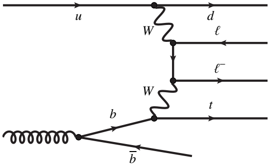
tqZ diagram with resonant l^+l^-



tqZ diagram with resonant l^+l^-



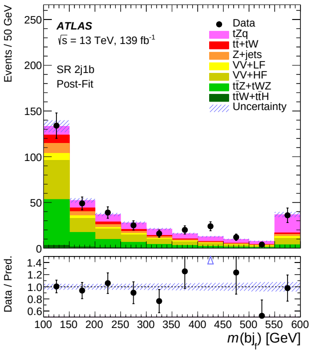
tqZ diagram with non-resonant l^+l^-



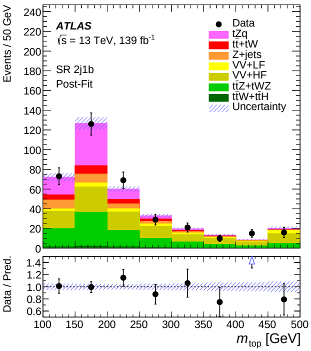
tqZ selection

- Define signal categories using jet and b-jet multiplicity:
  - CMS 3 SRs: 2/3 jets and 1 b-jet; $\geq$ 4 jets and 1 b-jet; $\geq$2 b-jets
  - ATLAS 2 SRs: 2 jets and 1 b-jet; 3 jets and 1 b-jet
- ATLAS (CMS) uses Neural Network (Boosted Decision Trees) to select tqZ signal
  - Aim to reconstruct top-quark and identify forward jet recoiling against the tZ system
  - Main background processes: WZ, $t\bar{t}Z$ and non-prompt leptons

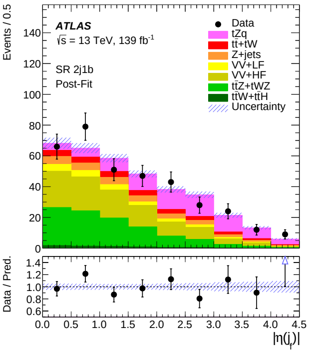
Invariant mass of b-jet and untagged jet



Reconstructed top-quark mass



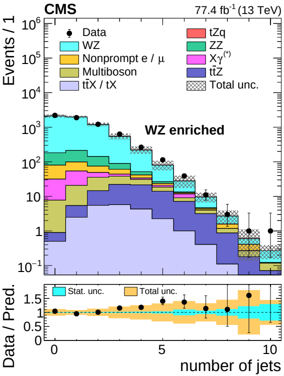
Pseudorapidity of the recoiling jet



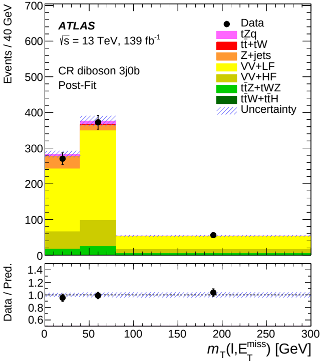
tqZ background control regions

- Control regions (CRs) to normalise dominant background processes (mainly WZ, $t\bar{t}Z$ and ZZ)
  - CMS: non-prompt leptons (from $t\bar{t}$ and Z+jets) estimated from data
  - ATLAS: MC based shapes for non-prompt backgrounds are normalised from 2 CRs
  - Remaining rare processes estimated from MC simulation

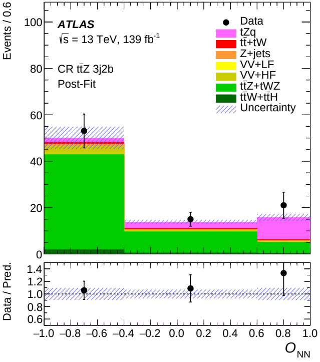
CMS SR 2 jets and 1 b-jet



Transverse mass of W boson candidate



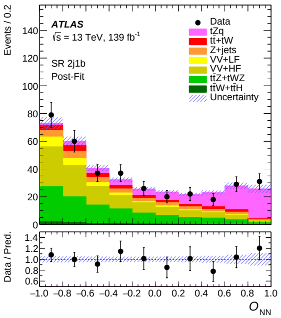
Neural network output in $t\bar{t}Z$ CR



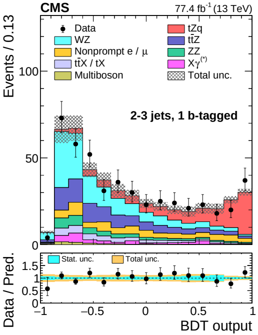
tqZ total cross-section

- Measure $\sigma(pp \to tqZ \to tl^+l^-q)$ for $m_{l^+l^-} > 30$ GeV from fitting SRs and CRs:
  - CMS measured: 111 ± 13 (stat.) $^{+11}_{-9}$ (syst.) fb; predicted at NLO in QCD: 94.2 ± 3.1 fb
  - ATLAS measured: 97 ± 13 (stat.) ± 7 (syst.) fb; predicted at NLO in QCD: 102^{+5}_{-2} fb
- Measurements are still limited by statistical uncertainty, leading sources of systematic uncertainty:
  - CMS: non-prompt lepton background 4.1%; lepton reconstruction 3.2%; jet energy scale 3.3%
  - ATLAS: prompt lepton backgrounds 3.3%; jet and E_T^{miss} reconstruction 2%; lepton reconstruction 2%

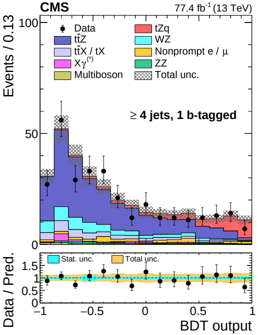
ATLAS SR 2 jets and 1 b-jet



CMS SR 2/3 jets and 1 b-jet



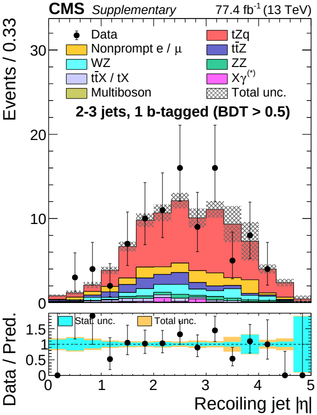
CMS SR $\geq$ 4 jets and 1 b-jet



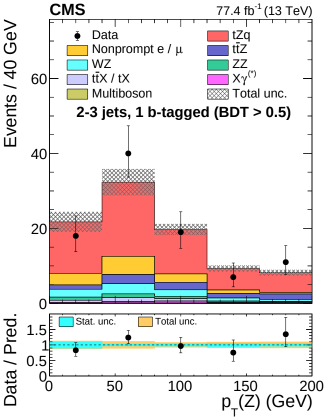
tqZ signal regions

- Kinematic properties of the candidate tqZ events (with high MVA score) are consistent with the predictions

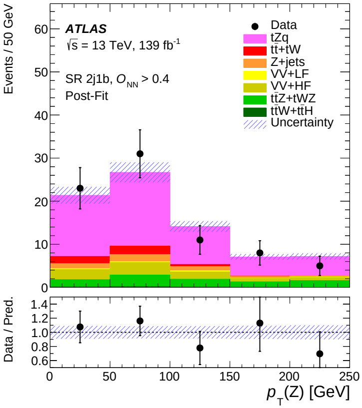
CMS recoiling jet $|\eta|$



CMS $p_T(Z)$ for tqZ candidate events

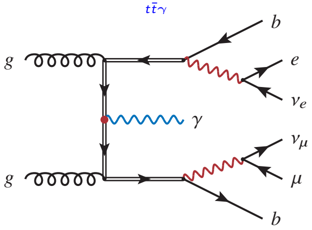


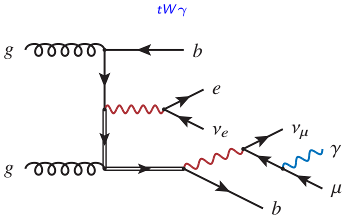
ATLAS $p_T(Z)$ for tqZ candidate events



$t\bar{t}\gamma$ production at LHC

- $t\bar{t}\gamma$ probes $t\gamma$ coupling and is sensitive to anomalous dipole-moments and EFT operators
  - Latest ATLAS results using 139 fb^{-1}: JHEP 09 (2020) 049
- Measure inclusive and differential cross-sections for the combined $t\bar{t}\gamma$ and $tW\gamma$ production
  - Compare to NLO QCD calculation for $pp \to bWbW\gamma$: arXiv:1803.09916 and arXiv:1809.08562
  - Includes resonant and non-resonant diagrams, interference and off-shell effects for the top-quarks and W boson
- $t\bar{t}\gamma$ and $tW\gamma$ processes are modelled with MadGraph5_MC@NLO at LO in QCD
  - $t\bar{t}\gamma$ modelled as $pp \to bl\nu bl\nu\gamma$ ($2 \to 7$ process)
  - $tW\gamma$ modelled as $pp \to tW\gamma$ and $pp \to bl\nu l\nu\gamma$ (complimentary diagrams)

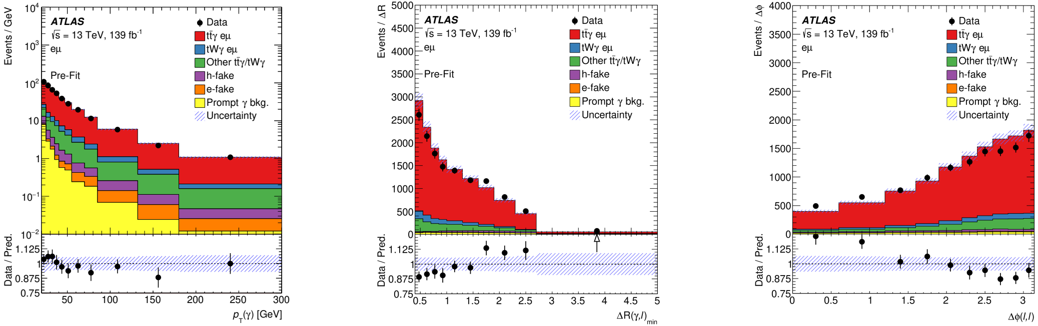




$t\bar{t}\gamma$ signal region

- $t\bar{t}\gamma$ is identified by the presence of isolated e and μ with one isolated photon with $E_T > 20$ GeV
  - Also require at least two jets $p_T > 25$ GeV and at least one b-jet
  - Selected objects are required to be away from each other, eg $\Delta R(\gamma, l/\text{jet}) > 0.4$
- Predict 2391 $t\bar{t}\gamma$ events and 156 $tW\gamma$ events
  - 279 events for $t\bar{t}\gamma/tW\gamma$ with $\tau \to e/\mu\nu\nu$ decay treated as background
  - 78 fake photons and 23 fake electrons - sub-leading sources of systematic uncertainty

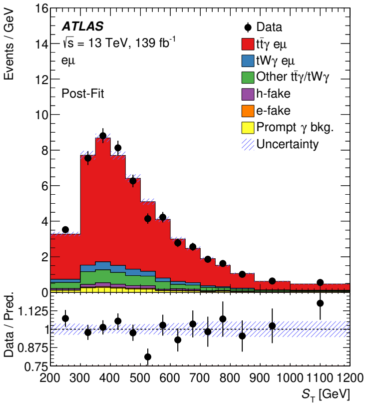
Photon p_T | $\Delta R(\gamma, l)$ | $\Delta\phi(e, \mu)$



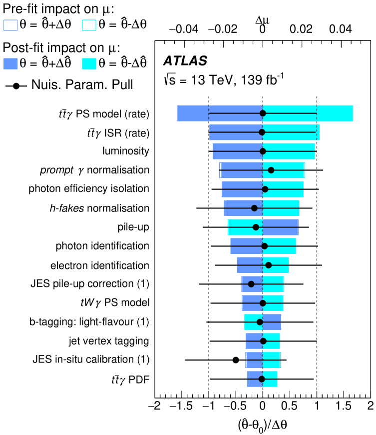
$t\bar{t}\gamma$ total cross-section

- Total cross-section is extracted by fitting $S_T = H_T + E_T^{miss} + p_T^{lepton}$
  - ATLAS: $\sigma_{fid.} = 39.6 \pm 0.8$ (stat.) $^{+2.6}_{-2.2}$ (syst.) fb
  - NLO at QCD: $\sigma_{fid.} = 38.5$ $^{+0.6}_{-2.2}$ (scale) $^{+1.0}_{-1.2}$ (PDF) fb

S_T



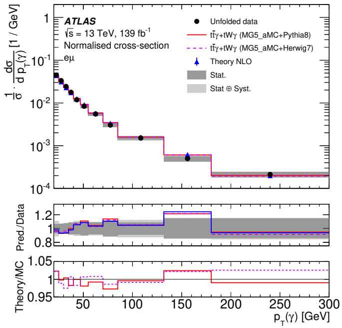
Ranked sources of systematic uncertainty



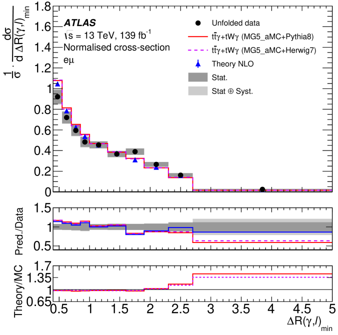
$t\bar{t}\gamma$ differential cross-section

- Measured differential cross-sections are compared to LO and NLO in QCD calculations
  - Good shape agreement of the normalised differential cross-sections with NLO in QCD calculation
  - NLO calculation includes all off-shell effects

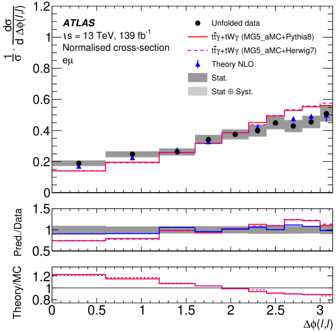
Normalised photon p_T



Normalised $\Delta R(\gamma, l)$



Normalised $\Delta\phi(e, \mu)$



Summary

- ATLAS and CMS studied rare $t\bar{t}W$, $t\bar{t}Z$, tqZ and $t\bar{t}\gamma$ processes with Run 2 data
- Entering precision era for rare processes involving top-quark
  - Both experiments observed rare tqZ process
  - Precise $t\bar{t}Z$ measurements are consistent with NLO+NNLL calculation
  - New differential measurements improve our understanding of the modelling of $t(\bar{t}) + X$ processes, and allow to set constraints on EFT parameters and BSM models
- Large datasets collected in combined Run 2 and Run 3 will push down statistical uncertainty
  - Improvements in experimental and theoretical methods are needed to reduce systematic uncertainty
- Experimental effects are becoming important sources of systematic uncertainty
  - BDT lepton selection helps CMS to suppress non-prompt background and reduce its uncertainty
- Theoretical sources of uncertainty are also important for measuring cross-sections
  - Dominant sources of uncertainty for ATLAS measurement of $t\bar{t}Z$ cross-section

Thank you!

BACKUP

- ATLAS $t\bar{t}Z$ theory uncertainties are consistently higher than those of CMS
  -

CMS sources of systematic uncertainty

Source	Uncertainty range (%)	Correlated between 2016 and 2017	Impact on the $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	×	2
PU modeling	1–2	✓	1
Trigger	2	×	2
Lepton ID efficiency	4.5–6	✓	4
Jet energy scale	1–9	✓	2
Jet energy resolution	0–1	✓	1
btagging light flavor	0–4	×	1
btagging heavy flavor	1–4	×	2
Choice in μ_R and μ_F	1–4	✓	1
PDF choice	1–2	✓	1
Color reconnection	1.5	✓	<1
Parton shower	1–8	✓	1
WZ cross section	10–20	✓	3
WZ + heavy flavor	8	✓	1
ZZ cross section	10	✓	1
$t(\bar{t})X$ background	10–15	✓	3
$X\gamma$ background	20	✓	1
Nonprompt background	30	✓	<1
Rare SM background	50	✓	2
Stat. unc. in nonprompt bkg.	5–50	×	<1
Stat. unc. in rare SM bkg.	5–100	×	<1
Total systematic uncertainty			6
Statistical uncertainty			5
Total			8

ATLAS sources of systematic uncertainty

Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
$WZ/ZZ+$jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + E_T^{miss}	2.1
Non-prompt/fake leptons	2.1
$t\bar{t}Z$ A14 tune	1.6
$t\bar{t}Z$ μ_f, μ_r scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematics	8.4
Data statistics	5.2
Total	9.9

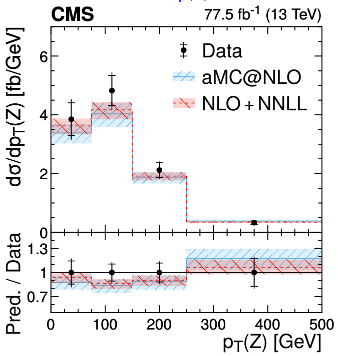
$t\bar{t}Z$ differential cross-sections

- ATLAS and CMS report absolute and normalised differential cross-sections at parton level
  - Parton level: $p_T(Z)$, $cos\theta^*_Z$ and $|y^Z|$ cross-sections (combined 3l+4l, after QCD/electroweak radiation)
  - ATLAS also reports differential cross-sections at particle level:

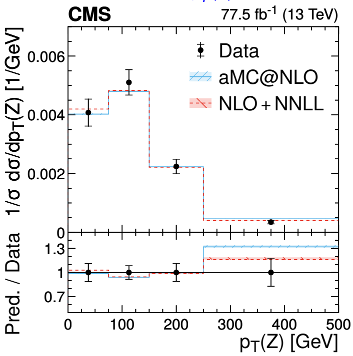
    3l N_{jet}, $p_{\mathrm{T}}^{l,\text{non-Z}}$, $\Delta\phi$ and Δy between Z and t decaying leptonically

    4l N_{jet}, $p_{\mathrm{T}}^{t\bar{t}}$, $\Delta\phi$ between Z and $t\bar{t}$, $\Delta\phi(ll)$ for $t\bar{t} \to ll$

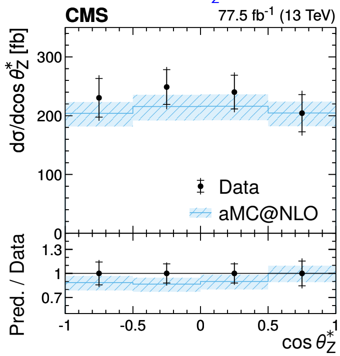
Absolute $p_T(Z)$



Normalised $p_T(Z)$



Absolute $cos\theta^*_Z$



$t\bar{t}Z$ differential cross-sections

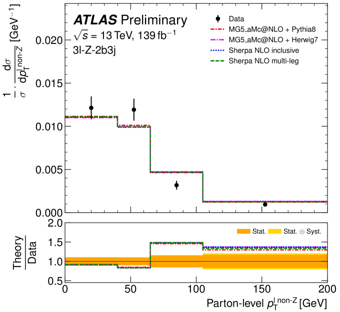
- ATLAS reports absolute and normalised differential cross-sections at parton and particle level

3l+4l $p_T(Z)$ and $|y^Z|$ cross-sections (after QCD/electroweak radiation)

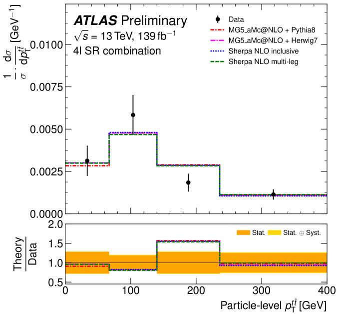
3l N_{jet}, $p_T^{l,\text{non-Z}}$, $\Delta\phi$ and Δy between Z and t decaying leptonically

4l N_{jet}, $p_T^{t\bar{t}}$, $\Delta\phi$ between Z and $t\bar{t}$, $\Delta\phi(ll)$ for $t\bar{t} \to ll$

Normalised $p_T(Z)$



Normalised $p_T^{t\bar{t}}$



Normalised 3l N_{jet}