14th International Workshop on Top Quark Physics (TOP2021)
September 13th–17th, 2021

Top quark production in association with a vector boson at the LHC

Recent results on $t\bar{t}\gamma$, $tW\gamma$, $t\bar{t}Z$, and tZq

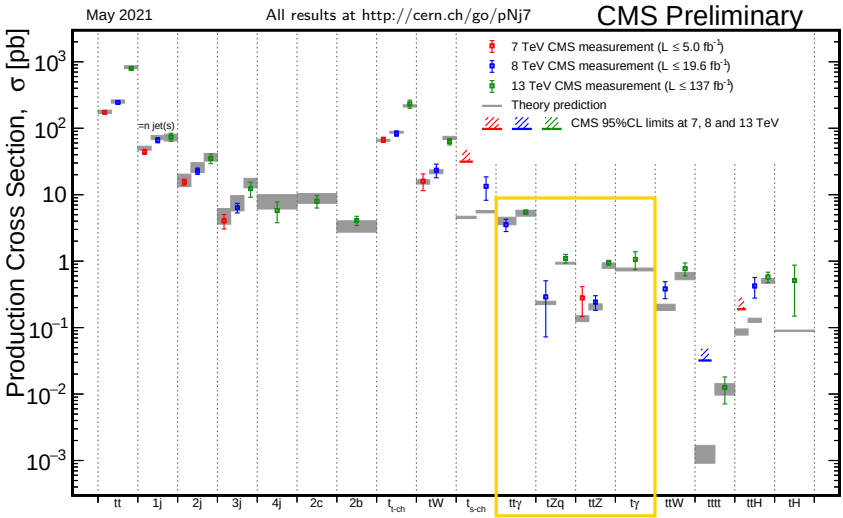
Joscha Knolle
on behalf of the ATLAS & CMS Collaborations

GHENT UNIVERSITY

ATLAS EXPERIMENT

Many thanks to
Dominik Babal
for his help with the
preparation of this talk!

Overview



$t\bar{t}\gamma + tW\gamma$
ATLAS, JHEP 09 (2020) 049

$t\bar{t}\gamma$
CMS, arXiv:2107.01508 (submitted to JHEP)
CMS-PAS-TOP-21-004

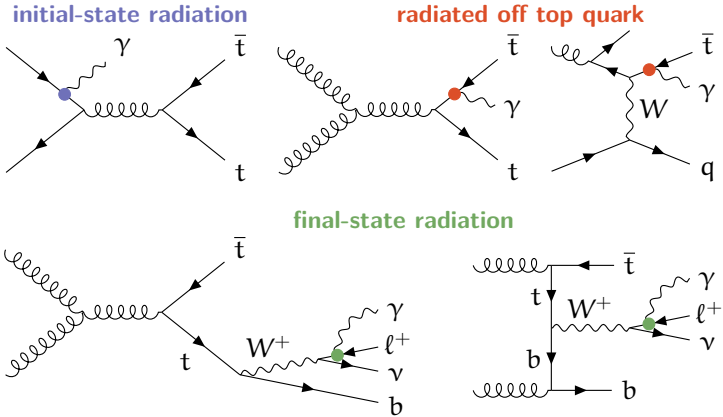
$t\gamma q$
CMS, Phys. Rev. Lett. 121 (2018) 221802

$t\bar{t}Z$
ATLAS, Eur. Phys. J. C 81 (2021) 737
CMS, JHEP 03 (2020) 056

tZq
ATLAS, JHEP 07 (2020) 124
CMS-PAS-TOP-20-010

$t\bar{t}W$
ATLAS, Phys. Rev. D 99 (2019) 072009
CMS, JHEP 08 (2018) 011

Top quarks and photons



- probe of electroweak top quark–photon coupling
- need phase space definition for cross section

$\mathrm{t\bar{t}\gamma + tW\gamma}$
JHEP 09 (2020) 049
$e\mu$ events, 139 fb^{-1}

fiducial $\mathrm{t\bar{t}\gamma}$
arXiv:2107.01508
(submitted to JHEP)
ℓ+jets events, 137 fb^{-1}

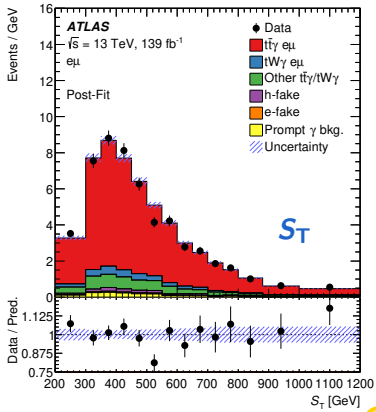
fiducial $\mathrm{t\bar{t}\gamma}$
CMS-PAS-TOP-21-004
2ℓ events, 138 fb^{-1}

fiducial $\mathrm{t\gamma q}$
Phys. Rev. Lett. 121
(2018) 221802
μ events, 35.9 fb^{-1}

$t\bar{t}\gamma + tW\gamma$ measurement: Inclusive cross section

JHEP 09 (2020) 049

- eμ events, $=1$ photon, ≥ 2 jets, ≥ 1 b-tag
- fiducial region at parton-level, close to selection
- backgrounds: hadronic fake, electron fake, and prompt γ; from MC
- template fit to S_T: p_T sum of ℓ's, γ's, jets, and p_T^{miss}
- signal modelling (PS model, ISR) is limiting uncertainty



Category	Uncertainty
$t\bar{t}\gamma/tW\gamma$ modelling	3.8%
Background modelling	2.1%
Photons	1.9%
Luminosity	1.8%
Jets	1.6%
Pile-up	1.3%
Leptons	1.1%
Flavour-tagging	1.1%
MC statistics	0.4%
Soft term E_T^{miss}	0.2%
$tW\gamma$ parton definition	2.8%
Total syst.	6.3%

measured cross section: $39.6 \pm 0.8\,(\text{stat})\,^{+2.6}_{-2.2}\,(\text{syst})$ fb

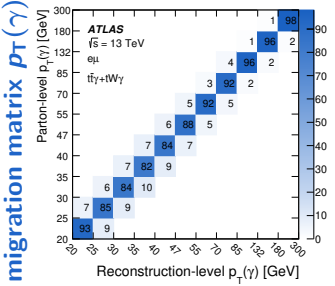
in agreement with NLO theory: $38.5\,^{+1.2}_{-2.5}$ fb ±6.3%

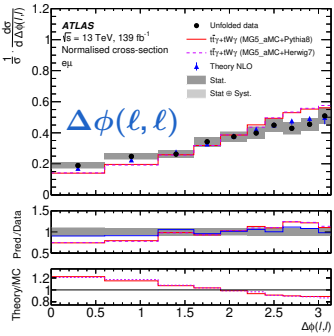
Bevilacqua, Hartanto, Kraus, Weber, & Worek, JHEP 10 (2018) 158, JHEP 01 (2019) 188

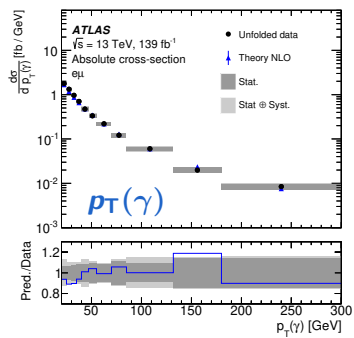
$t\bar{t}\gamma + tW\gamma$ measurement: Differential cross sections

JHEP 09 (2020) 049

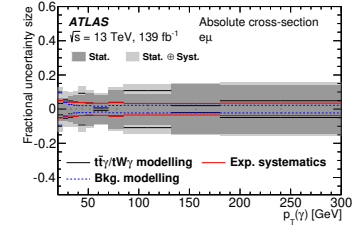
- iterative Bayesian unfolding, 2 iterations, RooUnfold
- binning optimized for statistics and resolution
- purity larger than 80%







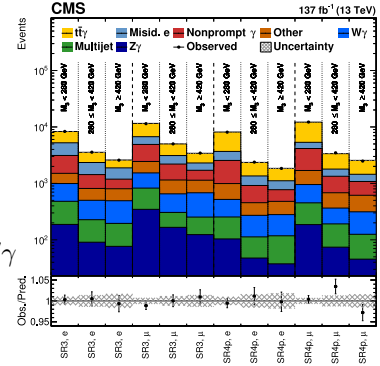
- $|\eta(\gamma)|$, $\Delta R(\gamma,\ell)_{\text{min}}$, $|\Delta\eta(\ell,\ell)|$
- NLO theory agrees better than LO MG5_aMC@NLO MC sample



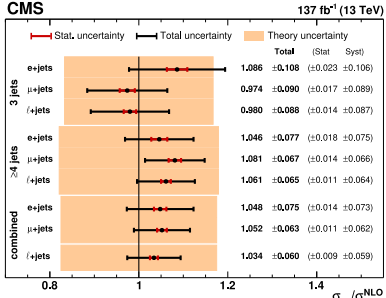
$t\bar{t}\gamma$ lepton+jets measurement: Inclusive cross section

arXiv:2107.01508 (submitted to JHEP)

- ℓ+jets events, $=1$ photon, ≥ 3 jets, ≥ 1 b-tag
- fiducial region at particle-level, close to selection
- from data: nonprompt γ, misID e, multijet
- control regions: misID e, Vγ
- template fit in $m(3j)$ bins by flavor & jet multiplicity, plus CR $p_{\mathrm{T}}(\gamma)$ bins
- uncertainties: Wγ, nonprompt γ jet energy scale, ISR/FSR scale, luminosity, misID e



$m(3j)$/flavor/# jets



measured cross section:

$800 \pm 7\,(\mathrm{stat}) \pm 46\,(\mathrm{syst})$ fb

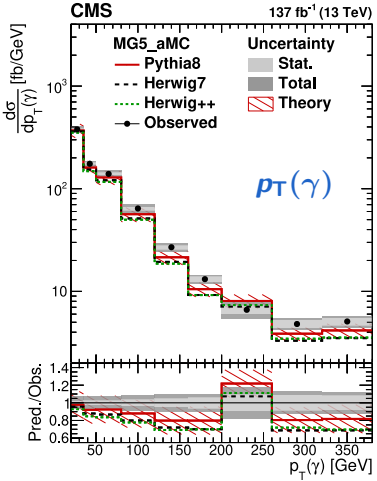
in agreement with NLO prediction: 773 ± 135 fb ±5.8%

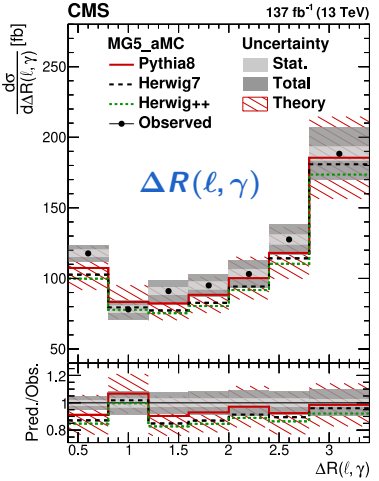
MG5_aMC@NLO+Pythia8

$t\bar{t}\gamma$ lepton+jets measurement: Differential cross section

arXiv:2107.01508 (submitted to JHEP)

- 1st step: template fit with separate signal strength for each bin, including CRs
- 2nd step: unregularized unfolding with TUnfold
- purity larger than 85%
- compared to MG5 prediction with different parton showers
- $|\eta(\gamma)|$





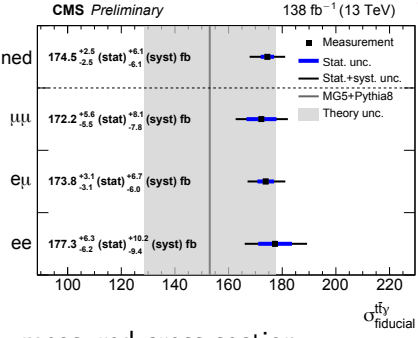
EFT interpretation discussed by Dennis Schwarz

$t\bar{t}\gamma$ dilepton measurement

CMS-PAS-TOP-21-004

CMS joker talk by Gianny Mestdach

- 2ℓ events, $=1$ photon, ≥ 1 b-jet
- fiducial region at particle-level, close to selection
- from data: nonprompt γ
- corrected from control region: $Z\gamma$
- inclusive cross section: template fit to $p_T(\gamma)$ per flavor
- differential cross sections: unregularized unfolding with TUnfold



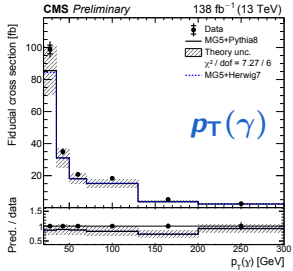
measured cross section:

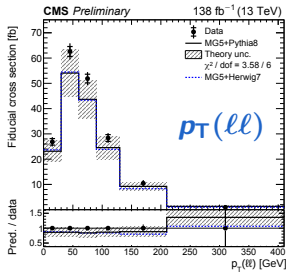
$174.4 \pm 2.5\,(\text{stat}) \pm 6.1\,(\text{syst})$ fb

±3.8%

in agreement with NLO prediction: 153 ± 25 fb

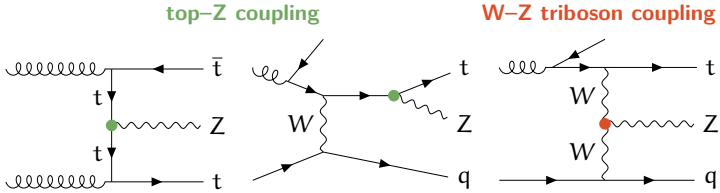
MG5_aMC@NLO+Pythia8





$|\eta(\gamma)|$, $\Delta R(\gamma,\ell)$, $\Delta R(\gamma,\ell_1)$, $\Delta R(\gamma,\ell_2)$, $\Delta R(\gamma,\text{b})$, $\Delta R(\ell,j)$, $|\Delta\eta(\ell\ell)|$, $\Delta\phi(\ell\ell)$, $p_T(\ell_1)+p_T(\ell_2)$, $p_T(j_1)$

Top quarks and a Z boson



- direct probe of electroweak top quark–Z boson coupling
  - sensitivity to anomalous couplings
  - important for EFT interpretations
- $t\bar{t}Z$: irreducible background in many searches (BSM, $t\bar{t}H$)
- tZq: electroweak production, also probes WWZ vertex
- differential cross sections to probe MC generators

$t\bar{t}Z$: incl. & diff.
JHEP 03 (2020) 056
$3\ell{+}4\ell$ events, 77.5 fb^{-1}

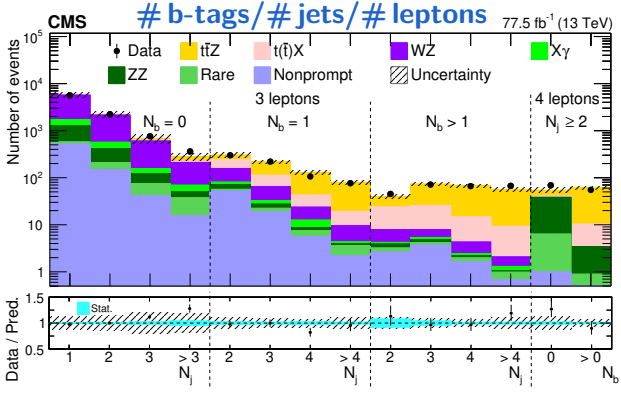
$t\bar{t}Z$: incl. & diff.
Eur. Phys. J. C 81 (2021) 737
$3\ell{+}4\ell$ events, 139 fb^{-1}

tZq: incl.
JHEP 07 (2020) 124
3ℓ events, 139 fb^{-1}

tZq: incl. & diff.
CMS-PAS-TOP-20-010
3ℓ events, 138 fb^{-1}

$t\bar{t}Z$ measurement: Inclusive cross section

JHEP 03 (2020) 056



- 3ℓ and 4ℓ events, binned by jet/b-tag multiplicity
- nonprompt from data
- diboson, Xγ validated in control regions
- tZq from MC

measured cross section: ±8.2%

$0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})$ pb

NLO+NNLL prediction: $0.86\,^{+0.08}_{-0.09}$ pb

Kulesza, Motyka, Schwartländer, Stebel, & Theeuwes, Eur. Phys. J. C 79 (2019) 249

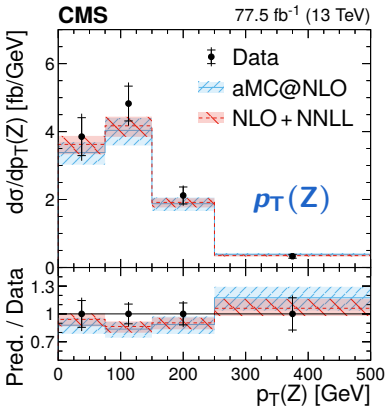
Source	Uncertainty range (%)	Correlated between 2016 and 2017	Impact on the tZ cross section (%)
Integrated luminosity	2.5	×	2
PU modeling	1–2	✓	1
Trigger	2	×	2
Lepton ID efficiency	4.5–6	✓	4
Jet energy scale	1–9	✓	2
Jet energy resolution	0–1	✓	1
btagging light flavor	0–4	×	1
btagging heavy flavor	1–4	×	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(t̄)X background	10–15	✓	3
Xγ 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

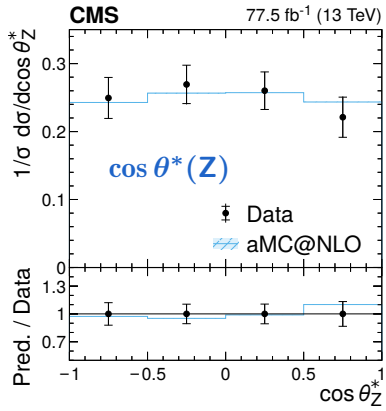
$t\bar{t}Z$ measurement: Differential cross sections

JHEP 03 (2020) 056

- 3ℓ events, ≥ 3 jets
- unregularized unfolding with TUnfold
- Z observables: excellent resolution, sensitive to anomalous t–Z couplings
- parton-level, absolute and normalized
- in agreement with NLO+NNLL prediction

Kulesza, Motyka, Schwartländer, Stebel, & Theeuwes, arXiv:1905.07815



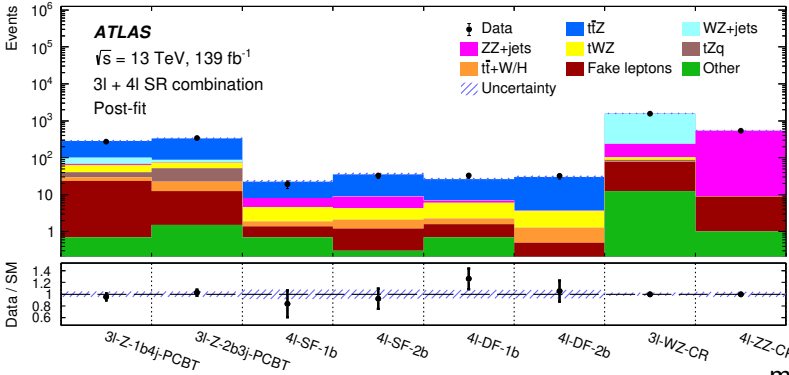


angle between ℓ^- and Z in Z rest frame

$t\bar{t}Z$ measurement: Inclusive cross section

Eur. Phys. J. C 81 (2021) 737

YSF talk by Laurynas Mince



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 + $E_{\mathrm{T}}^{\mathrm{miss}}$	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	1.6
$t\bar{t}Z$ μ_{f} and μ_{r} scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic	8.4
Data statistics	5.2
Total	10

- 3ℓ and 4ℓ events, binned by jet/b-tag multiplicity
- control regions for WZ, ZZ
- tWZ, tZq, … from MC
- fake leptons from data
- template fit to categories

measured cross section: ±9.5%

$0.99 \pm 0.05\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})$ pb

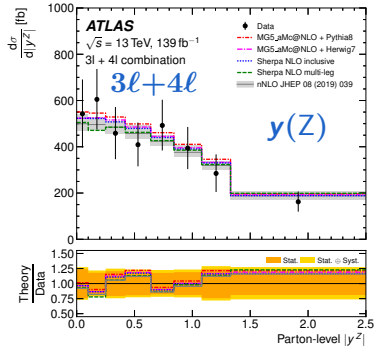
NLO+NNLL theory: $0.86\,^{+0.08}_{-0.09}$ pb

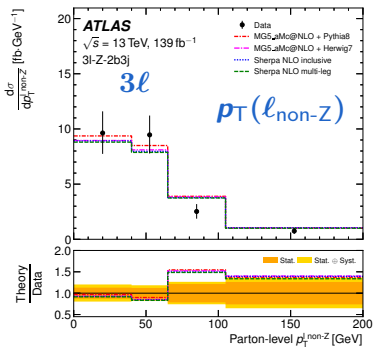
Kulesza, Motyka, Schwartländer, Stebel, & Theeuwes, Eur. Phys. J. C 79 (2019) 249

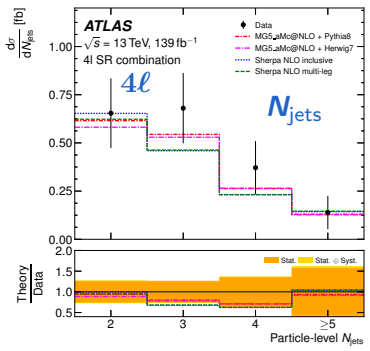
$t\bar{t}Z$ measurement: Differential cross sections

Eur. Phys. J. C 81 (2021) 737

YSF talk by Dominik Babal







- iterative Bayesian unfolding, 2–5 iter., RooUnfold
- $t\bar{t}$ reconstruction (partially for 4ℓ)
- binning optimized for statistics & migrations

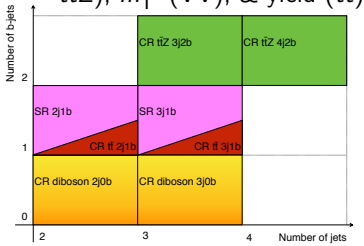
- $p_{T}(Z)$, $|\Delta\phi(Z, t_{lep})|$, $|\Delta y(Z, t_{lep})|$, $|\Delta\phi(t\bar{t}, Z)|$, $|\Delta\phi(\ell_{t}, \ell_{\bar{t}})|$, $p_{T}(t\bar{t})$
- compared to MC generators, and NLO/NLO+NNLL/nNLO theory

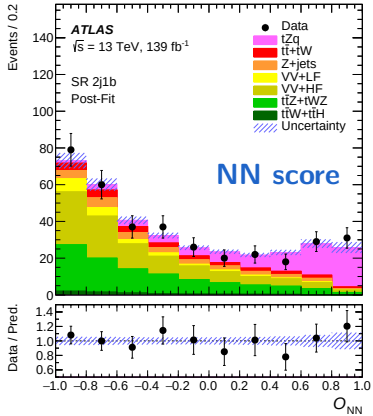
Broggio, Ferroglia, Frederix, Pagani, & Pecjak, JHEP 08 (2019) 039

tZq measurement

JHEP 07 (2020) 124

- 3ℓ events, 2–3 jets, $=1$ b-tag
- control regions: $t\bar{t}Z$, $t\bar{t}$, VV
- nonprompt from $2\ell 2b$ MC
- neural network: Z, top, and forward jet properties
- template fit: NN score (SR, $t\bar{t}Z$), m_T^W (VV), & yield ($t\bar{t}$)





Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and E_T^{miss} reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pile-up modelling	1.2
MC statistics	1.0
tZq modelling (QCD radiation)	0.8
tZq modelling (PDF)	0.7
Jet flavour tagging	0.4
Total systematic uncertainty	7.0
Data statistics	12.6
$t\bar{t}+tW$ and Z+jets normalisation	2.1
Total statistical uncertainty	12.9

cross section definition: $t\ell^+\ell^-q$ with $m(\ell\ell) > 30\,\text{GeV}$

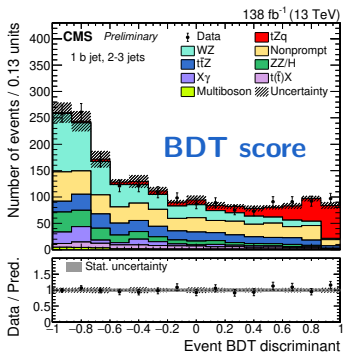
measured cross section: $97 \pm 13\,(\text{stat}) \pm 7\,(\text{syst})\,\text{fb}$ $\pm 14\%$

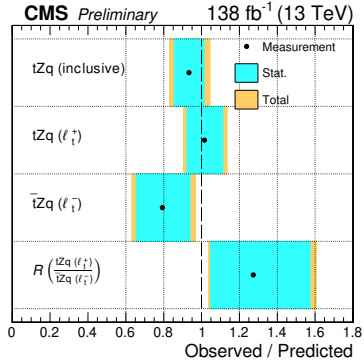
in agreement with NLO prediction: $102\,^{+5}_{-2}\,\text{fb}$ MG5_aMC@NLO

tZq measurement: Inclusive cross section

CMS-PAS-TOP-20-010

- 3ℓ events, binned by jet/b-tag multiplicity
- nonprompt from data
- control regions: VV, $t\bar{t}Z(4\ell)$, $Z\gamma$, nonprompt
- BDT: Z, top, and forward jet properties
- template fit to categories: BDT score, m_T^W, jet/b-tag multiplicity, or yield
- uncertainties: tZq modelling, nonprompt, WZ, b-tagging, $X\gamma$





cross section definition: $t\ell^+\ell^-q$ with $m(\ell\ell) > 30$ GeV

measured cross section: $87.9\,^{+7.5}_{-7.3}\,(\text{stat})\,^{+7.3}_{-6.0}\,(\text{syst})$ fb ±11%

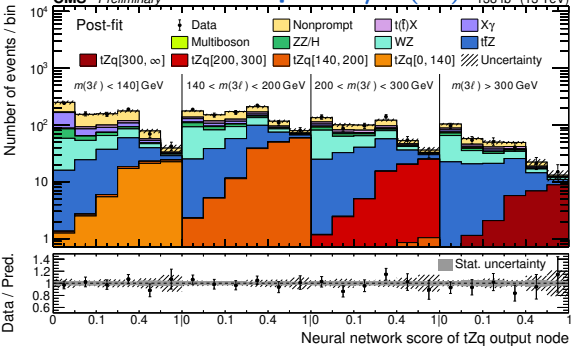
in agreement with NLO 5FS prediction: 94 ± 3 fb

MG5_aMC@NLO

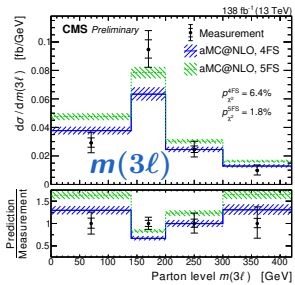
tZq measurement: Differential cross section

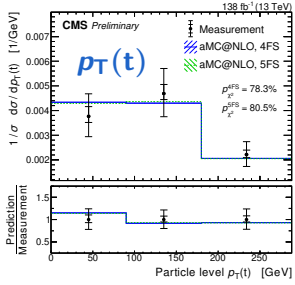
CMS-PAS-TOP-20-010

- multiclass NN
- template fit: observable × NN tZq score
- include CRs: NN $t\bar{t}Z$ score, m_T^W, e/b-tag multiplicity, or yield



- $p_T(Z)$, $\Delta\phi(\ell\ell)$, $p_T(\ell_t)$, $m(tZ)$, $\cos\theta^\star_{pol}$, $p_T(j')$, $|\eta(j')|$
- compared to NLO 4F & 5F predictions, mainly different normalization
- good agreement except for $m(3\ell)$





Summary

process		measured	diff.
fid. $t\bar{t}\gamma + tW\gamma$ (eμ)	ATLAS	39.6 fb $\pm$ 6.3%	✔
fid. $t\bar{t}\gamma$ (ℓ+jets)	CMS	800 fb $\pm$ 5.8%	✔
fid. $t\bar{t}\gamma$ (2ℓ)	CMS NEW!	174.4 fb $\pm$ 3.8%	✔
fid. $t\gamma q$ (μ+jets)	CMS	115 fb $\pm$ 30%	
$t\bar{t}Z$	CMS	950 fb $\pm$ 8.2%	✔
	ATLAS	990 fb $\pm$ 9.5%	✔
tZq, $Z \to \ell\ell$	ATLAS	97 fb $\pm$ 14%	
	CMS NEW!	87.9 fb $\pm$ 11%	✔
$t\bar{t}W$	CMS	770 fb $\pm$ 22%	
	ATLAS	870 fb $\pm$ 22%	

- LHC Run-2 data and refined analysis techniques allow for precision $t(\bar{t})V$ measurements
- Inclusive measurements become systematics limited
- Many differential measurements available, limited by statistics
- Stay tuned: More results are on their way!

$t\bar{t}V$ summary plot