Universidad de Oviedo
Universidá d'Uviéu
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Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

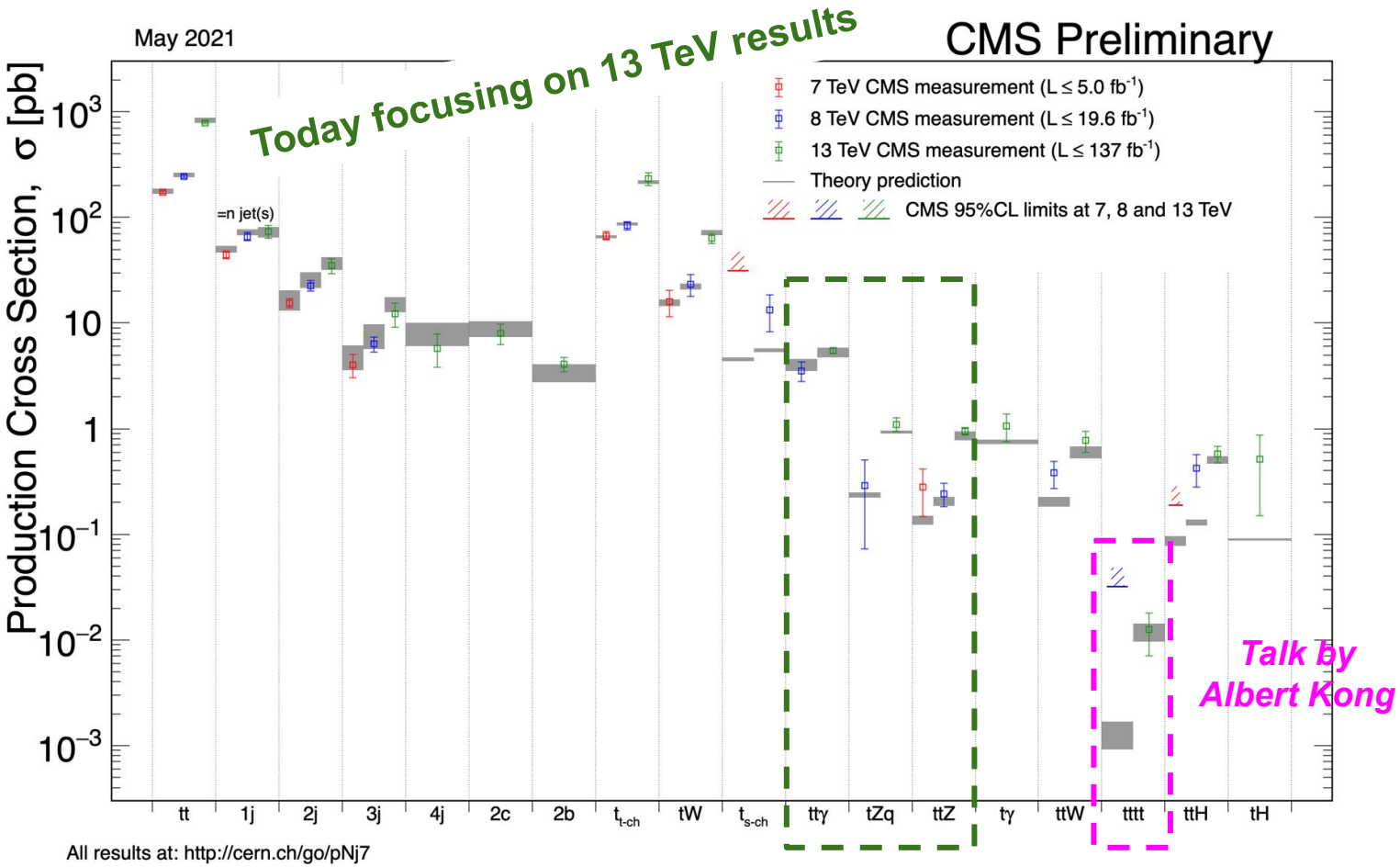
ATLAS EXPERIMENT

CMS
Compact Muon Solenoid

Associated Top Production at the LHC

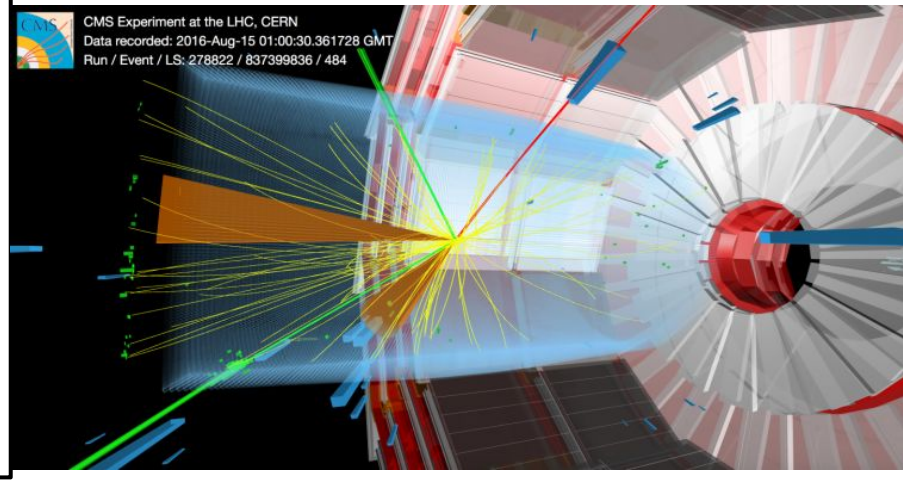
Barbara Alvarez Gonzalez, ICTEA and Universidad de Oviedo
on behalf of the ATLAS and CMS Collaborations

tt+X and t+X Sector



Introduction

- Rare top production modes become fully accessible with Run2 data
- **ttV** among the **most massive** signatures that can be studied at the LHC with **high precision**
- **ttZ** production is the **most sensitive** process for directly measuring the coupling of the top quark to the Z boson
- Receive significant enhancements in BSM
- **ttW and ttZ** important *backgrounds* for searches and measurements such as **ttH** in multilepton final states

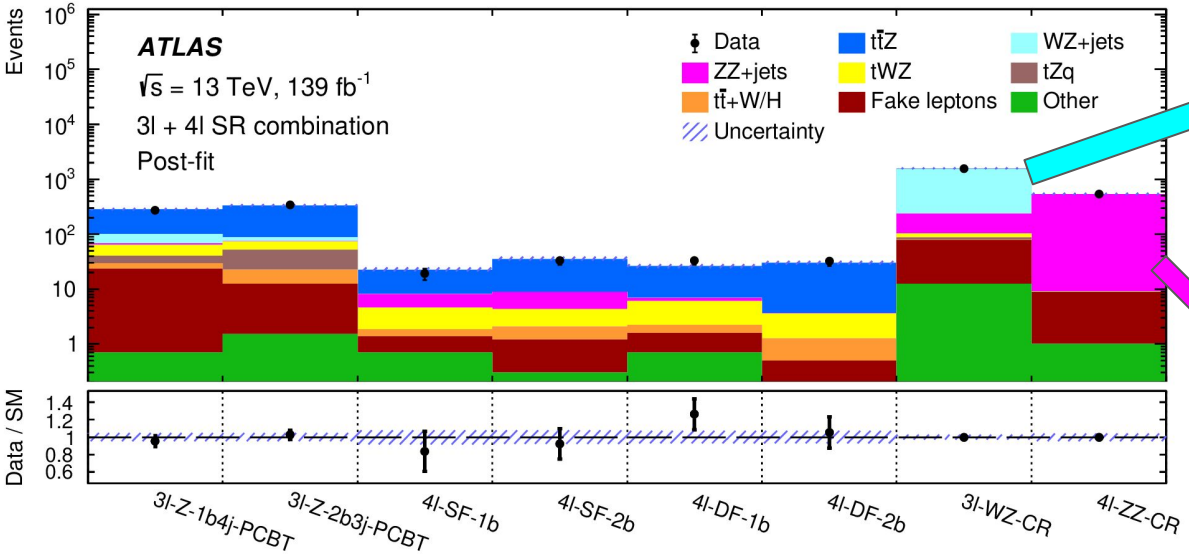


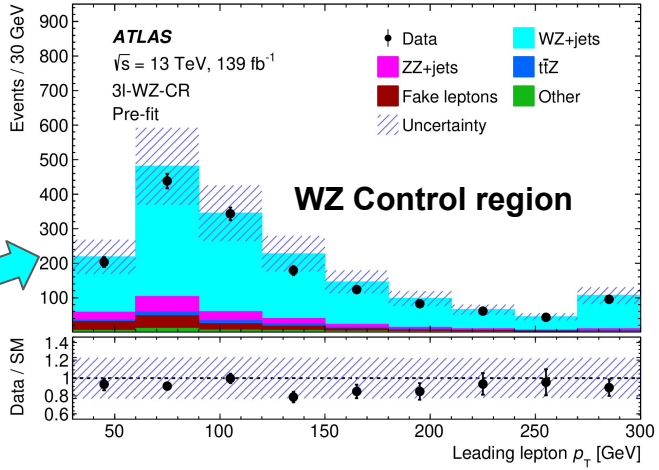
Event display of a collision consistent with tZq production

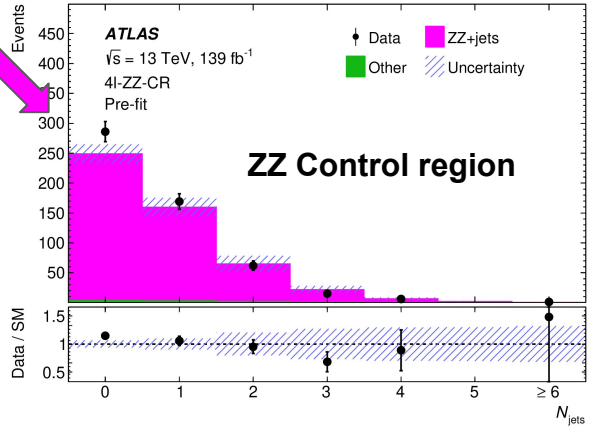
2103.12603 submitted to EPJC

ttZ Inclusive - 139 fb^{-1}

- Targeting final states with 3 or 4 isolated leptons (e or μ)
- Further categorization based on the N**jets** & N **btagged jets**







- Main **backgrounds** are WZ/ZZ + jets and fake leptons
- Main **syst.** unc.: parton shower, tZ/WZ/ZZ modeling, b-tagging

2103.12603

ttZ Inclusive and Differential - 139 fb^{-1}

Channel	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$
Combination ($3\ell + 4\ell$)	$1.19 \pm 0.06\,(\text{stat.}) \pm 0.10\,(\text{syst.})$

Theory calculation (NLO+NNLL)

σ_{ttZ} = 0.86 ± 0.08 (scale) ± 0.02 (PDF) pb

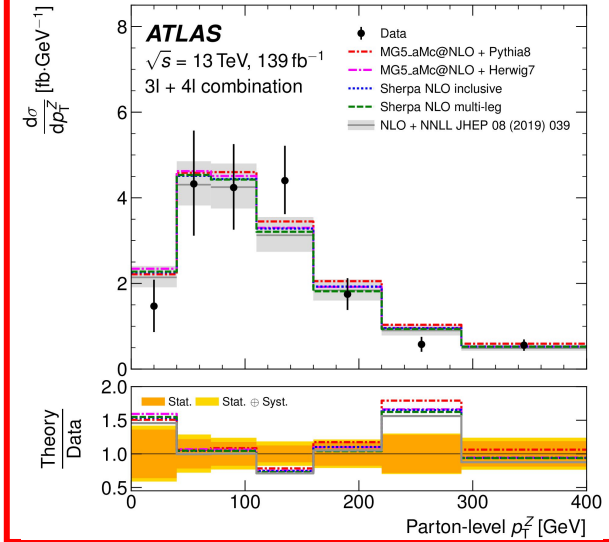
Eur. Phys. J. C 80 (2020) 428

σ_{ttZ} = 0.99 ± 0.05 (stat.) ± 0.08 (syst.) pb

*Result in **agreement** with the most precise theoretical predictions*

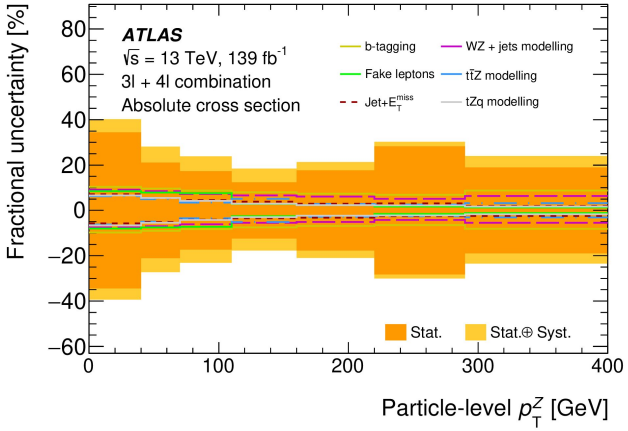
Differential Result

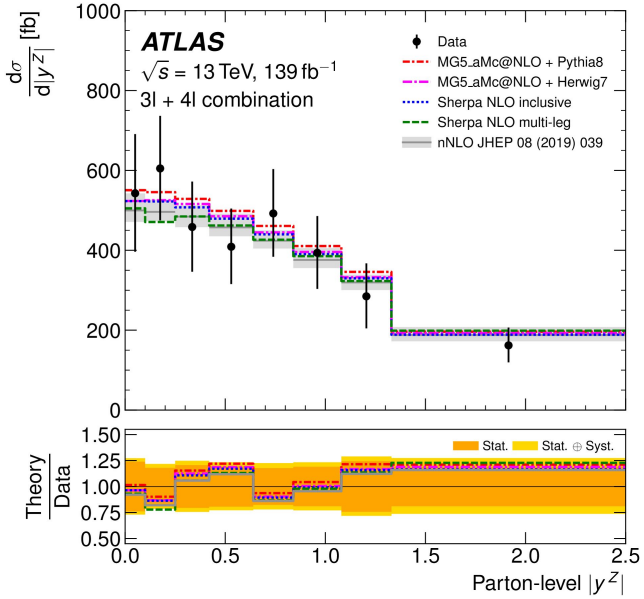
10 observables probing the kinematics of the ttZ



Good agreement observed

Statistically limited





JHEP 03 (2020) 056

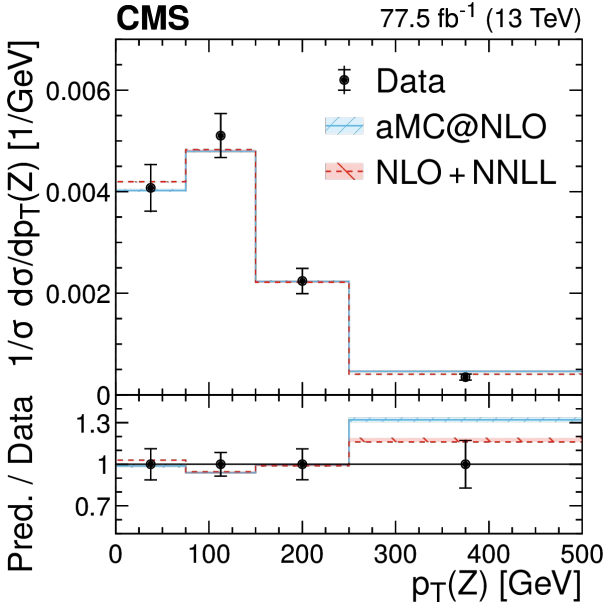
ttZ Inclusive and Differential - *77.5 fb^{-1}*

- Exactly **3** leptons or exactly **4** leptons
- Main bkg from t(t)+ *W, Z or H*
- **Main syst:** lepton ID, bkg normalization

Measured cross section more precise than NLO prediction

σ_{ttZ} = **0.95 ± 0.05 (stat) ± 0.06 (syst) pb**

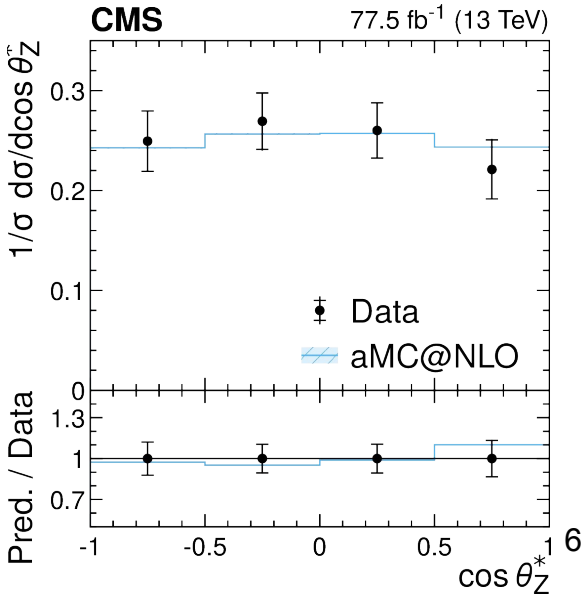
- Differential xs measured as a function of the $p_T(Z)$ and $\cos\theta^*_Z$
- **Main syst:** lepton ID, jet energy, non-prompt background



Signal enriched region:

- Exactly 3 leptons
- At least 3 jets
- At least 1 b-tagged jet

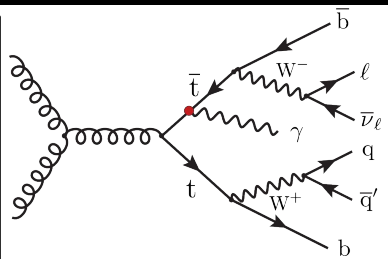
$\cos\theta^*_Z$ (between the negative charged lepton and the Z candidates in the Z rest frame)

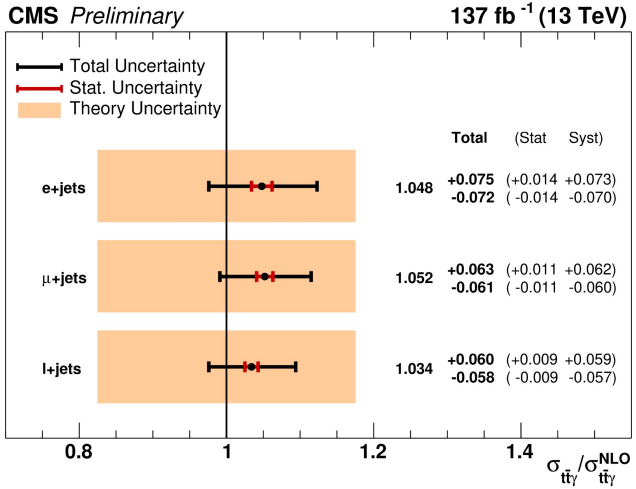


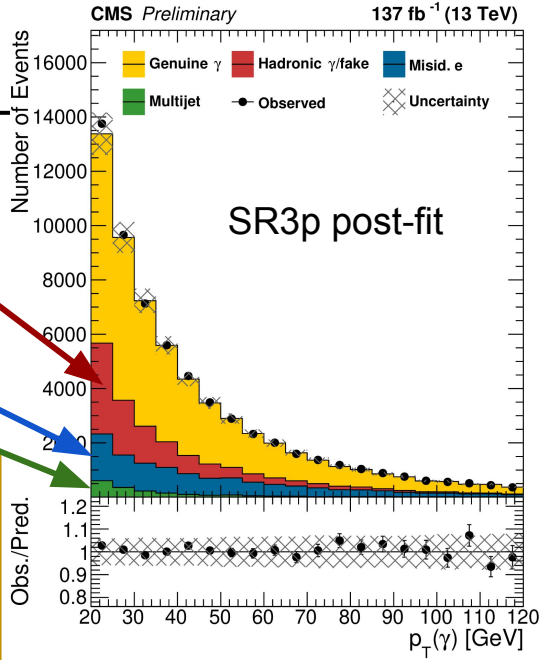
$t\bar{t}\gamma$ Inclusive - 137 fb^{-1}

CMS-PAS-TOP-18-010

- 1 isolated highly energetic lepton (e or μ), with ≥ 3 jets and 1 isolated γ
- The **photon** may be emitted in production, from the top, as well as from decay products of the top
- Simultaneous likelihood fits in **12 SRs and 34 CRs**
- **Main syst. unc.**: ttγ modeling, background estimation, JES







exploited in an ABCD method

electrons misidentified as γ obtained from CRs

from data loosening isolation criteria

Inclusive cross section with $p_T(\gamma) \geq 20$ GeV:

$\sigma_{t\bar{t}\gamma}$ = 800 ± 46 (syst) ± 7 (stat) fb

In good agreement with theory NLO prediction

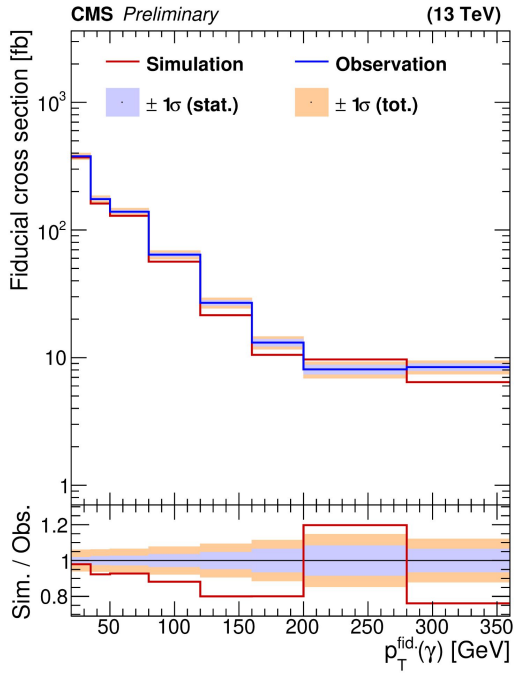
Theory $\sigma_{t\bar{t}\gamma}$ (NLO) = 773 ± 135 fb
(@ MadGraph5+aMC@NLO)

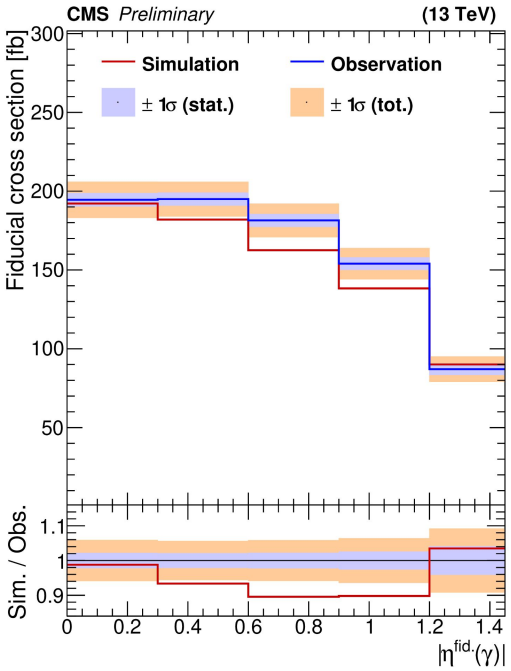
$t\bar{t}\gamma$ Differential - 137 fb^{-1}

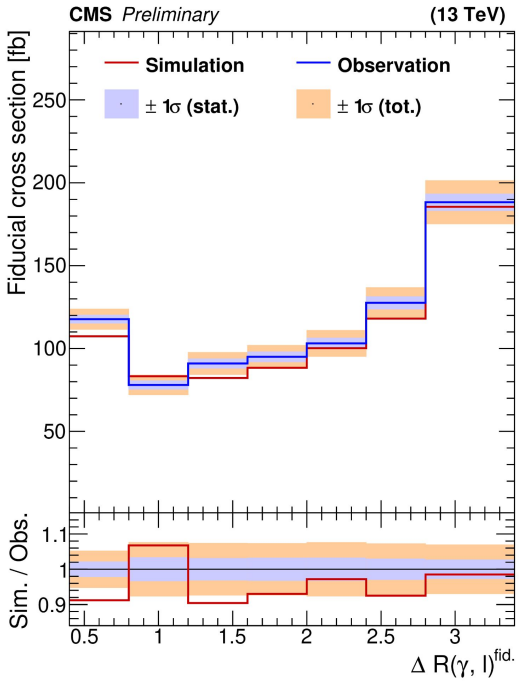
CMS-PAS-TOP-18-010

- **Particle level** unfolding as a function of $p_T(\gamma)$, $|\eta(\gamma)|$, and $\Delta R(l, \gamma)$
- Results obtained simultaneously for the e and μ channels, the 3 and ≥ 4 jet bins
- All results in **agreement** with predictions

The EFT Interpretation in Juan Rodrigo's talk







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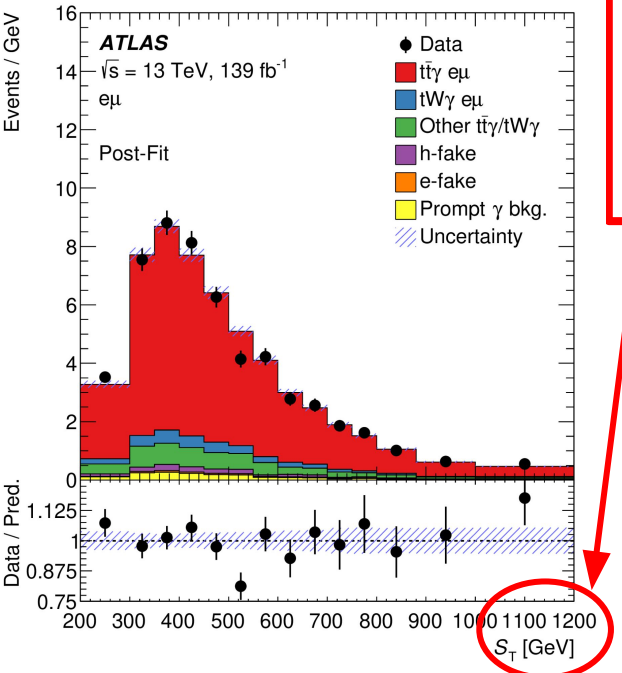
$t\bar{t}\gamma$+$tW\gamma$ Fiducial - 139 fb^{-1}

ATLAS EXPERIMENT

- Events with exactly 1 γ, 1 e and 1 μ of opposite sign, ≥ 2 jets, ≥ 1 b-tagged
  - **High purity, no MVA is needed**
  - $E_T(\gamma)$>20 GeV for **fiducial region**



- Profile **likelihood fit** to the distribution of scalar sum (**ST**) of all transverse momenta in the event

Fiducial region also requires:

- ΔR(γ,ℓ) > 0.4
- ΔR(e,μ) > 0.4
- ΔR(b,b) > 0.4
- ΔR(b,ℓ) > 0.4

	Events
$t\bar{t}\gamma$ $e\mu$	2391 ± 130
$tW\gamma$ $e\mu$	156 ± 15
Other $t\bar{t}\gamma/tW\gamma$	279 ± 15
h-fake	78 ± 40
e-fake	23 ± 12
Prompt γ bkg.	87 ± 40
Total	3014 ± 160
Data	3014

Main systematic unc.: *PS and ISR* signal modeling

Theory σ_{fid}(NLO) = 38 $^{+1}_{-2}$ fb
JHEP 10 (2018) 158

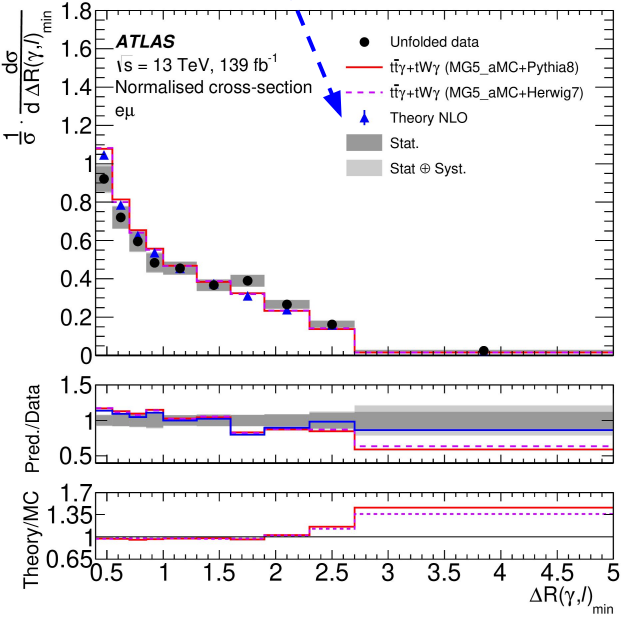
The fiducial cross section is measured to be

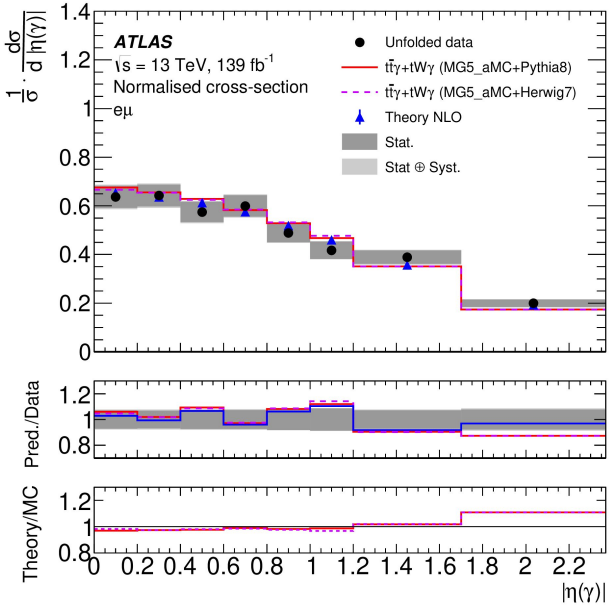
σ_{fid} = 39.6 ± 0.8 (stat) $^{+2.6}_{-2.2}$ (syst) fb = 39.6$^{+2.7}_{-2.3}$fb

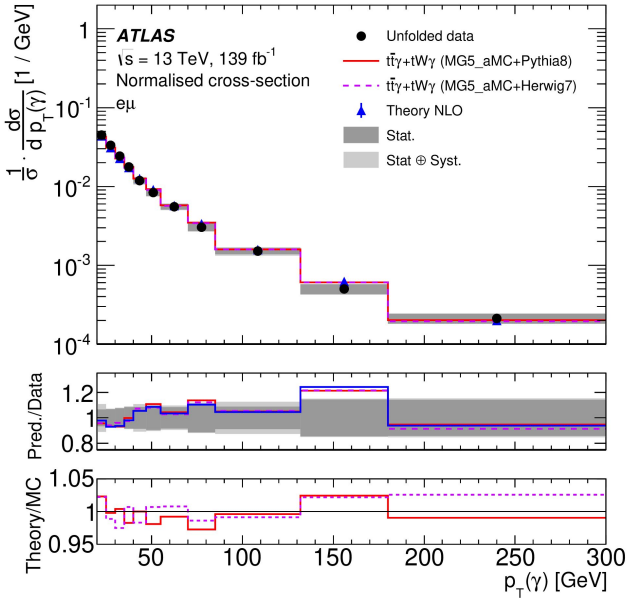
JHEP 09 (2020) 049

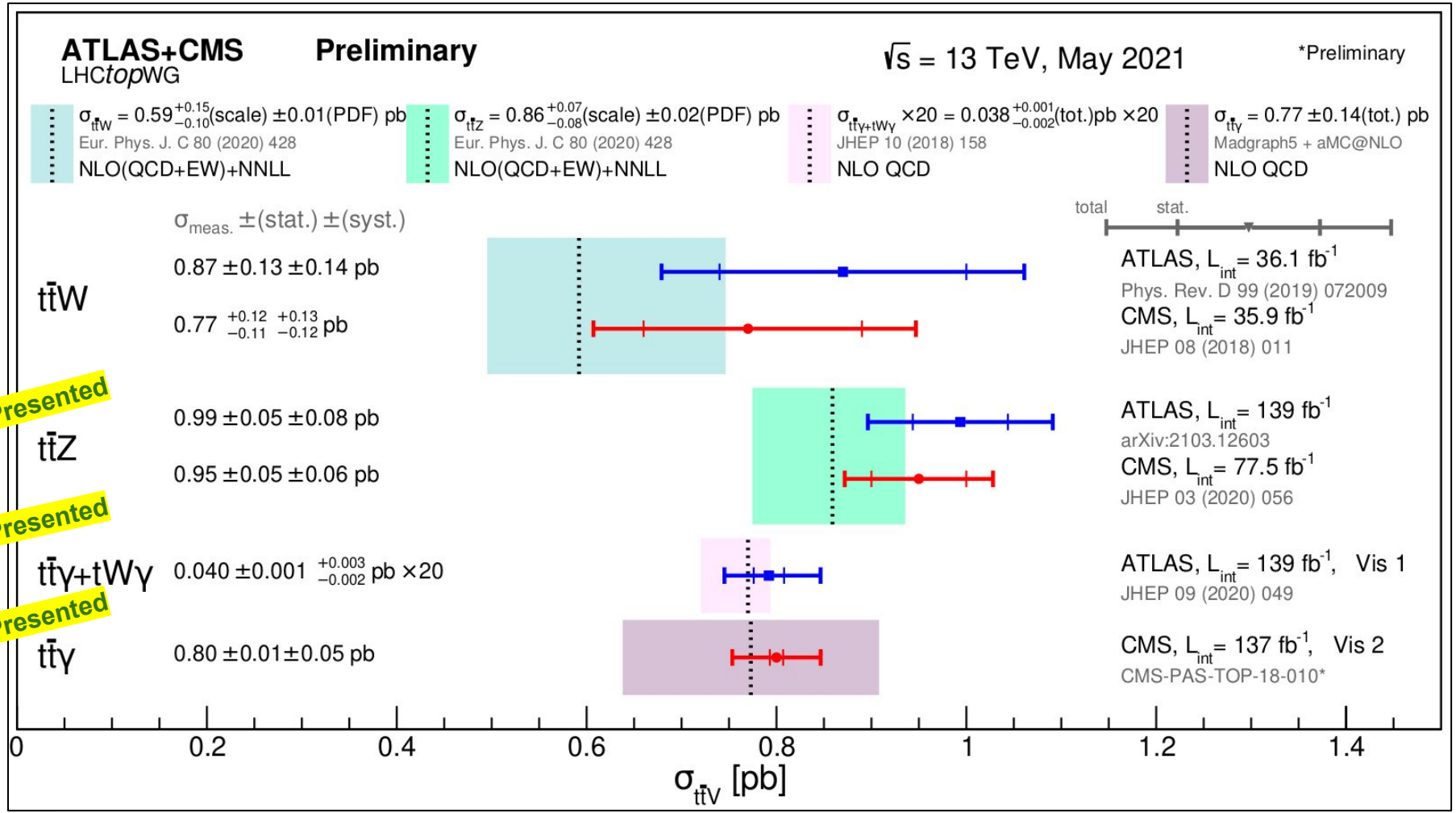
$t\bar{t}\gamma$+$tW\gamma$ Differential - 139 fb^{-1}

- Cross sections as functions of *photon kinematic variables*, *angular variables* related to the photon and the leptons, and *angular separations* between the two leptons in the event
- **NLO calculations**: First full computation at **NLO** in QCD for **bWbWγ**, including all resonant and non-resonant diagrams, interferences, and off-shell effects of the tops and the W bosons
- All measurements are in **agreement** with the predictions from the Standard Model





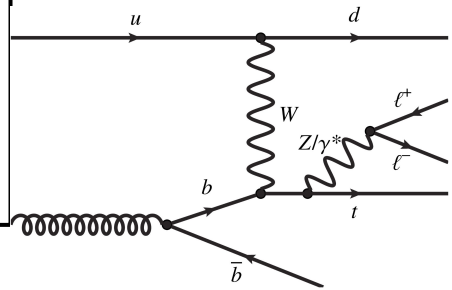


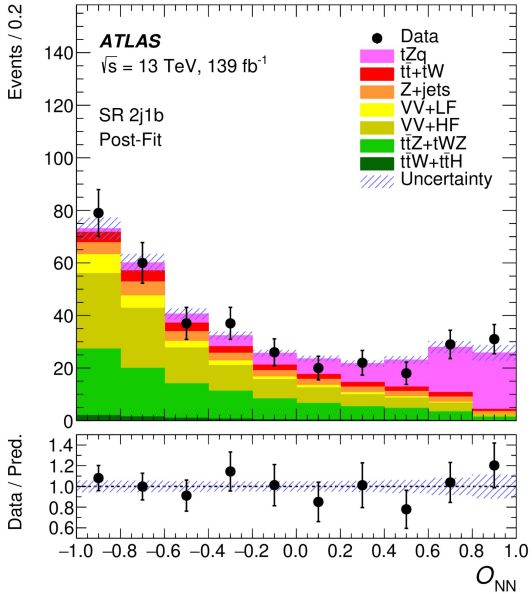

ATLAS+CMS
LHCtopWG
Preliminary
√s = 13 TeV, May 2021
*Preliminary
σ_tt̄W = 0.59 +0.15 −0.10 (scale) ±0.01(PDF) pb
Eur. Phys. J. C 80 (2020) 428
NLO(QCD+EW)+NNLL
σ_tt̄Z = 0.86 +0.07 −0.08 (scale) ±0.02(PDF) pb
Eur. Phys. J. C 80 (2020) 428
NLO(QCD+EW)+NNLL
σ_tt̄γ+tWγ ×20 = 0.038 +0.001 −0.002 (tot.)pb ×20
JHEP 10 (2018) 158
NLO QCD
σ_tt̄γ = 0.77 ±0.14(tot.) pb
Madgraph5 + aMC@NLO
NLO QCD
σ_meas. ±(stat.) ±(syst.)
total
stat.
tt̄W
0.87 ±0.13 ±0.14 pb
0.77 +0.12 −0.11 +0.13 −0.12 pb
ATLAS, L_int = 36.1 fb^-1
Phys. Rev. D 99 (2019) 072009
CMS, L_int = 35.9 fb^-1
JHEP 08 (2018) 011
Presented
tt̄Z
0.99 ±0.05 ±0.08 pb
0.95 ±0.05 ±0.06 pb
ATLAS, L_int = 139 fb^-1
arXiv:2103.12603
CMS, L_int = 77.5 fb^-1
JHEP 03 (2020) 056
Presented
tt̄γ+tWγ
0.040 ±0.001 +0.003 −0.002 pb ×20
ATLAS, L_int = 139 fb^-1, Vis 1
JHEP 09 (2020) 049
Presented
tt̄γ
0.80 ±0.01±0.05 pb
CMS, L_int = 137 fb^-1, Vis 2
CMS-PAS-TOP-18-010*
0
0.2
0.4
0.6
0.8
1
1.2
1.4
σ_tt̄V [pb]

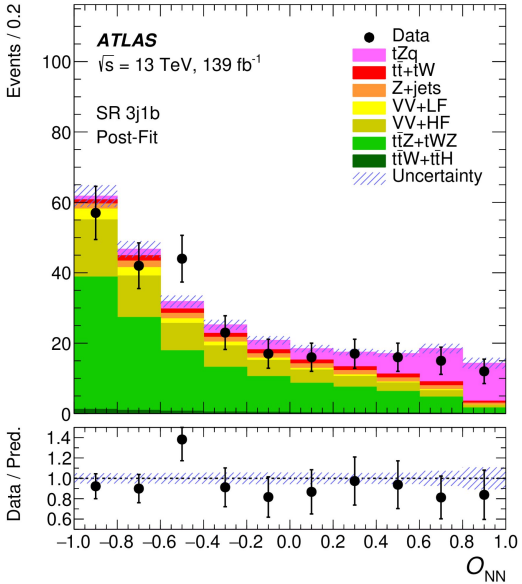
JHEP 07 (2020) 124

tZq Inclusive - 139 fb^{-1}

- Measured in the **trilepton** channel
- 3 leptons (e or μ), 2 or 3 jets and exactly 1 b-tagged jet
- The main backgrounds are from ***ttZ*** and **diboson** production
- **NNs** are used to improve the background rejection and extract the signal







Measured xs for $t\ell^+\ell^-q$, including non-resonant dilepton pairs with $m_{\ell^+\ell^-} > 30$ GeV

$\sigma(tZ(\ell^+\ell^-)q) = 97 \pm 13\ (\text{stat}) \pm 7\ (\text{syst})$ fb

Result consistent with the SM prediction

Theory $\sigma(\text{NLO}) = 102\ ^{+5.3}_{-1.3}$ (scale) ± 1.0 (PDF) fb

MadGraph5+aMC@NLO

CMS-PAS-TOP-20-010

tZq Inclusive - 138 fb^{-1}

- 3 leptons (e or μ), ≥ 2 jets and ≥ 1 b-tagged jet
- Events are divided into 3 categories based on N_{jets} & $N_{b\text{-}tags}$
- In each of these categories, a dedicated **BDT** is trained
- **Main discriminating features:** presence of a forward jet
- Simultaneous template fit to **BDT** outputs and yields of control regions is performed to measure tZq signal strength

$$\sigma(tZ(\ell^+\ell^-)q) = 87.9\ ^{+7.5}_{-7.3}\ (\text{stat})\ ^{+7.3}_{-6.0}\ (\text{syst})\ \text{fb}$$

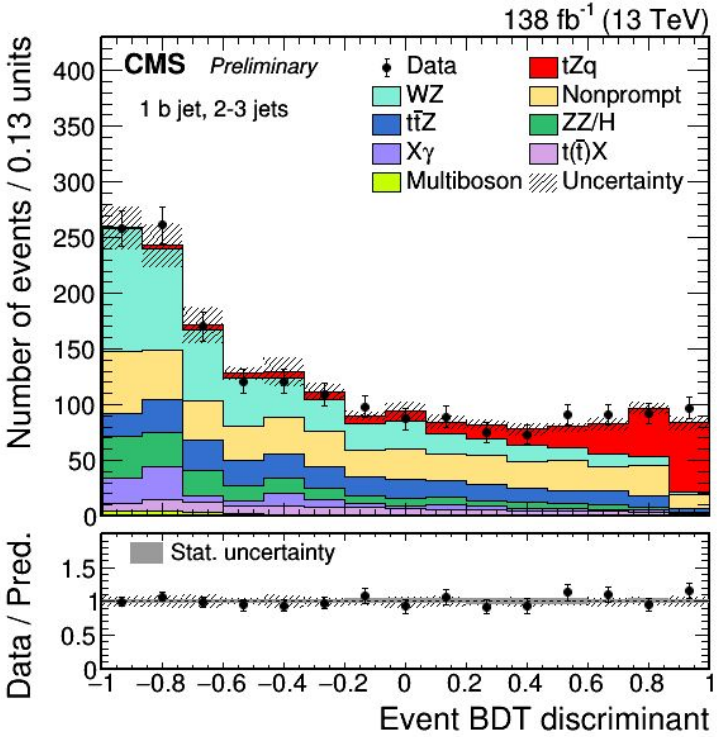
$$[m(\ell^+\ell^-) > 30\ \text{GeV}/c^2]$$

- **Main systematics:** bkg normalization, signal renormalization and factorization and b-tagging

Result consistent with the SM prediction

Theory σ(NLO) = $94.2\ ^{+1.9}_{-1.8}$ (scale) ± 2.5 (PDF) fb

MadGraph5+aMC@NLO

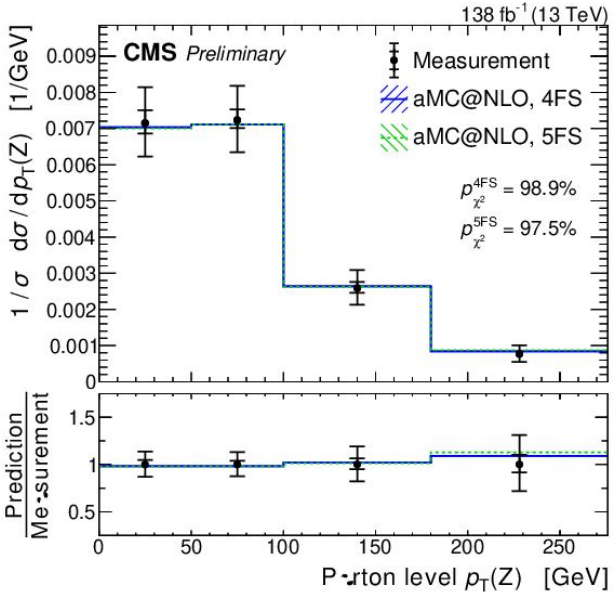


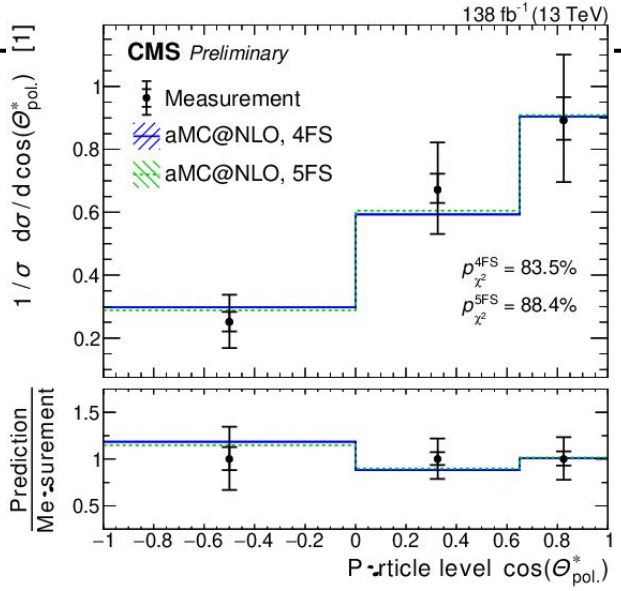
Top and antitop cross section measured separately and their ratio **(plot in back-up)**

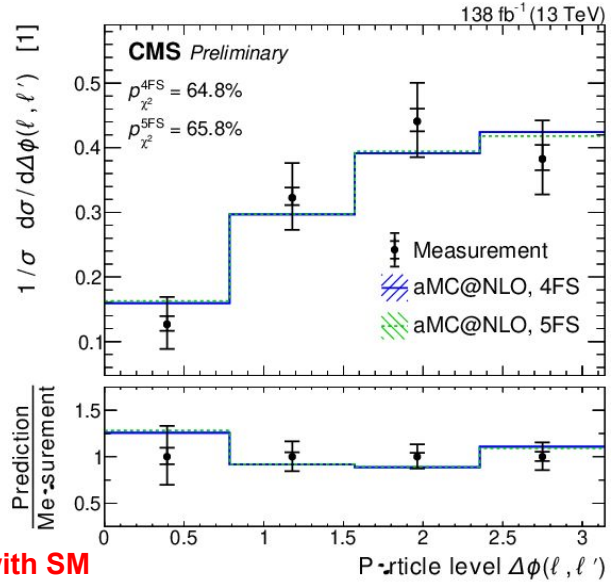
CMS-PAS-TOP-20-010

tZq Differential- 138 fb^{-1}

- Signal region inclusive in N_{jets} & $N_{b\text{-}tags}$ and **multiclass NN** discrimination
- Particle and parton level differential cross sections: $p_T(Z)$, $p_T(j)$, $|\eta(j)|$, $\Delta\phi(l,l')$, $p_T(l_t)$, m(3l), $p_T(t)$, m(t,Z) & cos(θ*pol)
- Compared to both **4FS** and **5FS** prediction
- Good agreement observed







Spin asymmetry measurement in agreement with SM

$$A_\ell = 0.58\ ^{+0.15}_{-0.16}\ (\text{stat})\ \pm 0.06\ (\text{syst})$$

Summary

- The large amount of LHC data recorded up to date allows probing very rare SM processes, very small production cross sections
- Rare processes with top quarks are **sensitive** to beyond the SM interactions
- Many processes are explored for the first time at the LHC — and some presented analyses do not use the full 13 TeV data sample yet
- All results are in good agreement with **SM** predictions
- **New results since last LHCP:**
  - CMS ttɣ and tZq: **CMS-PAS-TOP-18-010**, **CMS-PAS-TOP-20-010**
  - ATLAS ttZ and tZq: **JHEP 09 (2020) 049**, **JHEP 07 (2020) 124**
- **Stay tuned:** New results with more data are on their way…

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

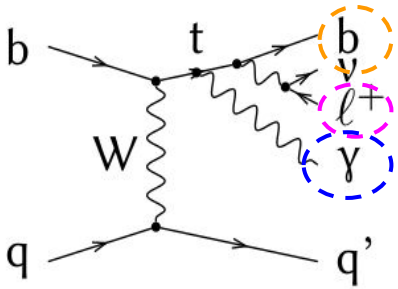
THANK YOU

Additional Material

tγ Evidence

Phys. Rev. Lett. 121, 221802 (2018)

- First evidence of **tγ** production
- Single-muon channel:
  - exactly 1 **muon**, 1 **photon**, ≥ 2 jets & exactly 1 **b-tagged jet**
  - p_T^{miss} > 30 GeV
- Fake photon background: data-driven, exploiting independence of photon isolation and shower shape
- **Main systematic uncertainties:** jet energy scale, signal modeling, Zγ+jets and b-tagging



Process	Event yield
$t\bar{t}+\gamma$	1401 ± 131
$W\gamma$+jets	329 ± 78
$Z\gamma$+jets	232 ± 55
Misidentified photon	374 ± 74
$t\gamma$ (s- and tW-channel)	57 ± 8
$VV\gamma$	8 ± 3
Total background	2401 ± 178
Expected signal	154 ± 24
Total SM prediction	2555 ± 180
Data	2535

tγ Evidence

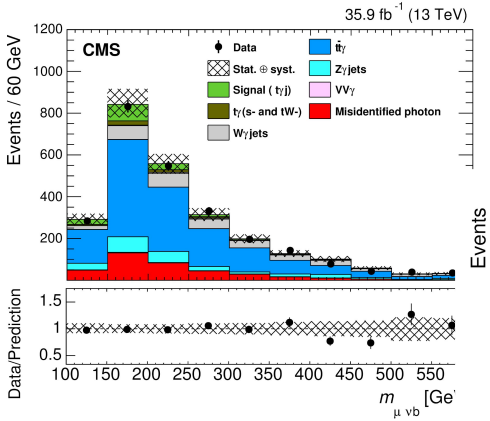
Phys. Rev. Lett. 121, 221802 (2018)

- Template fit to kinematic **B**oosted **D**ecision **T**ree classifier distribution
- **Fiducial** region: $p_{T,\gamma} > 25$ GeV, $|\eta_\gamma| < 1.44$ and $\Delta R(\{\mu, b, j\}, \gamma) > 0.5$

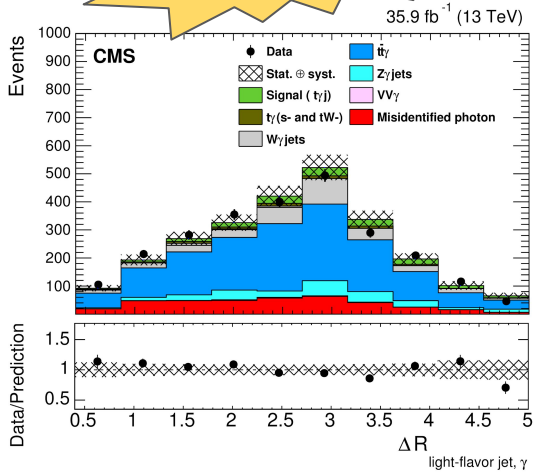
1st Evidence 4.4 σ

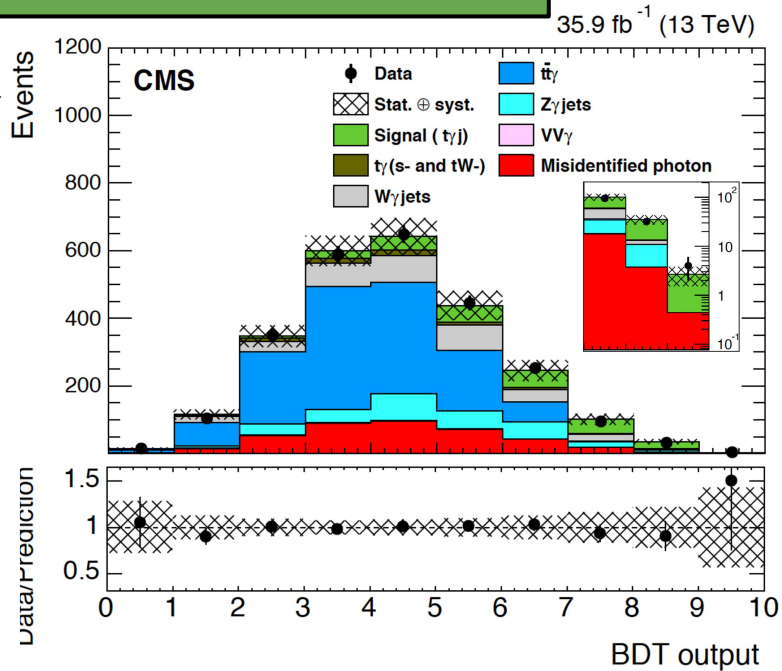
Fiducial xs: $\sigma(pp \rightarrow t\gamma q) \times BR(t \rightarrow \mu\nu b) = 115 \pm 17$ (stat) ± 30 (syst) fb

SM: 81 ± 4 fb



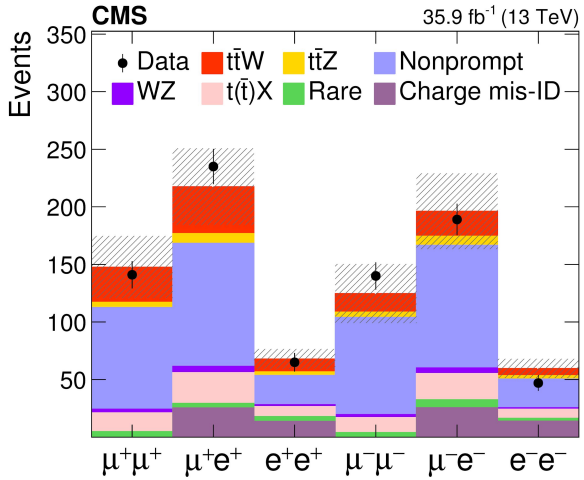
Some Inputs to the BDT



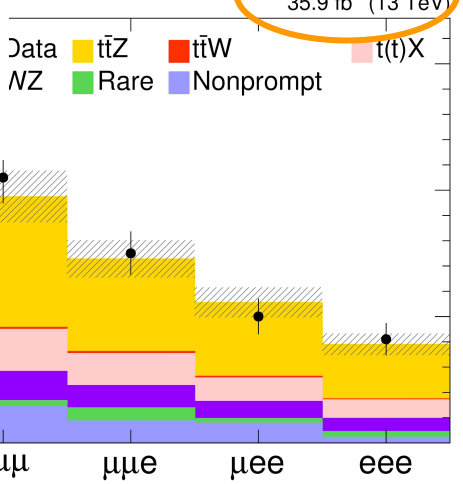


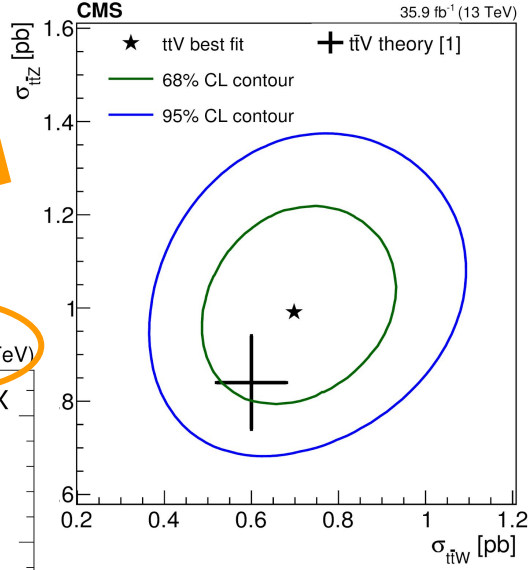
ttW and ttZ production

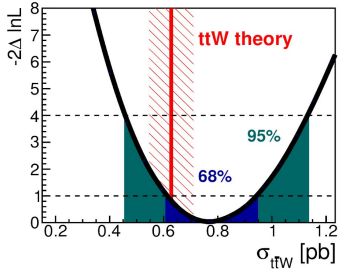
Measurement performed in the SS dilepton (ttW), 3 and 4-lepton final states (ttZ)

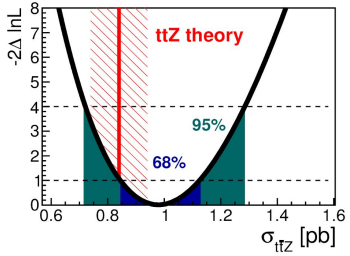


JHEP 08 (2018) 011









Mains syst: luminosity, lepton ID, trigger, jet energy and non-prompt bkg

ttW: 4.5 σ (5.3 σ) obs. (exp.)

$$\sigma(pp \to t\bar{t}W) = 0.77^{+0.12}_{-0.11}\,(\text{stat})^{+0.13}_{-0.12}\,(\text{syst})\,\text{pb}$$

ttZ > 5 σ

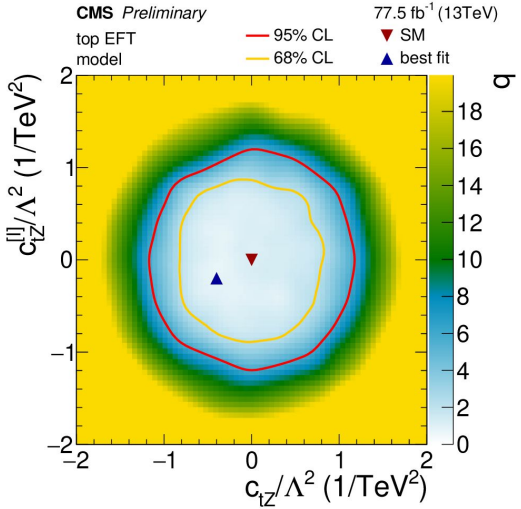
$$\sigma(pp \to t\bar{t}Z) = 0.99^{+0.09}_{-0.08}\,(\text{stat})^{+0.12}_{-0.10}\,(\text{syst})\,\text{pb}$$

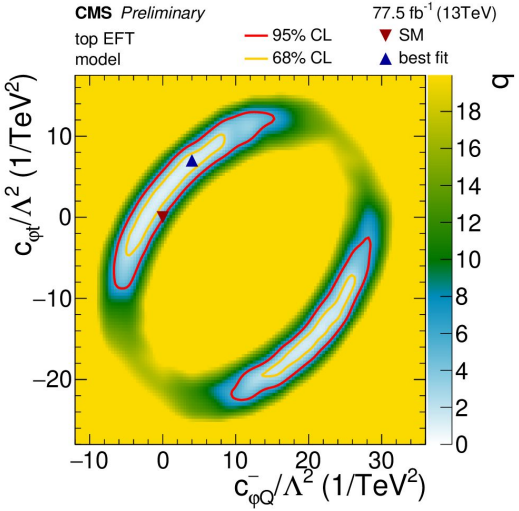
Inclusive ttZ result

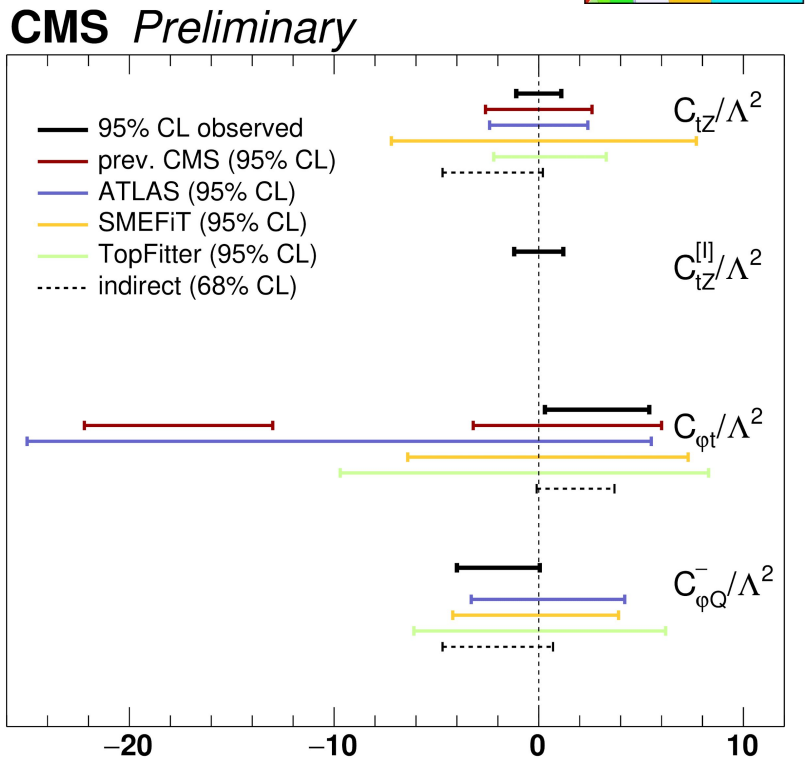
Search for anomalous couplings and EFT interpretation

CMS-PAS-TOP-18-009

- Different regions defined by $p_T(Z)$ and $\cos\theta^*_Z$ probes 4 dim-6 operators
- New stringent limits on the **anomalous couplings** of the top quark to the Z boson are obtained, including estimates of Wilson coefficients of SM EFT







Inclusive ttZ result

Source	Uncertainty range (%)	Correlated in 2016 and 2017	Impact on the ttZ 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
B tagging light flavor	0–4	×	1
B tagging 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
$t(\bar{t})X$ bg.	10–15	✓	3
$X\gamma$ background	20	✓	1
Nonprompt background	30	✓	< 1
Rare SM background	50	✓	2
Stat. unc. in nonprompt bg.	5–50	×	< 1
Stat. unc. in rare SM bg.	5–100	×	< 1
Total uncertainty			7

CMS-PAS-TOP-18-009

Inclusive ttZ result

Definition of the signal and control regions

CMS-PAS-TOP-18-009

N_ℓ	N_j	N_b	N_Z	$p_T(Z)$ (GeV)	$-1 \leq \cos(\theta^*) < -0.6$	$-0.6 \leq \cos(\theta^*) < 0.6$	$0.6 \leq \cos(\theta^*)$
3	≥ 3	≥ 1	1	0–100	SR1	SR2	SR3
				100–200	SR4	SR5	SR6
				200–400	SR7	SR8	SR9
				≥ 400	SR10	SR11	SR12
4	≥ 1	≥ 1	1	0–100	SR13		
				100–200	SR14		
				≥ 200	SR15		
3	≥ 1	0	1	0–100	CR1	CR2	CR3
				100–200	CR4	CR5	CR6
				200–400	CR7	CR8	CR9
				≥ 400	CR10	CR11	CR12
4	≥ 1	≥ 0	2	0–100	CR13		
				100–200	CR14		
				≥ 200	CR15		

Inclusive ttZ result

CMS-PAS-TOP-18-009

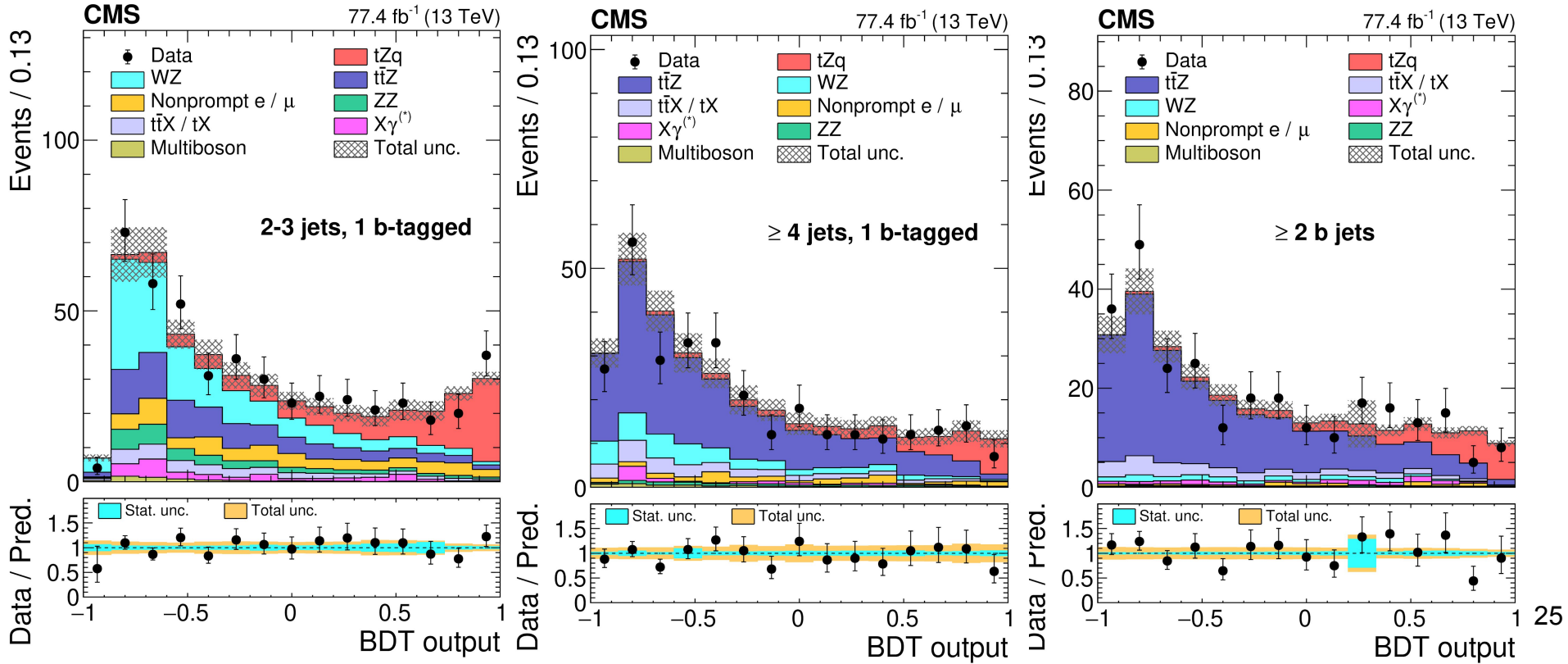
Expected and observed 68% and 95% CL intervals from the ttZ measurement for the listed Wilson coefficients

Coefficient	Expected		Observed		Previous CMS constraints		Indirect constraints
	68% CL	95% CL	68% CL	95% CL	Exp, 95% CL	Obs, 95% CL	68% CL
c_{tZ}/Λ^2	$[-0.7, 0.7]$	$[-1.1, 1.1]$	$[-0.8, 0.5]$	$[-1.1, 1.1]$	$[-2.0, 2.0]$	$[-2.6, 2.6]$	$[-4.7, 0.2]$
$c_{tZ}^{[I]}/\Lambda^2$	$[-0.7, 0.7]$	$[-1.1, 1.1]$	$[-0.8, 1.0]$	$[-1.2, 1.2]$	–	–	–
$c_{\phi t}/\Lambda^2$	$[-1.6, 1.4]$	$[-3.4, 2.8]$	$[2.2, 4.7]$	$[0.7, 5.9]$	$[-20.2, 4.0]$	$[-22.2, -13.0]$ $[-3.2, 6.0]$	$[-0.1, 3.7]$
$c_{\phi Q}^{-}/\Lambda^2$	$[-1.1, 1.1]$	$[-2.1, 2.2]$	$[-3.0, -1.0]$	$[-4.0, 0.0]$	–	–	$[-4.7, 0.7]$

tZq Observation

Phys. Rev. Lett. 122, 132003 (2019)

Simultaneous template fit to BDT outputs and yields of control regions



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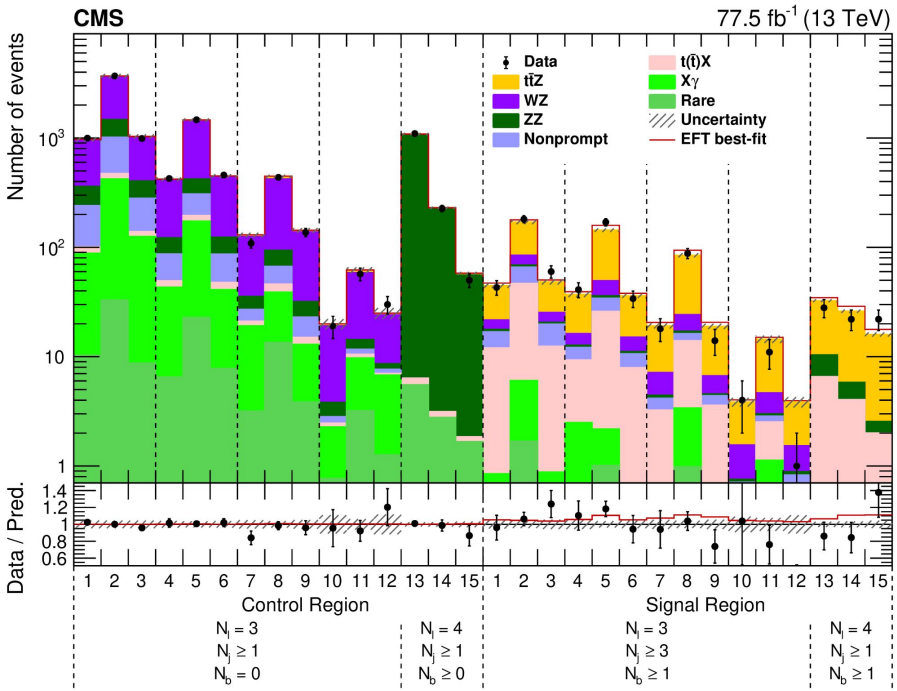
ttZ Inclusive - 77.5 fb^{-1}

- Update the previous result adding **2017 data,** similar strategy to previous analysis
- Exactly **3** leptons or exactly **4** leptons
- Main backgrounds are from at least one top quark in association with a *W, Z or H*
- Improved lepton ID and more incl. triggers
- **Main syst:** lepton ID, bkg normalization

Process	$\mu\mu\mu(\mu)$	$e\mu\mu(\mu)$	$ee\mu(\mu/e)$	$eee(e)$	Total
$t\bar{t}Z$	143 ± 7.1	122 ± 6.1	112 ± 5.5	77 ± 3.9	455 ± 22
$t\bar{t}H$	4.1 ± 0.5	3.5 ± 0.4	3.3 ± 0.4	2.1 ± 0.3	13 ± 1.6
$t(\bar{t})X$	34 ± 4.2	28 ± 3.4	24 ± 2.9	18 ± 2.3	105 ± 13
WZ	18 ± 4.7	15 ± 4.2	10 ± 2.8	11 ± 3.1	54 ± 15
$X\gamma$	1.8 ± 1.8	2.1 ± 2.7	0.6 ± 0.6	4.6 ± 1.6	9.0 ± 3.9
ZZ	2.8 ± 0.4	2.7 ± 0.4	2.5 ± 0.3	2.2 ± 0.3	10 ± 1.3
Rare	2.9 ± 1.5	2.1 ± 1.1	1.8 ± 1.0	1.4 ± 0.7	8.3 ± 4.2
Nonprompt	6.9 ± 2.9	11 ± 4.0	6.9 ± 2.9	8.5 ± 3.5	33 ± 13
Total	214 ± 12	187 ± 12	161 ± 9.0	125 ± 8.2	687 ± 40
Observed	192	175	152	141	660

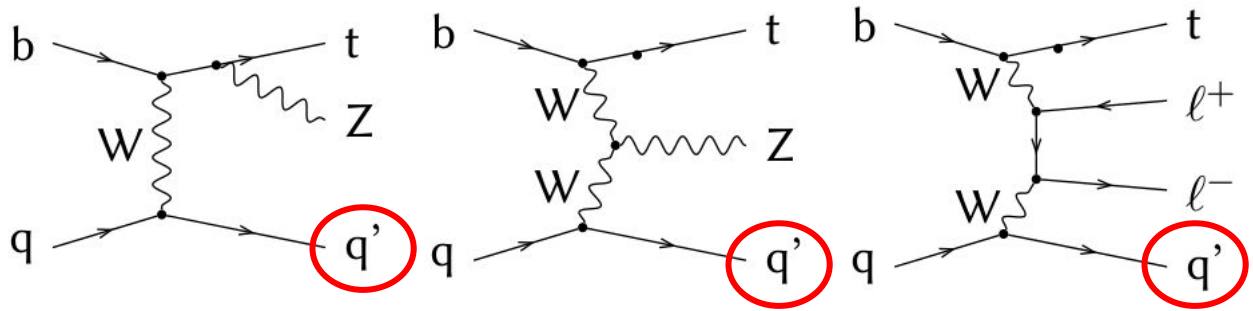


Measured cross section more precise than NLO prediction

σ_{ttZ} = 0.95 ± 0.05 (stat) ± 0.06 (syst) pb

Phys. Rev. Lett. 122, 132003 (2019)

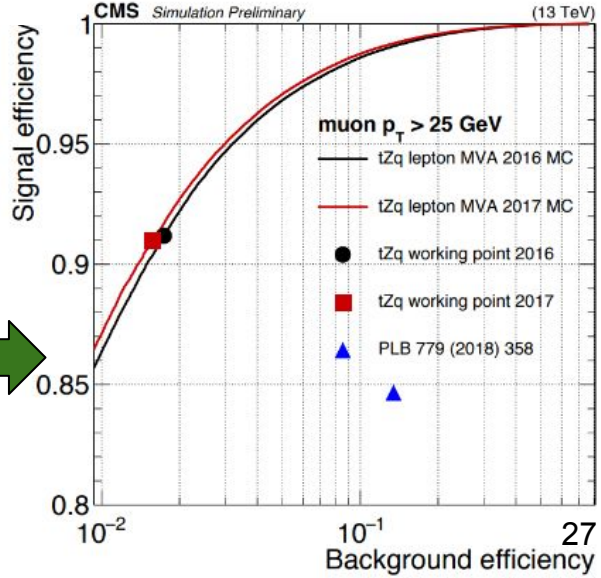
tZq Inclusive - 77.4 fb^{-1}



2016+2017: 77.4 fb^{-1} @ 13 TeV

forward jet: significant diff between tZq and bkgs

- Single top quark production in association with a Z boson and a quark in the **leptonic decay channel**
- 3 leptons (ele or muons), at least 2 jets and exactly 1 b-tagged jet
- Non-prompt and fake lepton background: MVA classifier exploiting ID and isolation information
- The increased **integrated luminosity**, a **multivariate lepton identification**, and a **redesigned analysis strategy** improve significantly the sensitivity of the analysis compared to previous searches for **tZq** production



Phys. Rev. Lett. 122, 132003 (2019)

tZq Inclusive - 77.4 fb^{-1}

- 3 leptons (e or μ), ≥ 2 jets and exactly 1 b-tagged jet
- Events are divided into 3 categories based on N_{jets} & $N_{b\text{-}tags}$
- In each of these categories, a dedicated BDT is trained
- **Most discriminating input:** |*η(light jet)*|
- Simultaneous template fit to **BDT** outputs and yields of control regions is performed to measure tZq signal strength

$$\sigma(pp \to tZ(\to \ell^+\ell^-)q) = 111 \pm 13(stat)^{+11}_{-9}(syst)\ fb$$

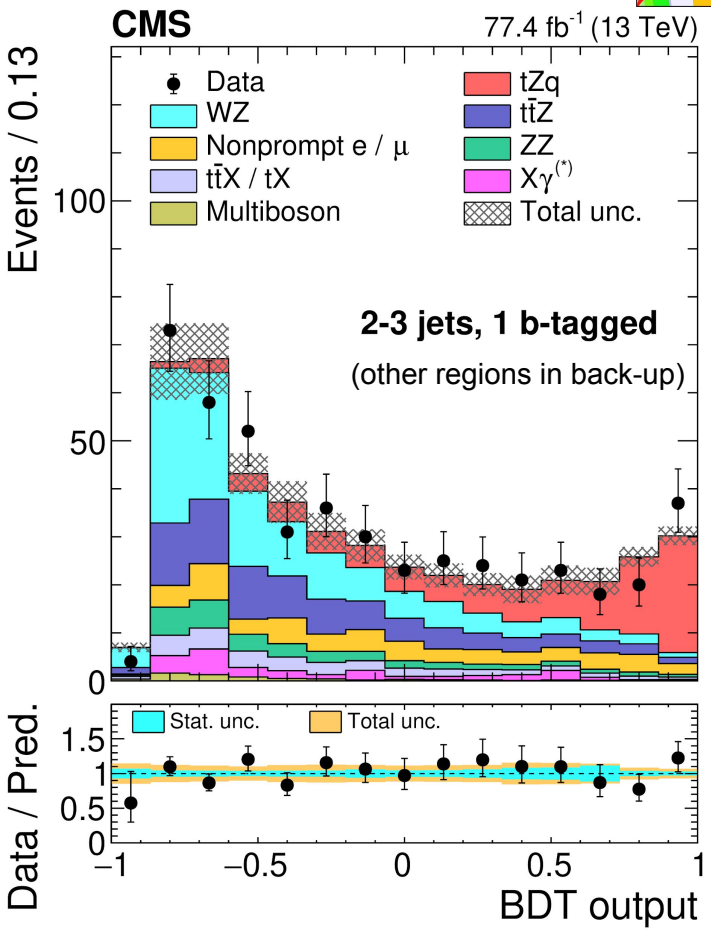
$$[m(\ell^+\ell^-) > 30\ GeV/c^2]$$

- **Main systematics:** non-prompt bkg, lepton ID, FSR modeling, jet energy

Result consistent with the SM prediction

Theory σ(NLO) = 94.2 $^{+1.9}_{-1.8}$ (scale) ± 2.5 (PDF) fb

MadGraph5+aMC@NLO



CMS-PAS-TOP-20-010

tZq Inclusive - 138 fb^{-1}