RARE SINGLE TOP QUARK PRODUCTION MODES IN ATLAS AND CMS

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On behalf of the ATLAS and CMS collaborations

OUTLINE

Introduction

Photon associated single top production

- Standard Model $t\gamma q$ production
- Search for FCNC in $t\gamma$ New

Z boson associated single top production by ATLAS and CMS New

Summary

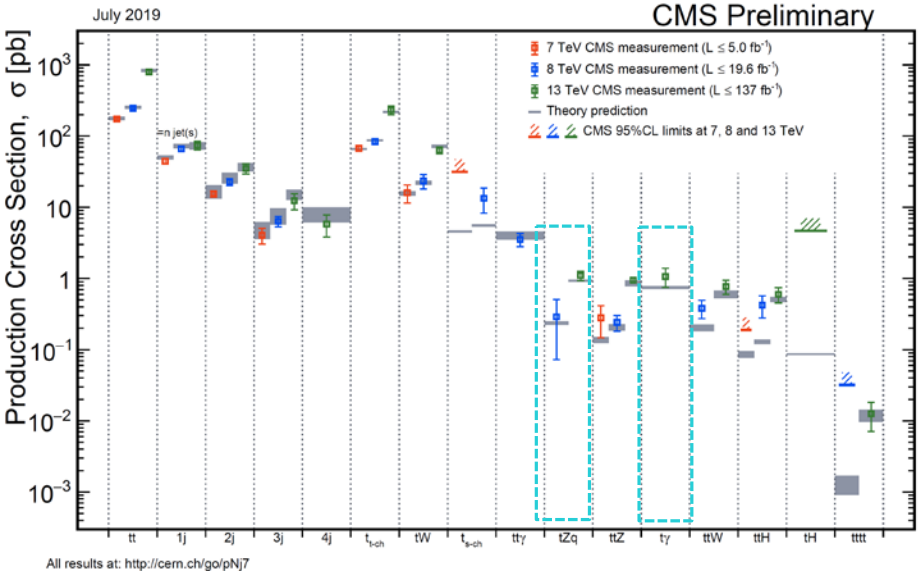
RARE SINGLE TOP QUARK PRODUCTIONS

Production of single top quark and additional gauge boson is a probe

- Gauge boson triple couplings
- Electroweak couplings to top quark
- Non-standard couplings to top quark could enhance flavor changing neutral current (FCNC)

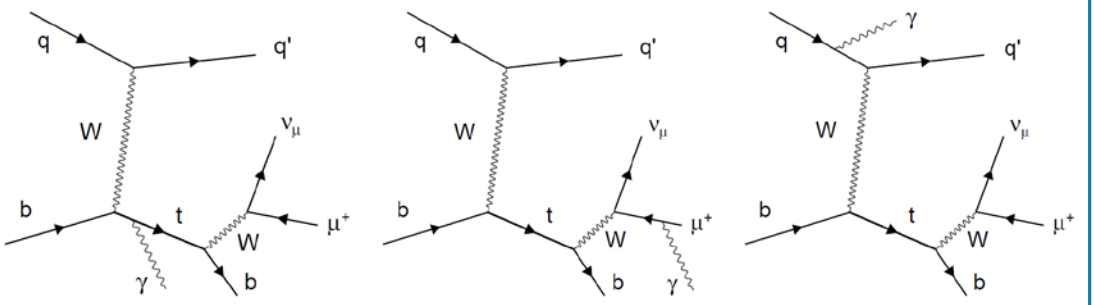
These rare modes are becoming accessible due to large amount of data accumulated at the LHC

Measured cross sections in $t + X$ compared with SM

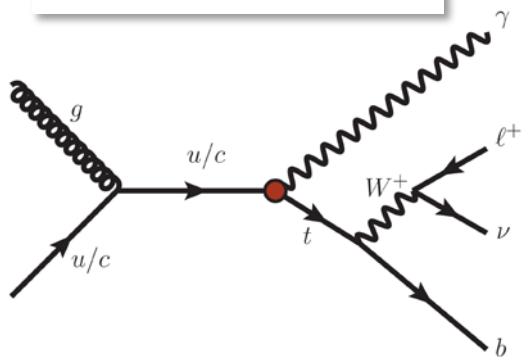


PHOTON ASSOCIATED SINGLE TOP QUARK PRODUCTION

Standard Model tree-level diagrams



FCNC in production



Probe of top quark's charge, electric and magnetic dipole moment, FCNC

SM Signature: Isolated photon + top quark + 1 forward hadronic jet

FCNC signature: Isolated photon + top quark

- When FCNC involved in production

Phys. Rev. Lett. 121 (2018) 221802

STANDARD MODEL $t\gamma q$

Search for SM $t\gamma q$ performed by CMS

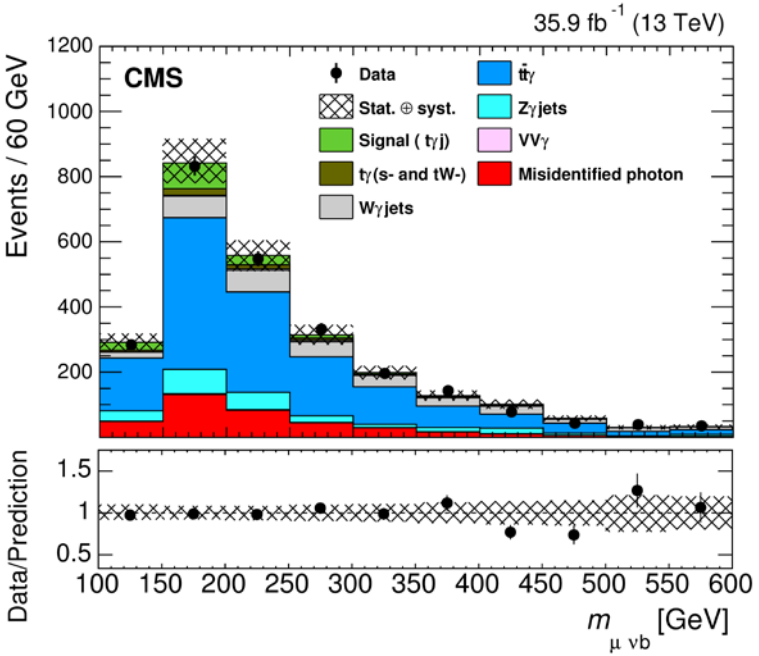
- $36\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13\ \mathrm{TeV}$ (2016)
- Single muon trigger looking for $t \to b\mu\nu$

Event Selection

- One isolated muon, one isolated photon
- Two hadronic jets ($p_T > 40\ \mathrm{GeV}$, b-jet in $|\eta| < 2.5$, another jet in $|\eta| < 4.7$)

Backgrounds

- $t\bar{t}\gamma$ and mis-id γ estimated from control region
- Madgraph5_amc@NLO + PYTHIA 8 for others



Phys. Rev. Lett. 121 (2018) 221802

EVIDENCE FOR SM $t\gamma q$

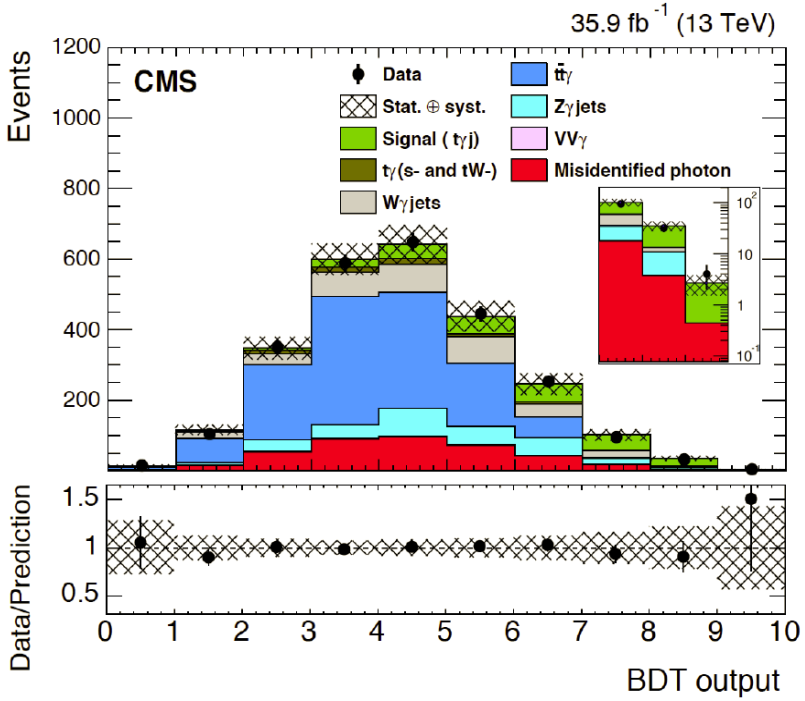
4.4 s.d. significance observed (3.0 s.d. expected)

- 220 ± 63 signal events from simultaneous fit of signal and control regions of 2535 events

Fiducial cross section

$$\sigma(pp \to t\gamma j) \times Br(t \to \mu\nu b) = 115 \pm 17(stat) \pm 30(syst)\ \text{fb}$$

- phase space: $p_{T,\gamma} > 25\ GeV$, $|\eta_\gamma| < 1.44$, $\Delta R(X,\gamma) > 0.5$
- SM expectation: 81 ± 4 fb
- Major systematics: JES, signal modeling, $Z\gamma + jets$, b-tagging



New arXiv:1908.08461

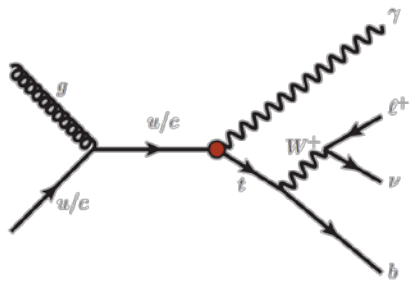
SEARCH FOR FCNC IN $t\gamma$

ATLAS performed a search for FCNC

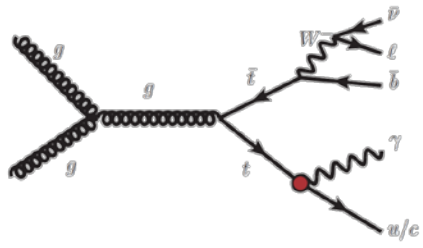
- Left-handed (LH) and Right-handed (RH), $tu\gamma$, $tc\gamma$ couplings treated separately

Data sample

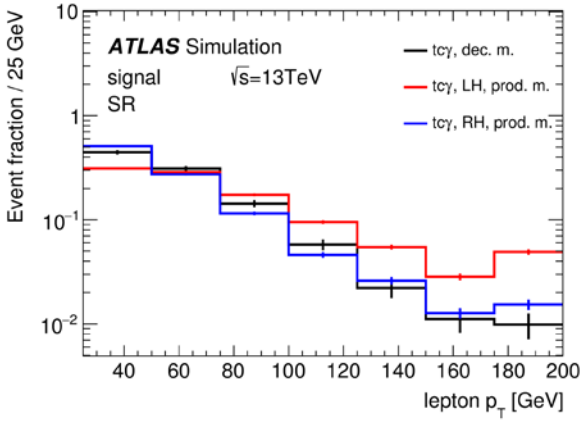
- 81 fb^{-1} at $\sqrt{s} = 13$ TeV (2015~2017)
- Single lepton triggers



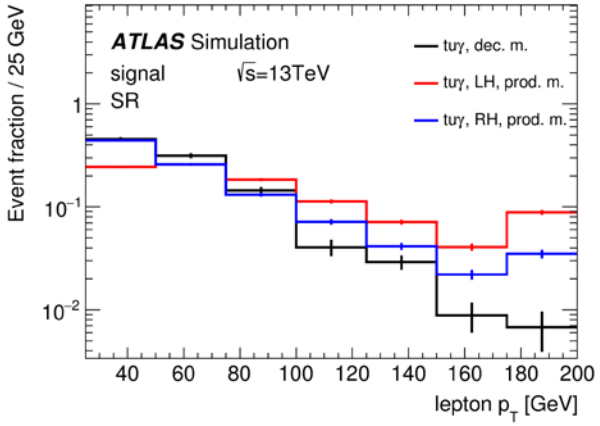
Top quark production via FCNC



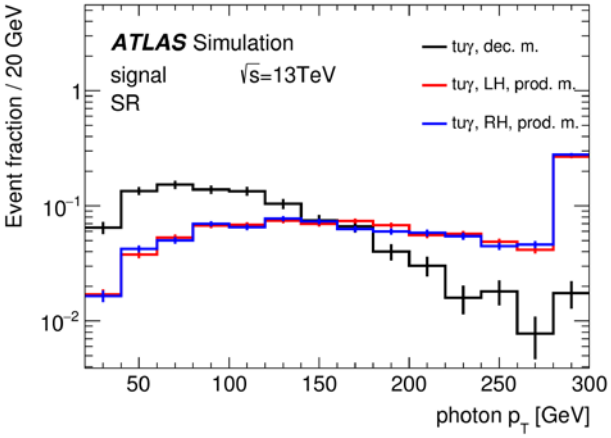
Top quark decay via FCNC



$tc\gamma$ vertex



$tu\gamma$ vertex



arXiv:1908.08461

ANALYSIS STRATEGY FOR FCNC SEARCH IN $t\gamma$

Signal region

- One lepton
- One photon
- Exactly one b-tagged jet and no more jets
- $E_T^{miss} > 30\ GeV$

Control region for $W + \gamma +$ jet

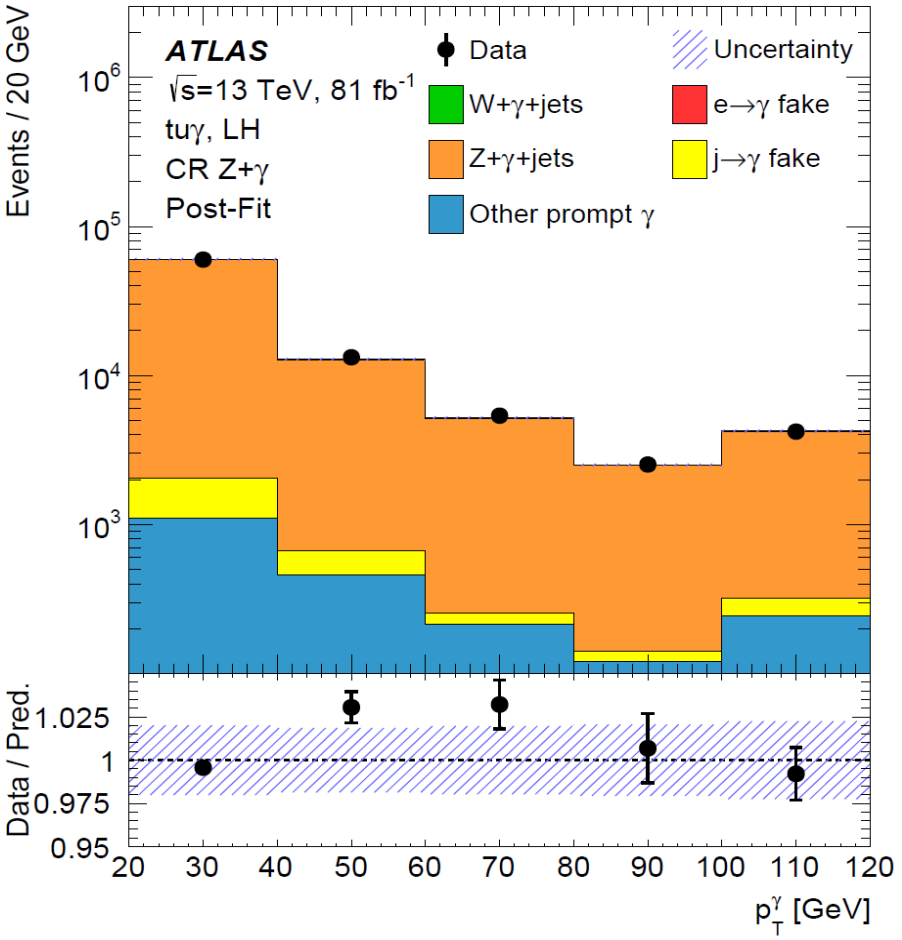
- Same as SR except jet not be b-tagged, $m_{\ell\gamma}$ be outside 60~100 GeV

Control region for $Z + \gamma +$ jet

- One photon
- Two opposite sign same flavor (OSSF) leptons

Mis-identified photon

- Electron with lost track or γ from hadron decays



arXiv:1908.0846

ARTIFICIAL NEURAL NETWORK FOR FCNC IN $t\gamma$

Artificial Neural Networks used for discrimination

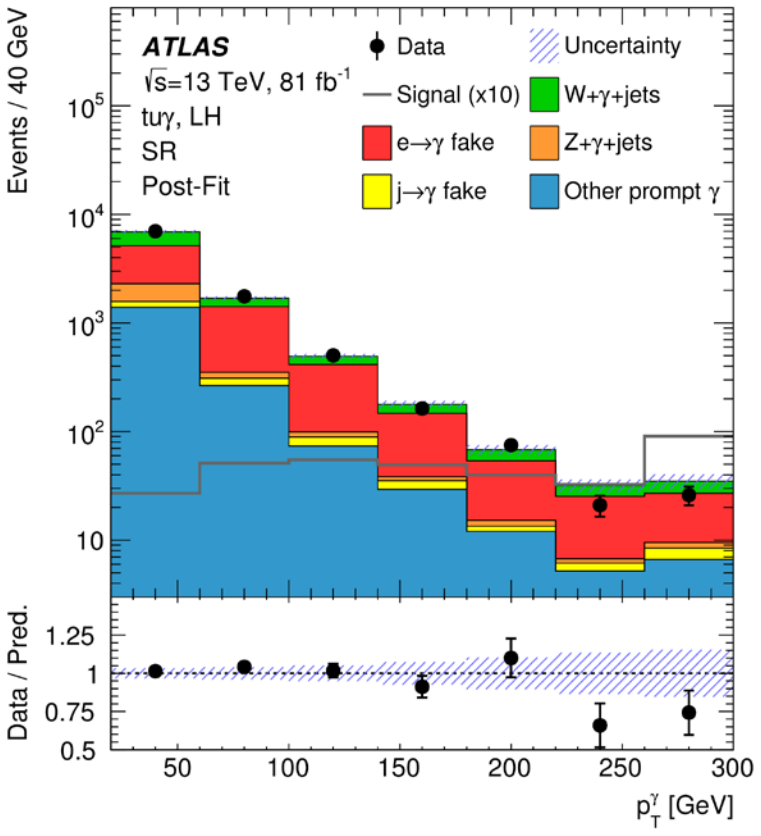
- Separate NN's for FCNC processes – $tc\gamma$, $tu\gamma$, LH, RH
- Production mode chosen for signal sample

Discriminating variables

- Photon p_T, lepton p_T, jet p_T, Charge of lepton, Missing ET, $m(\ell\gamma)$, $m(\ell j)$, $\Delta R(\ell,\gamma)$, $\Delta R(\ell,j)$

Signal extraction

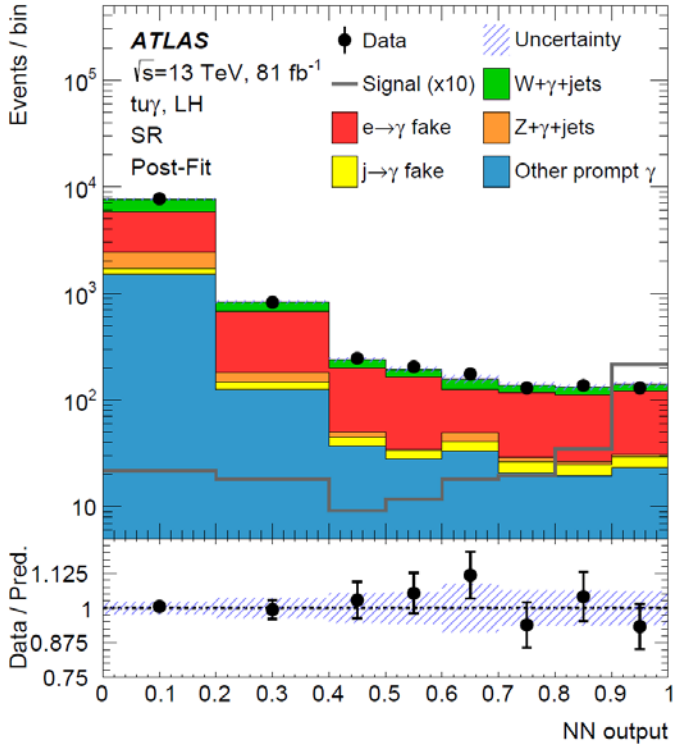
- Signal and $W/Z+\gamma$ contributions determined from simultaneous fit to NN output in SR and $W+\gamma$ CR, and photon p_T distribution in $Z+\gamma$ CR



arXiv:1908.08461

RESULTS OF FCNC SEARCH IN $t\gamma$

No significant excess observed

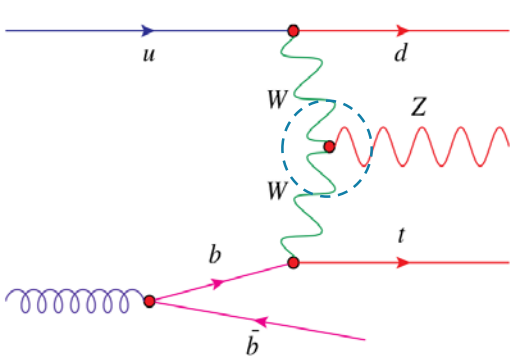


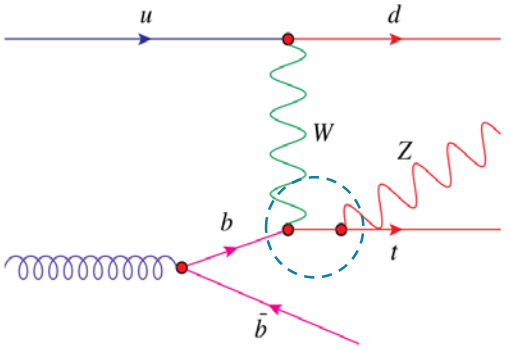
Cross section upper limits from CL_s method. EFT interpretation performed.

95% CL Upper Limits

Observable	Vertex	Coupling	Obs.	Exp.
$\left\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*} \right\rvert$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\left\lvert C_{uW}^{(31)} + C_{uB}^{(31)} \right\rvert$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\left\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*} \right\rvert$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\left\lvert C_{uW}^{(32)} + C_{uB}^{(32)} \right\rvert$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

SINGLE TOP QUARK + Z BOSON PRODUCTION (tZq)





Sensitive to electroweak couplings: WWZ, tbW, ttZ

- Unitary cancelations in tZq means it might be affected more by modified interactions than $t\bar{t}Z$ and single top productions

Both ATLAS and CMS searched for tZq

- Signature: Trilepton and forward jet

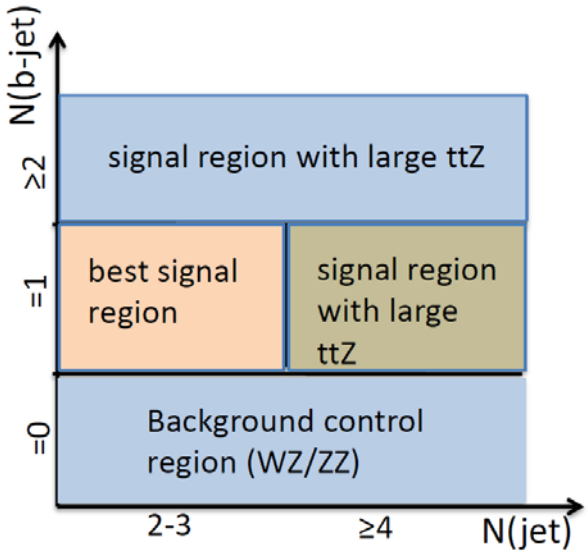
Phys. Rev. Lett. 122 (2019) 132003

tZq IN CMS

CMS searched for tZq in $\int \mathcal{L}dt = 77\ \mathrm{fb}^{-1}$ collected with lepton triggers (2016-2017)

Analysis strategy

- OR of single, dilepton, trilepton triggers
- Require exactly 3 leptons OSSF with $|m_{\ell\ell} - m_Z| < 15\ \mathrm{GeV}$
- BDT for prompt vs non-prompt lepton
- At least two hadronic jets: $p_T > 25\ \mathrm{GeV}$, $|\eta| < 5.0$
- Several signal regions (SR) and control regions (CR) with different background compositions
- Data-driven background estimation for major backgrounds from $t\bar{t}Z$, WZ, and fake leptons



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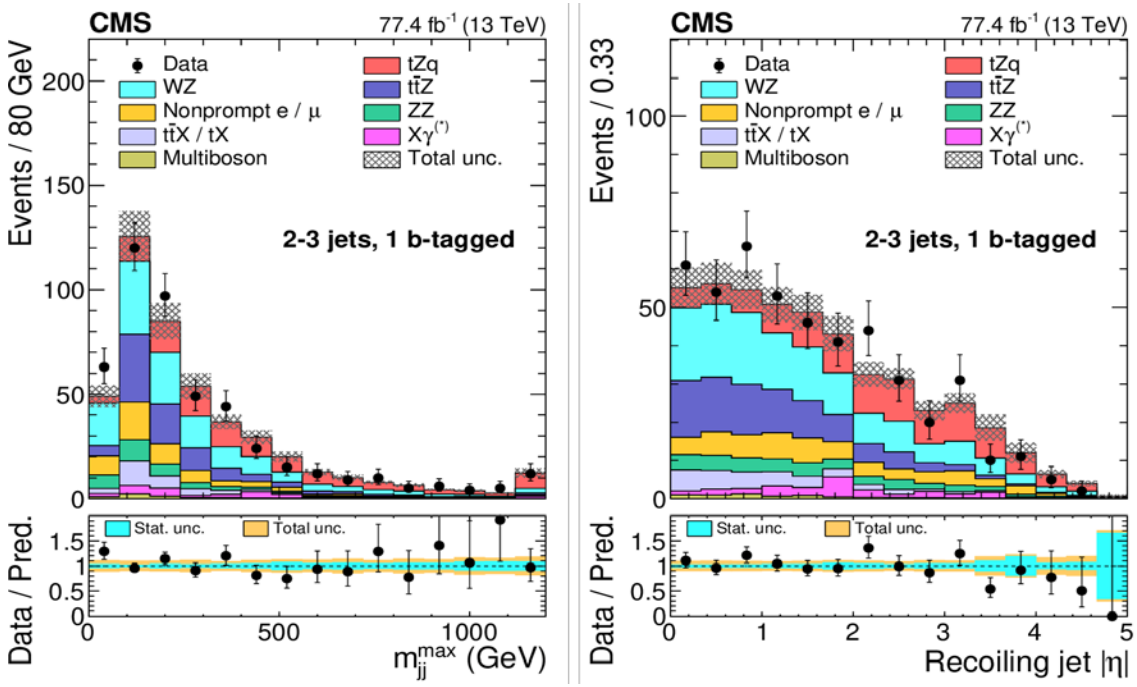
tZq IN CMS

Various signal regions (SR) and dedicated BDT for each SR



Simultaneous binned max. likelihood fit to BDT distributions in SRs, Diboson yields in CR

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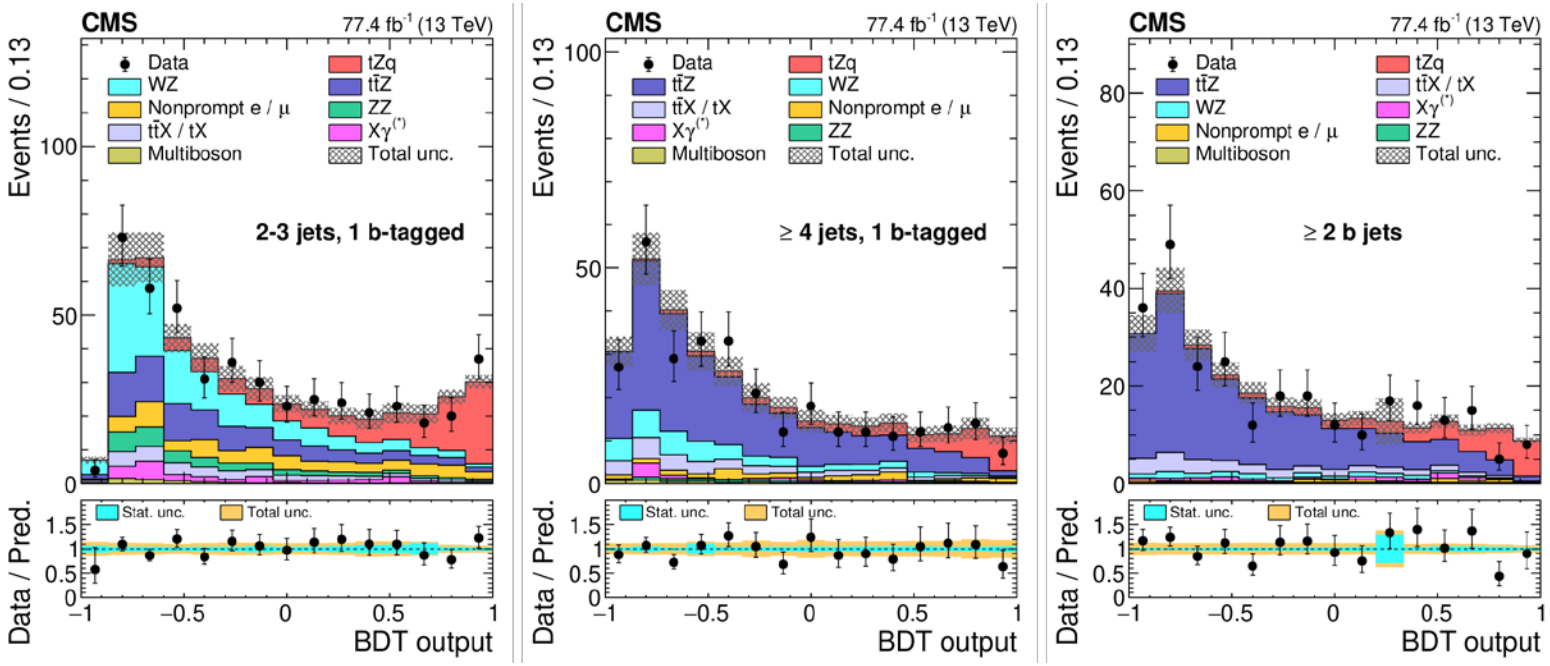
tZq IN CMS



Observed significance >8 s.d.

Measured cross section

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

- SM expectation: 94.2 ± 3.1 fb

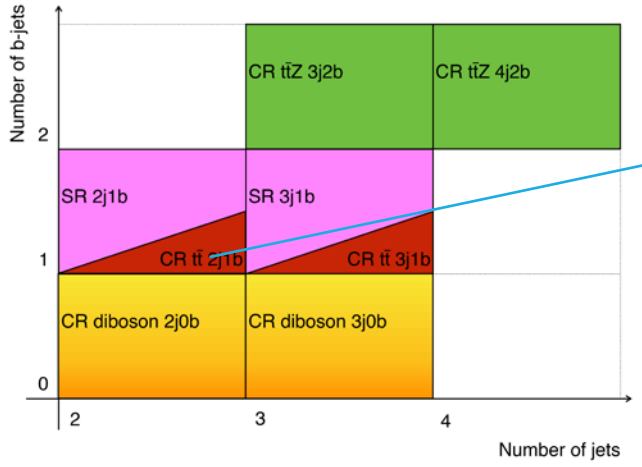
tZq IN ATLAS

New

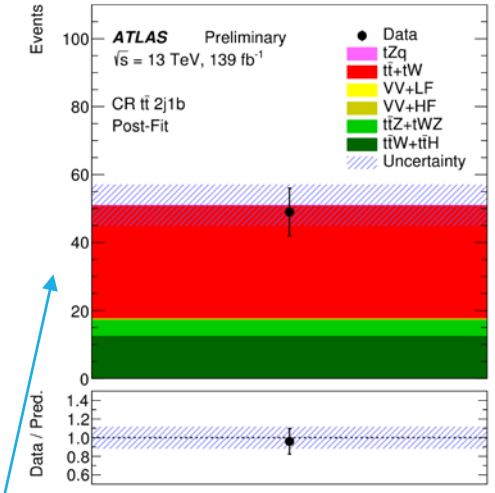
ATLAS-CONF-2019-043

tZq analysis with full run 2 data 139 fb^{-1} from ATLAS

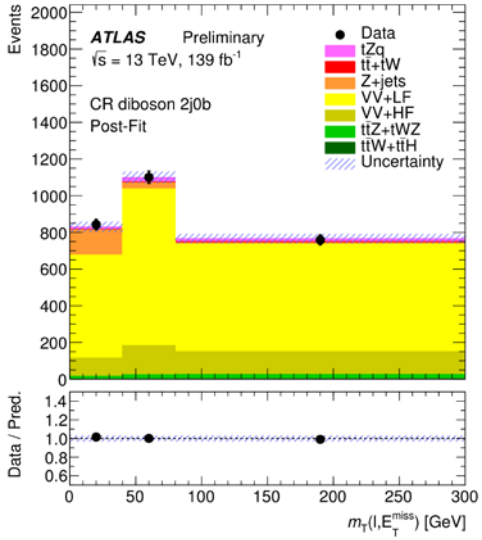
- OR of single electron/muon triggers
- Require exactly 3 leptons OSSF with $|m_{\ell\ell} - m_Z| < 10$ GeV
- At least two hadronic jets: $p_T > 35$ GeV, $|\eta| < 4.7$
- Several SR and CR defined



OSDF



$t\bar{t}$ CR



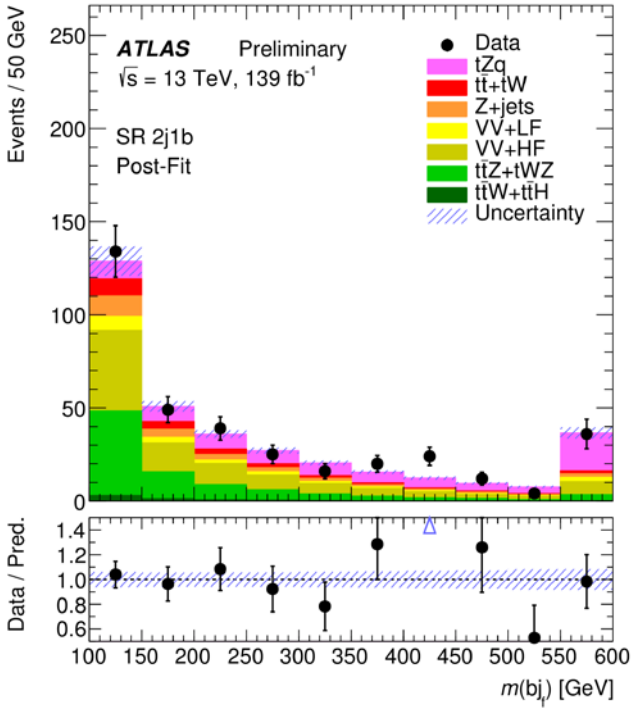
Diboson CR

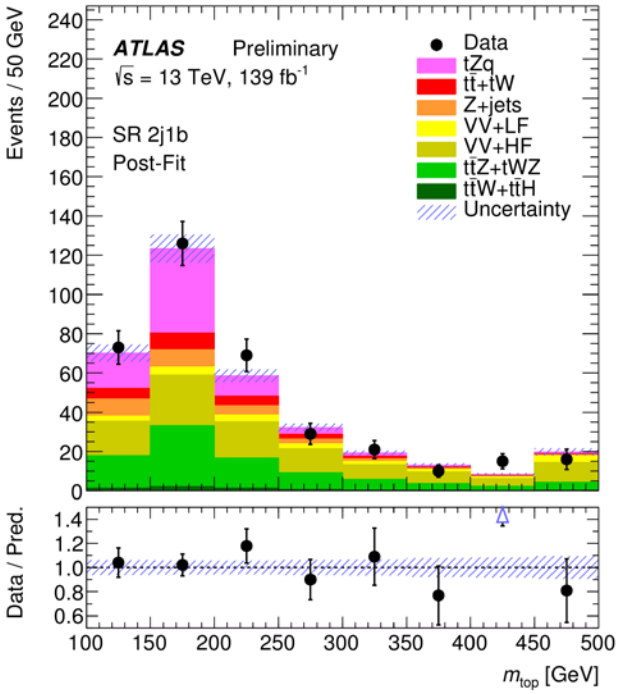
tZq IN ATLAS

ATLAS-CONF-2019-043

Neural network-based analysis

- Separate NN for each SR
- 15 inputs used. Most sensitive: $m(bj_f)$, m_{top}^{rec}, $|\eta(j_f)|$, $m_T(\ell, MET)$





tZq IN ATLAS

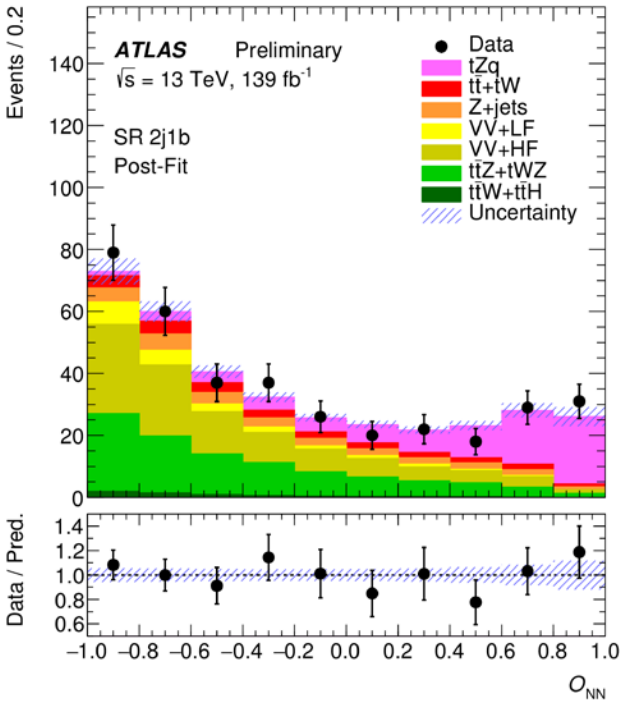
ATLAS-CONF-2019-043

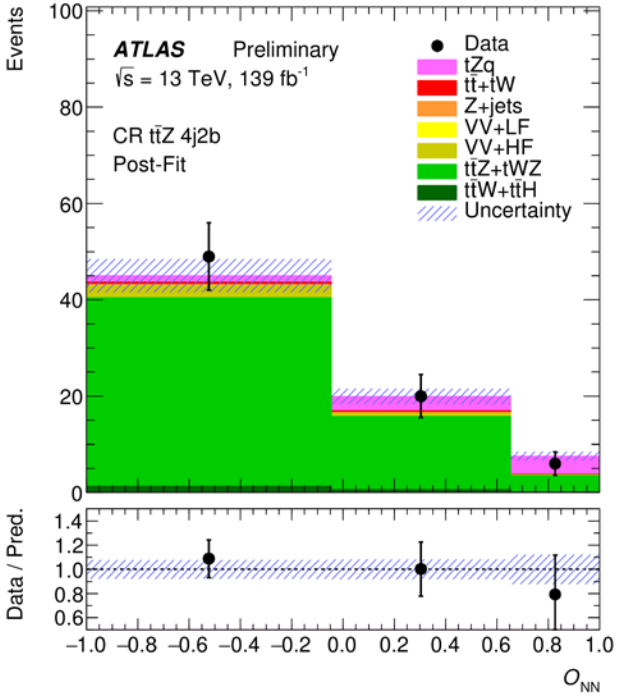
Simultaneous profile likelihood fits to SR and CR

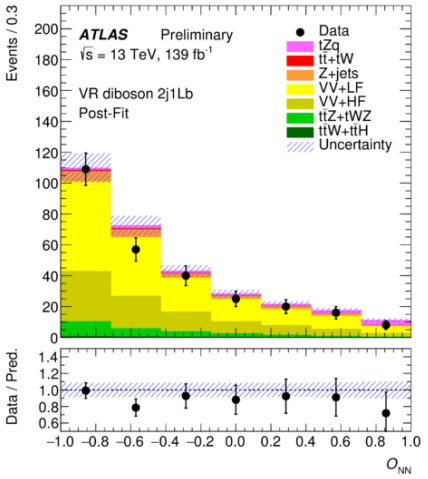
- NN distributions in SRs, NN distr. in $t\bar{t}Z$ CR, m_T distr. in diboson CR

$\sigma(t\ell^+\ell^-q) = 98 \pm 12(stat) \pm 8(syst)$ fb $(m_{\ell\ell} > 30$ GeV$)$ 9.2 s.d.

- SM expectation 102^{+5}_{-2} fb







Validation region
2 jet, 1loose b-tag

SUMMARY

We presented:

- Evidence for single $tq\gamma$ production by CMS
- Most stringent limits on FCNC in $t\gamma$
- Observations of tZq production by ATLAS and CMS

We can go further and measure differential cross sections

REFERENCES

Evidence for $t\gamma q$ in CMS: *Phys. Rev. Lett. 121 (2018) 221802*

Search for FCNC in $t\gamma$ in ATLAS: *arXiv:1908.08461*

Observation of tZq boson in CMS: *Phys. Rev. Lett. 122 (2019) 132003*

Observation of tZq boson in ATLAS: ATLAS-CONF-2019-043

BACKUP

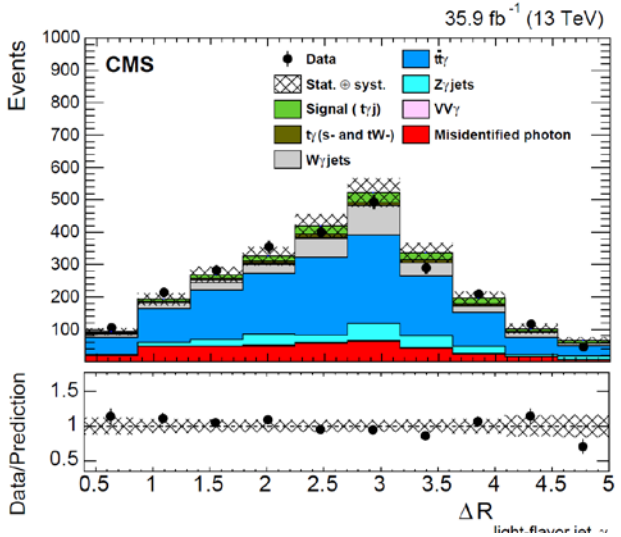
STANDARD MODEL $t\gamma q$

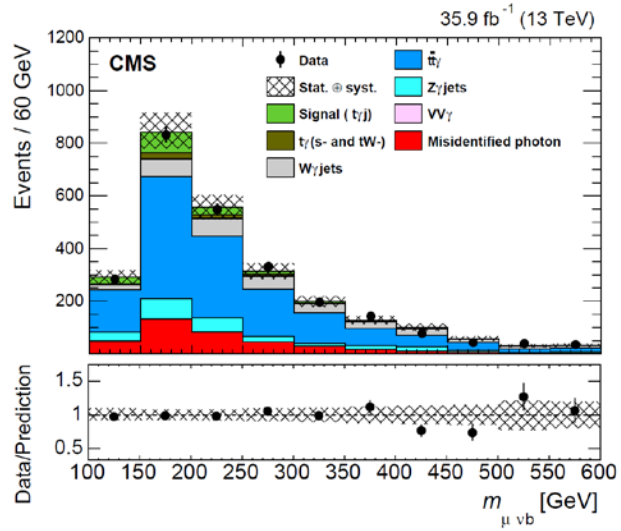
Boosted decision tree for $t\gamma q$

- η of light-flavored jet
- muon-jet angular separation
- Photon-jet angular separation
- Reconstructed top quark mass
- Jet multiplicity
- Reconstructed transverse mass

Templates

- $t\bar{t} + \gamma$ and mis-id photon templates
- from data-driven





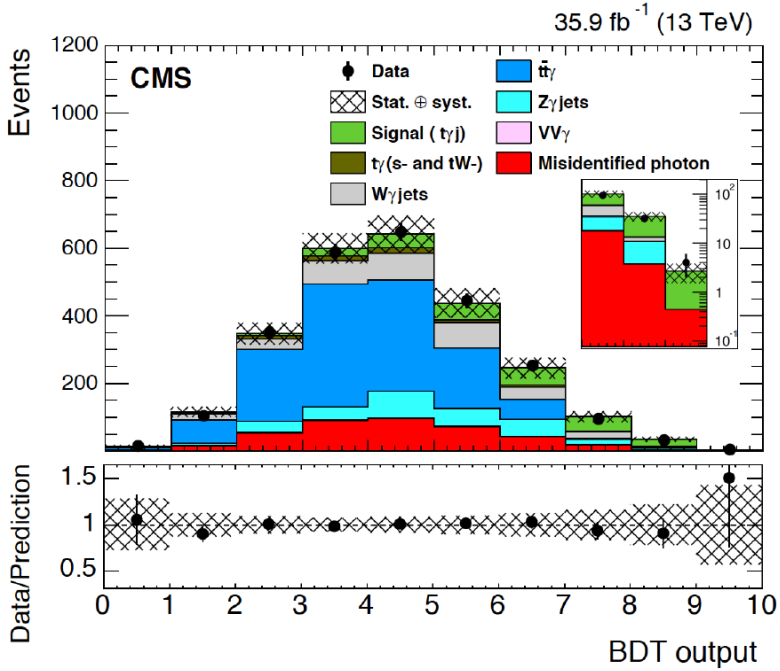
STANDARD MODEL $t\gamma q$

Systematics

- Lepton trigger, reco, id efficiencies
- Photon selection eff. And energy scale
- Jet related: JES and JER
- b-jet tagging
- Modeling

Signal extraction

- Binned likelihood fit done on signal region and determine $t\bar{t}\gamma$ in the control region simultaneously
- Each systematic source treated as a nuisance parameter



OBJECT SELECTION FOR FCNC SEARCH IN $t\gamma$

Lepton

- Electron: $p_T > 27\ GeV$ and $|\eta_{cluster}| < 2.47$
  - excluding $1.37 < |\eta_{cluster}| < 1.52$
- Muon: $p_T > 27\ GeV$ and $|\eta| < 2.5$
- Isolation from calorimeter energy deposits and tracks

Photon

- $p_T > 20\ GeV$ and $|\eta_{cluster}| < 2.37$
  - excluding $1.37 < |\eta_{cluster}| < 1.52$
- No matching tracks
- Isolation from calorimeter energy deposits and tracks

Jet

- Anti k_T $R = 0.4$
- $p_T > 25\ GeV$ and $|\eta| < 2.5$
- No overlaps with leptons or photons

Missing E_T

- From vector sum of leptons, photons, jets, tracks

OBJECT SELECTION FOR SINGLE TOP + Z BOSON

Hadronic jets

- Anti-k_T, $R = 0.4$
- $|\eta| < 5.0$, $p_T > 25\ GeV$
  - $p_T > 60\ GeV$ in 2017 data
- Separated in $\Delta R > 0.4$ from id'd leptons
- B-tagging: $|\eta| < 2.4$, 68% efficiency with 1% mistag rate for light-flavor jets

Leptons

- Relative isolation cone size dependent on lepton p_T

Prompt/non-prompt leptons

- Distinguished by a BDT improves rejection by factor of 2(8) for electron(muon) compared to previous
- 85 (92) % efficiency for prompt electron (muon) $p_T > 25\ GeV$
- 1.5% mis-id probability

tZq IN TRILEPTON CHANNEL

CMS Data Sample

- 77 fb^{-1} collected with single lepton trigger (2016-2017)

Simulation

- MadGraph5_amc@NLO generators used at NLO precision in QCD
- Signal: tZq
- Backgrounds: $t\bar{t}V$, tHV, tHq, $t\bar{t}VV$, VVV
- NNPDF3.0 and 3.1 used
- FxFx(MLM) Matching for NLO(LO) samples
- PYTHIA 8.212 (8.230): parton showering, hadronization, underlying event (CUETP8M1) in 2016 (2017) data

BACKGROUNDS IN tZq

WZ estimated from simulation after normalizing in a control region enriched in WZ

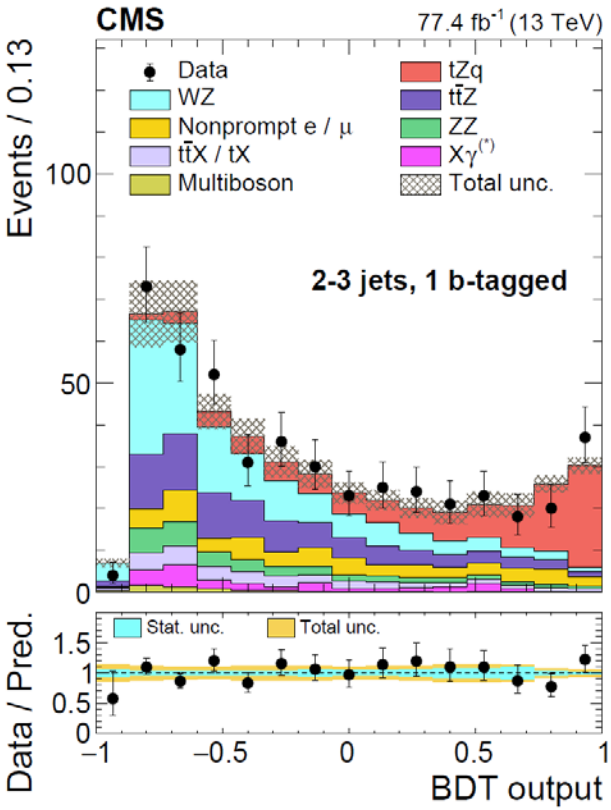
- No requirements on # of jets and veto on b-tagged jet
- $p_T^{miss} > 50\ GeV$ required

$t\bar{t}Z$ backgrounds

- Dominant backgrounds in various SR's
- Shape and normalization constrained in final fit from low BDT bins
  - Prior uncertainty 15%

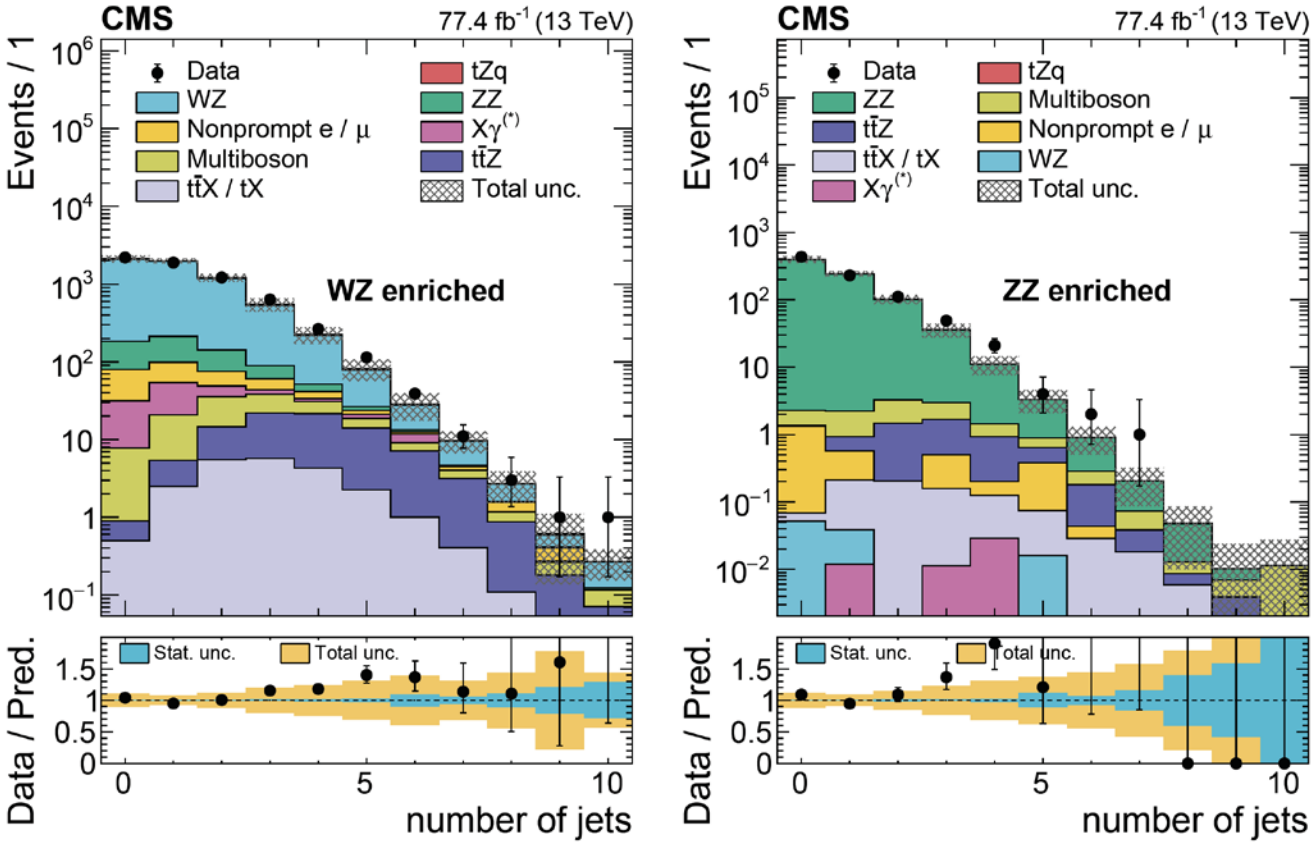
Non-prompt lepton backgrounds

- Mostly $t\bar{t}$ or DY with additional non-prompt leptons
- Tight-loose method used to estimate contribution

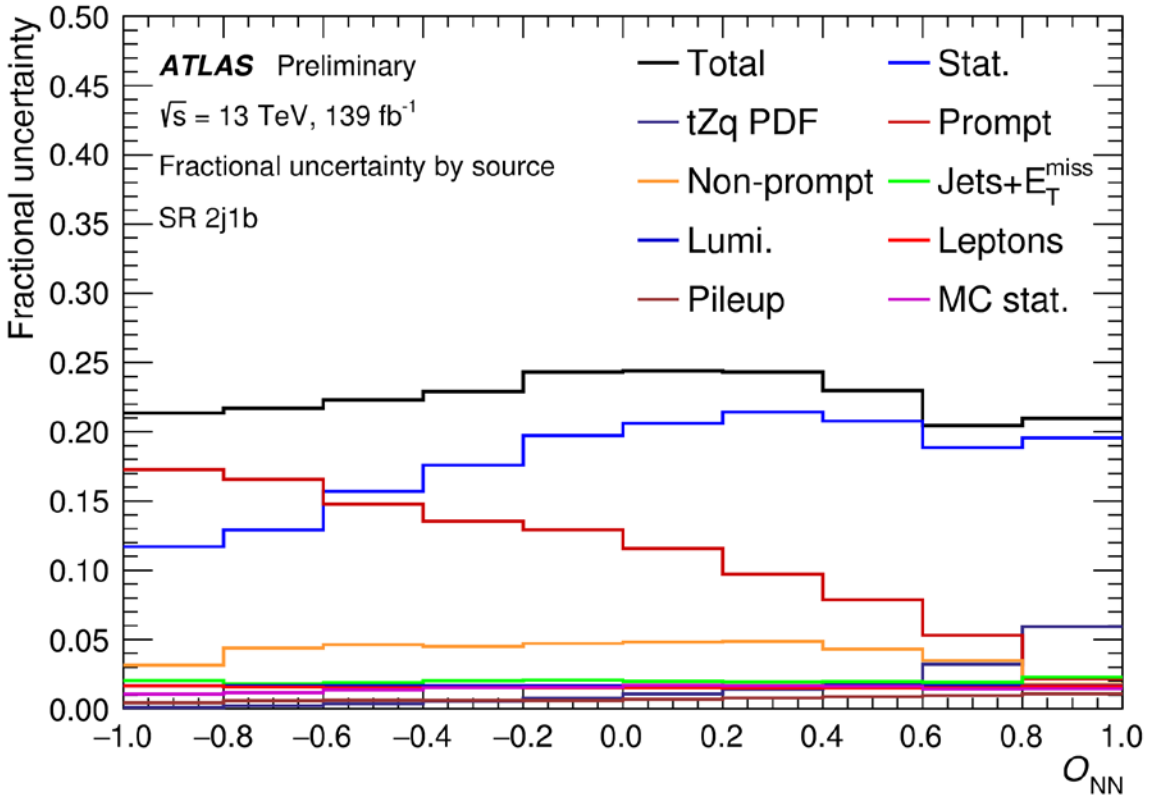


BACKGROUNDS IN tZq

Diboson CR – prefit distribution



UNCERTAINTIES BY SOURCES



COMPARISON OF SYSTEMATICS IN tZq

ATLAS

Uncertainty source	$\Delta\sigma/\sigma$ [%]
tZq PDF	4.2
Prompt lepton background modelling and normalisation	3.4
Non-prompt lepton background modelling and normalisation	2.3
Jets+$E_{\mathrm{T}}^{\mathrm{miss}}$	2.1
Luminosity	1.7
Lepton reconstruction and calibration	1.7
Pile-up	1.2
MC statistics	1.0
tZq QCD radiation	0.8
b-tagging	0.4
Total systematic uncertainty	8.0
Statistical uncertainty	12

CMS

Uncertainty	Impact (%)
Experimental	
lepton selection	3.2
trigger efficiency	1.4
jet energy scale	3.3
b-tagging efficiency	1.7
nonprompt normalization	4.1
$t\bar{t}Z$ normalization	1.0
luminosity	1.7
pileup	1.9
other	1.3
Theoretical	
final-state radiation	2.0
tZq QCD scale	2.0
$t\bar{t}Z$ QCD scale	1.4