Rare single top-quark processes

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On behalf of the ATLAS and CMS collaborations

Introduction

- Rare processes : associated production of **single top-quark** with a **boson** (Z or photon).

- With high luminosity at the LHC, the observation of rare (SM) single top processes becomes possible.
  - Results presented here are based on 2016 (+2015) datasets, ~36 fb^{-1}.

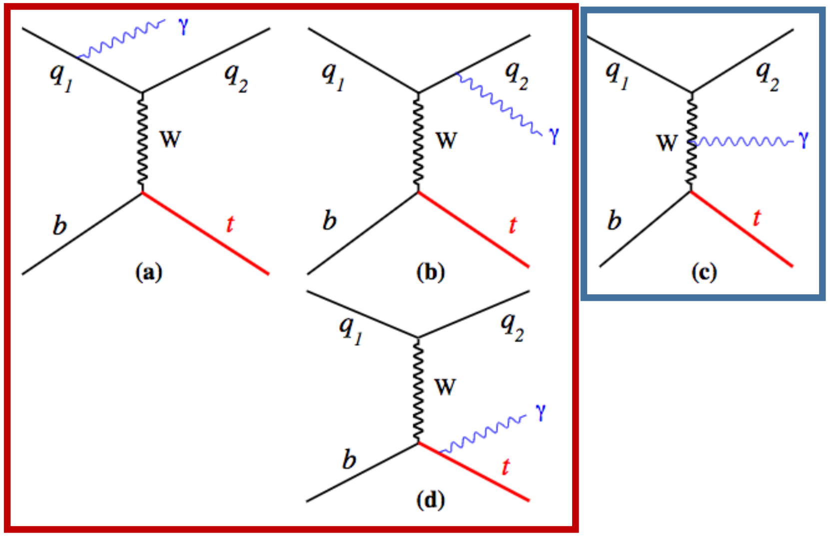
- Motivations :
  - Improve our understanding of these important backgrounds for other processes and searches,
  - Sensitive to triple gauge couplings,
  - Sensitive to new physics, **EFT and FCNC**.

- Outline :
  - arXiv:1808.02913 (submitted to PRL) : CMS evidence of **single top-quark + γ**,
  - PLB 779 (2018) 358 : CMS evidence of **single top-quark + Z,**
  - PLB 780 (2018) 557 : ATLAS evidence of **single top-quark + Z.**

Search for tγq in the muon+jet channel at 13 TeV

tγq Motivations

- Associated production of a single top quark (t-channel) with a photon.
- Photons arising either from ISF/FSR or via a triple gauge couplings (WWγ).
- Sensitivity to **"anomalous" triple gauge couplings**.
- Signature also sensitive to top-γ FCNC.



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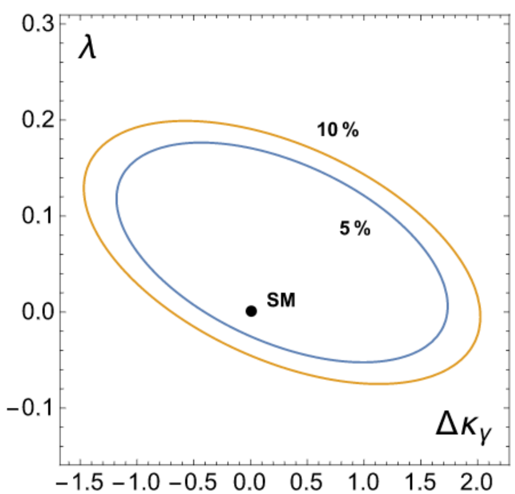


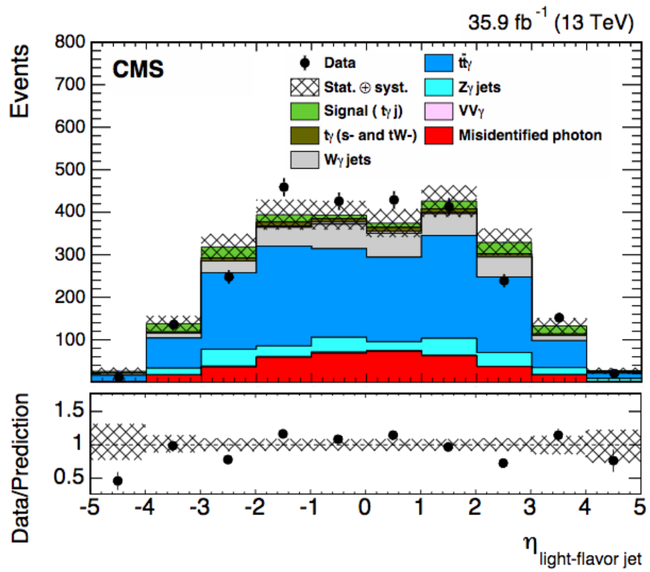
- Ambiguity in the definition of signal, **overlap** between single top+"soft" photons emissions from PS (t-chan) and "hard" photons from ME (tγj).
- Apply cuts to minimize the overlap: E_T^γ >25GeV, $\Delta R(X-\gamma)$ >0.5 with X=lepton or jets.

arXiv:1808.02913, submitted to PRL

Event selection and background estimations

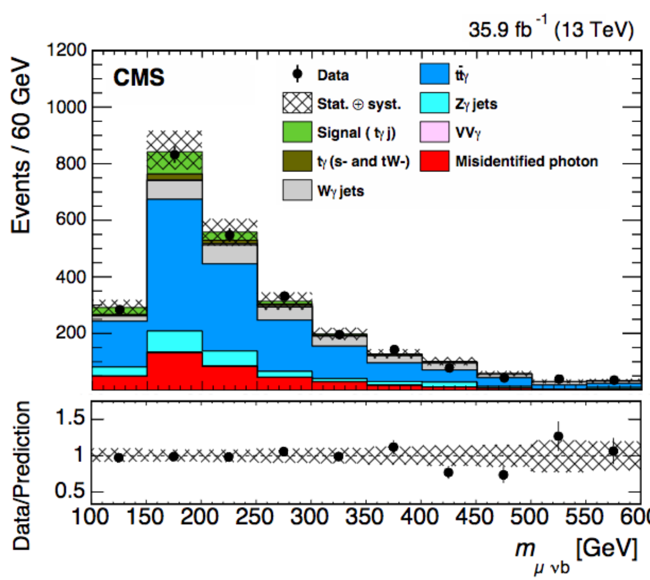
arXiv:1808.02913, submitted to PRL

- Event selection :
  - Single muon trigger,
  - One isolated muon with p_T> 26 GeV, $|\eta|$<2.4,
  - 2 jets with p_T> 40 GeV : 1 light jet potentially **forward $|\eta|$<4.7**, **1 b-tag** ($|\eta|$<2.4),
  - 1 isolated photon with p_T> 25 GeV, $|\eta|$<1.44 (restricted to barrel => better signal/noise),
  - p_T^{miss}> 30 GeV,
  - $\Delta R(X-\gamma)$ >0.5.



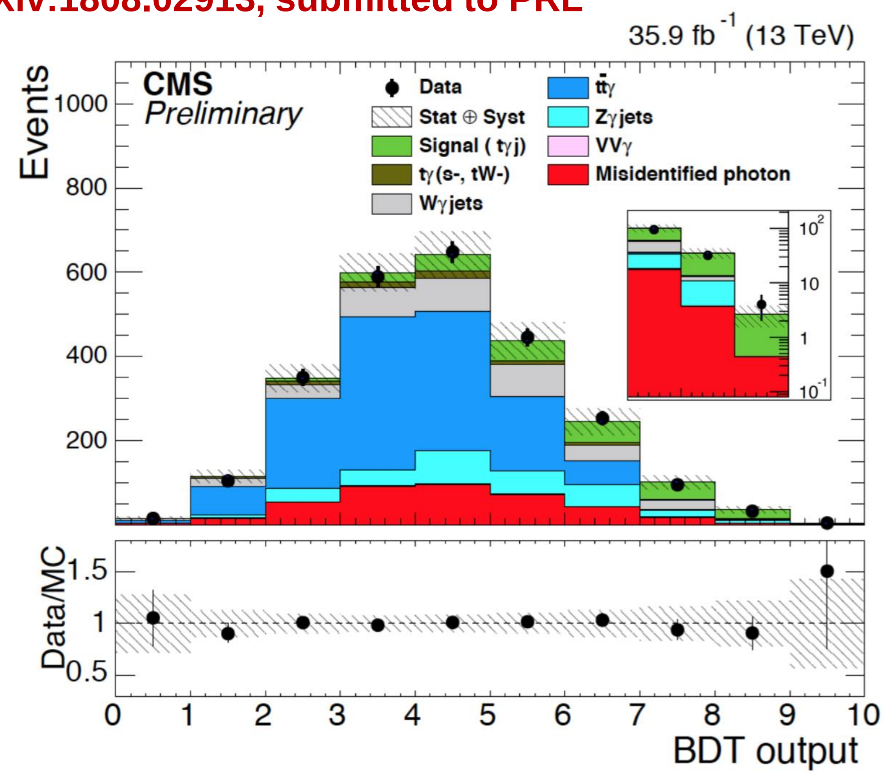
- Backgrounds with real photons estimated from simulation.

- Backgrounds with fake photons estimated from data:
  1. Select sample enriched in jets faking photons (isolation/shower shape inversion, looser photon ID),
  2. Estimate p_T dependent probability for a jet to fake a photon (ABCD method, isolation/shower),
  3. Weight the sample with the probability.



Evidence for $t\gamma q$

arXiv:1808.02913, submitted to PRL



$p_{T,\gamma} > 25\,\text{GeV}$, $|\eta_\gamma| < 1.44$, and $\Delta R(X,\gamma) > 0.5$

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

$$\sigma_{theo} = 81 \pm 4\,\text{fb}$$

~30%

- Signal extraction : likelihood fit of a multivariate discriminant (BDT).
- Input variables : $\eta(jet)$, $\cos\theta^*_W$, $\eta(\mu)$, $\Delta R(j-\gamma)$, m_{top}, N_{jets}, m_T^W, muon charge.
- **Observed (expected) significance of 4.4 (3.0).**

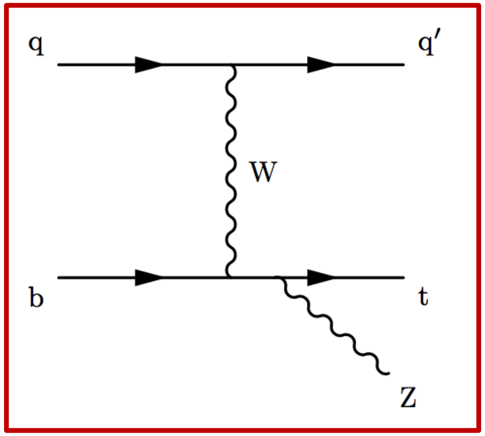
Dominant systematic source	Contribution
JES	12%
Signal mod.	9%
$Z\gamma$+jets	8%
b-tag/mistag	7%

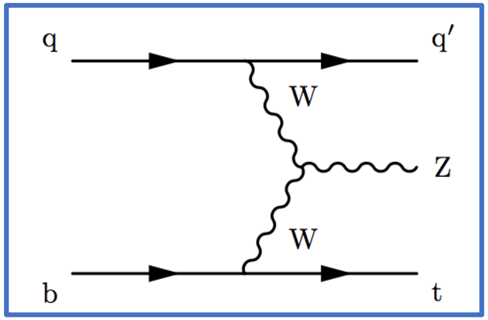
Search for tZq in trileptons at 13 TeV

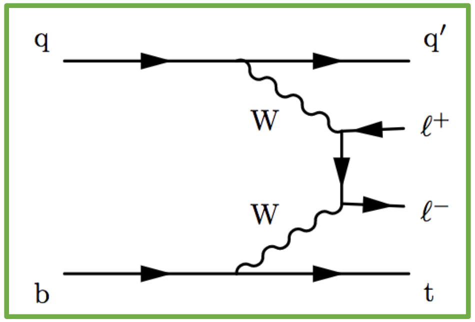
tZq : signal definition

Associated production of a single top and a Z boson:

Z from initial/final states, **WWZ triple gauge coupling**, **“off-peak” production**.







	ATLAS	CMS
QCD	LO (NLO norm.)	NLO
Dilepton pair	On-shell Z only	Off-shell Z accounted $m_{ll} > 30$ GeV
Flavour scheme	4^{th}	5^{th} (norm) and 4^{th} (MC)
Cross sections	800 fb $\pm$6/7% (scale)	94 fb $\pm$2% (scale) $\pm$2.5%(PDF)

- **Different signal definitions between ATLAS and CMS.**
- Accounting for $Z \rightarrow l^+l^-$ decay branching ratio, differences of FS and scale, cross sections are compatible.
- Differences of ~10% on NLO cross section (Eleni Vryonidou @LHCtopWP link).
- Difference in jet multiplicity description can still be larger.

Event selection and analysis strategy

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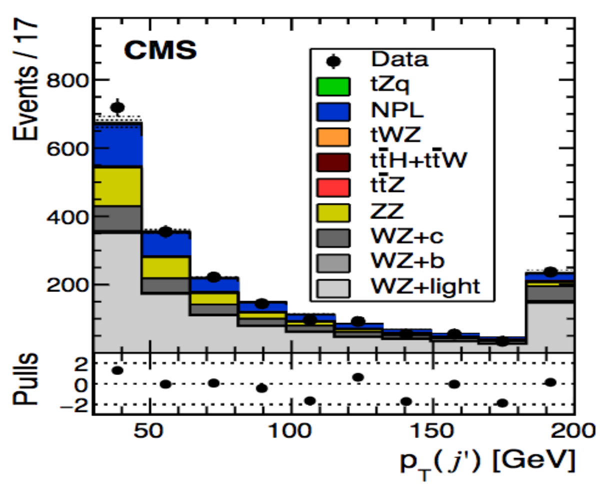
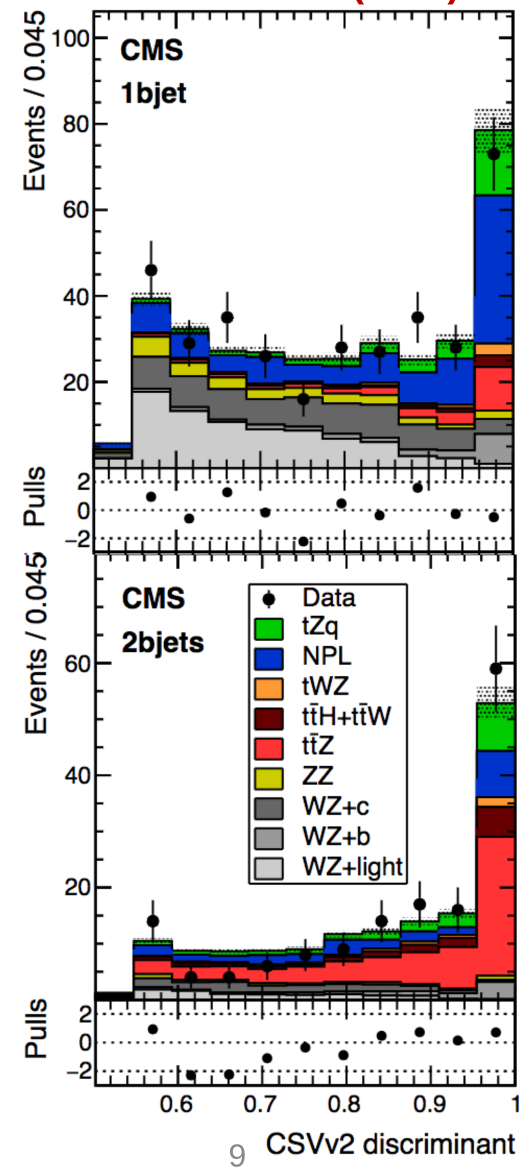
- Tri-leptonic channels ($eee, ee\mu, \mu\mu e, \mu\mu\mu$).
  - single, di- and tri- leptons triggers (~100% efficiency),
  - 3 isolated leptons $p_T > 25$ GeV $|\eta|$<2.4(2.5),
  - 2 same flavour opposite sign leptons ($|m_{ll}$-91|<15 GeV),
  - Jet selection $p_T > 30$ GeV, $|\eta|$<4.5, **b-tagging** eff 83%, mistag 10%.

- Analysis strategy :
  - Likelihood **fit in different samples** (Njets-Nbjets) and different channels : signal or enriched in backgrounds => constrains of the backgrounds,
  - Signal vs background discrimination from a boosted decision tree (BDT) variables (including MEM, 10-20% improvement).
  - **Data-driven background** : non prompt leptons free in the fit, templates obtained from data by inverting lepton isolation.

1b, 1-2j	≥2b	≥1 j, 0b
Signal	ttZ enriched	WZ, non prompt





Evidence of tZq

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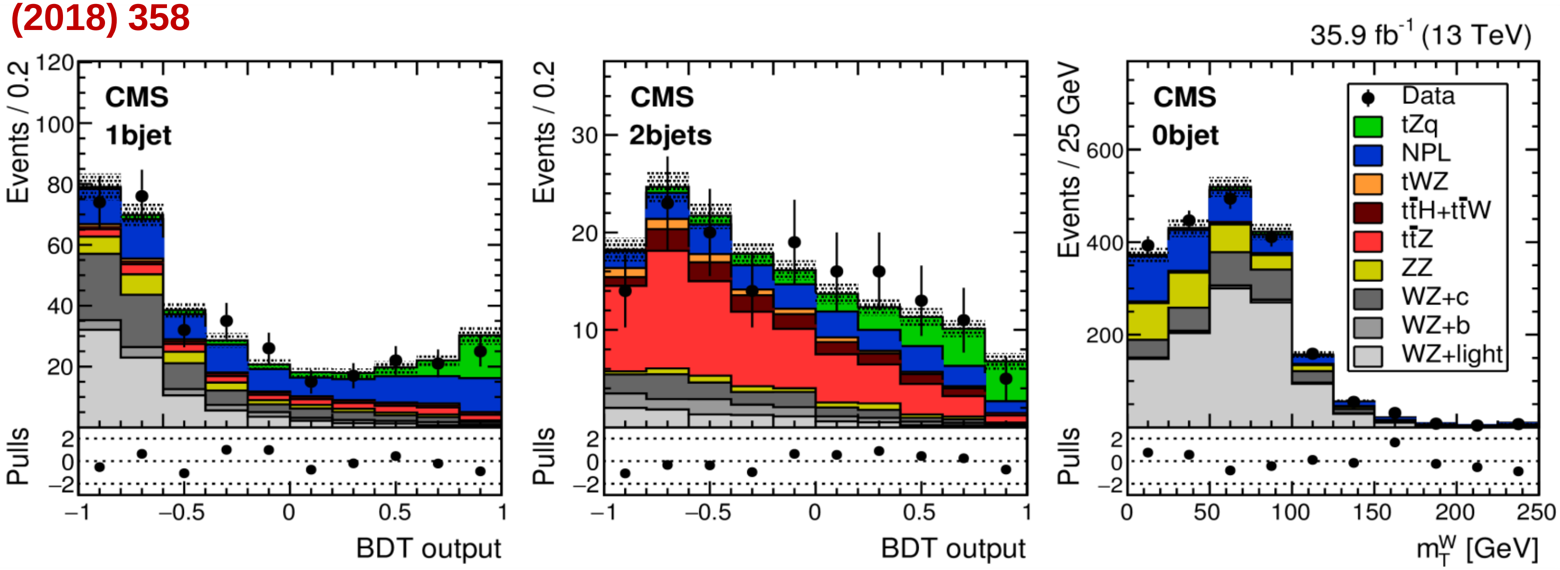

- Statistically dominated.
- Dominant systematics :
  - Non prompt background,
  - QCD scale,
  - B-tagging,
  - ttZ background contamination.
- **Observed (expected) significance of 3.7 (3.1).**

$$\sigma(t\ell^+\ell^-q) = 123^{+33}_{-31}\,(\text{stat})^{+29}_{-23}\,(\text{syst})\,\text{fb},$$

Event selection and analysis strategy

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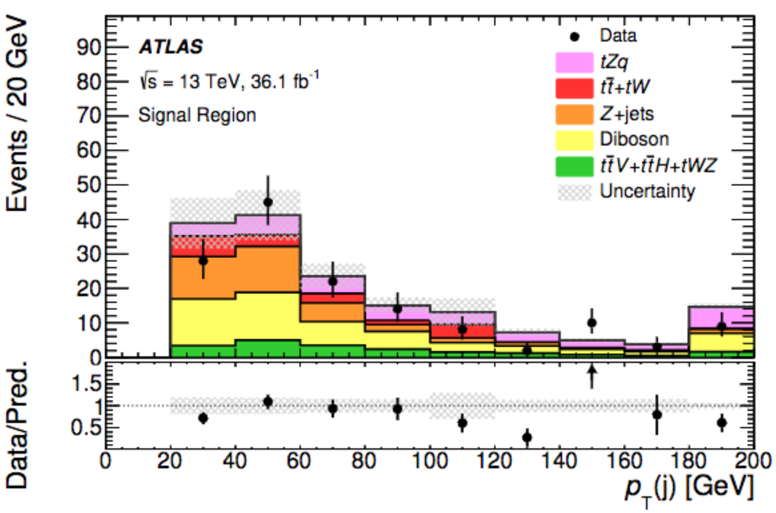
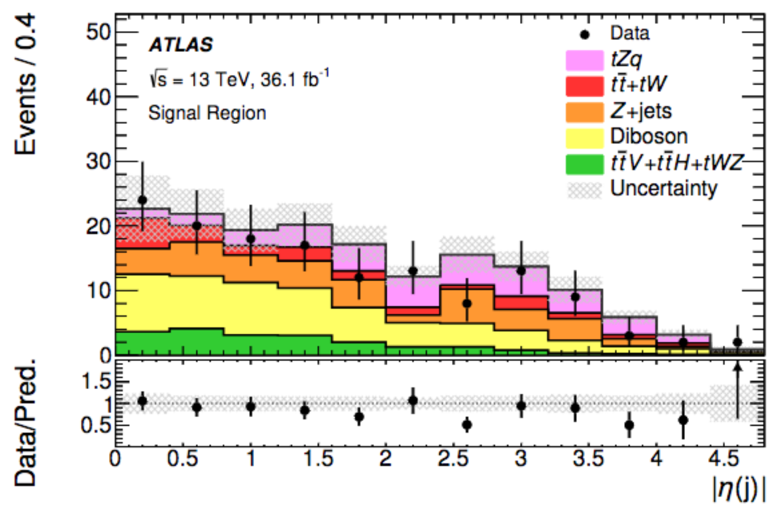
Common selections			
Exactly 3 leptons with $\lvert\eta\rvert < 2.5$ and $p_T > 15$ GeV			
$p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 25$ GeV, $p_T(\ell_3) > 15$ GeV			
p_T(jet) > 30 GeV			
$m_T(\ell_W, \nu) > 20$ GeV			
SR	**Diboson VR / CR**	**$t\bar{t}$ VR**	**$t\bar{t}$ CR**
≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSDF pair
$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV	No OSSF pair
2 jets, $\lvert\eta\rvert < 4.5$	1 jet, $\lvert\eta\rvert < 4.5$	2 jets, $\lvert\eta\rvert < 4.5$	2 jets, $\lvert\eta\rvert < 4.5$
1 b-jet, $\lvert\eta\rvert < 2.5$	—	1 b-jet, $\lvert\eta\rvert < 2.5$	1 b-jet, $\lvert\eta\rvert < 2.5$
—	VR/CR: $m_T(\ell_W, \nu) > 20/60$ GeV	—	—

- Signal extraction :
- fit of a Neural Network output in the signal region only,
- Backgrounds estimated in CR,
- Backgrounds validated in VR.





Data-driven background estimation

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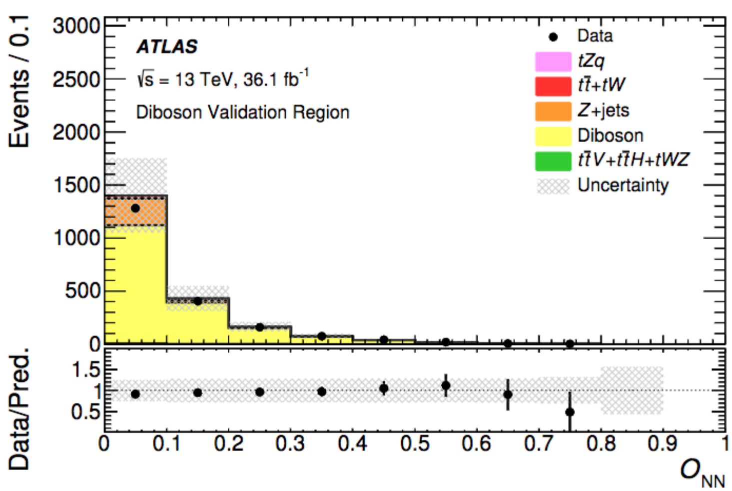
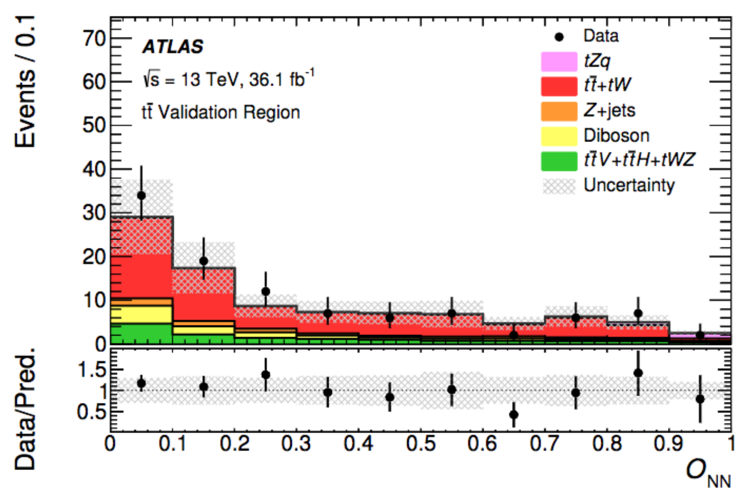
- Diboson :
  - Scale Factors from Control Region (b-tag veto, m_T^W>60 GeV), applied in SR,
  - Uncertainty : varying m_T^W cut and powheg/sherpa difference, total 30%.
- ttbar (fake leptons) :
  - Scale Factors from Control Region (emu-pair, no OSSF pairs), applied in SR,
  - Uncertainty : varying $m_{e\mu}$ cuts and MC stat, total ~40%.
- Z+jets (fake leptons) :
  - Fake Factor ($\#\boldsymbol{evts\ with\ 3\ iso\ leptons}/\#\boldsymbol{events\ with\ 2\ iso\ leptons}$), estimated at low m_T^W, applied to data sample enriched in Z+jets (dilepton+anti-isolated),
  - Uncertainty : MC closure test, other backgrounds contamination (diboson), stat uncertainty, total 40%.





Evidence of tZq

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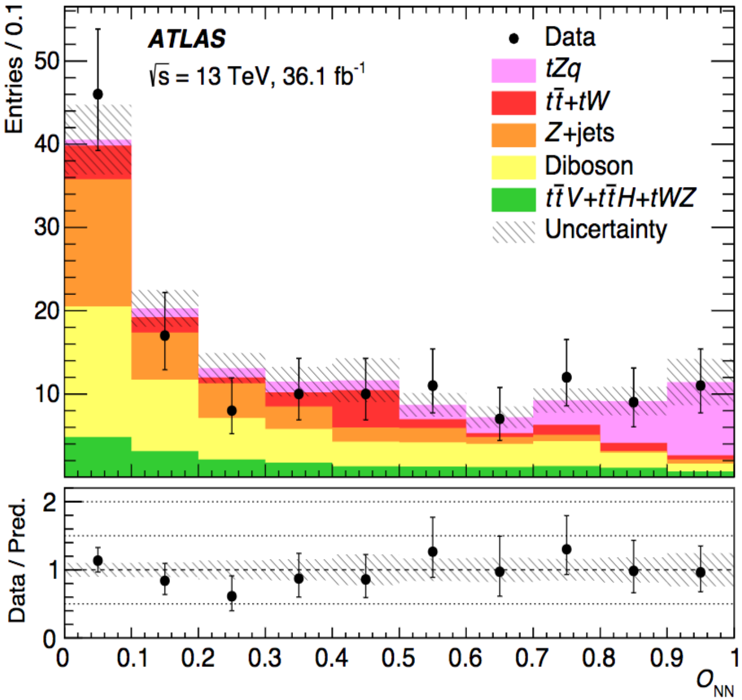
- **Observed (expected) significance of 4.2 (5.4).**
- Measured cross section :

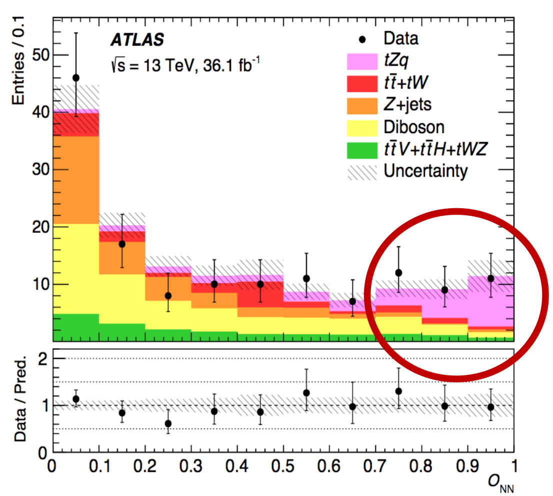
$600 \pm 170\ (stat.) \pm 140\ (syst.)$ fb

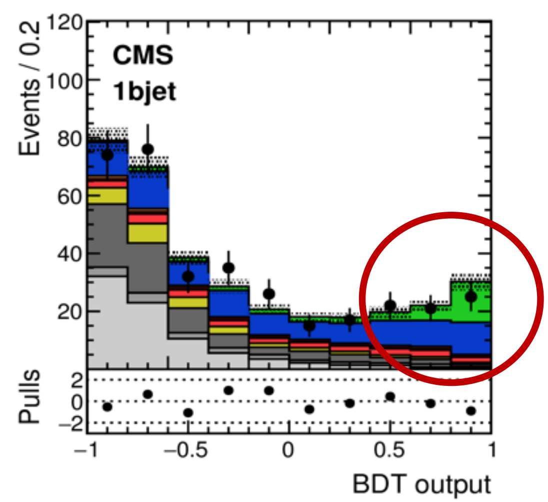


Source	Uncertainty [%]
tZq radiation	±10.8
Jets	±4.6
b-tagging	±2.9
MC statistics	±2.8
tZq PDF	±2.2
Luminosity	±2.1
Leptons	±2.1
E_T^{miss}	±0.3

ATLAS/CMS comparisons

	ATLAS	CMS
Obs(exp) significance	4.2 (**5.4**)	3.7 (**3.1**)
Cross section	$600 \pm 170\,(stat.) \pm 140\,(syst.)$fb $Z \to ll$ branching ratio :$60 \pm 18\,(stat.) \pm 14\,(syst.)$ fb	$123 \pm 33\,(stat.) \pm 29\,(syst.)$ fb Compatible within 1 sigma
btagging	b-tagging : 77%, light-mistag 1%, c-mistag 17%	b-tagging : 83%, mistag 10%
Lepton identification	-	not state-of-the-art lepton ID, resulting in a much larger non-prompt lepton contamination





ATLAS/CMS comparisons

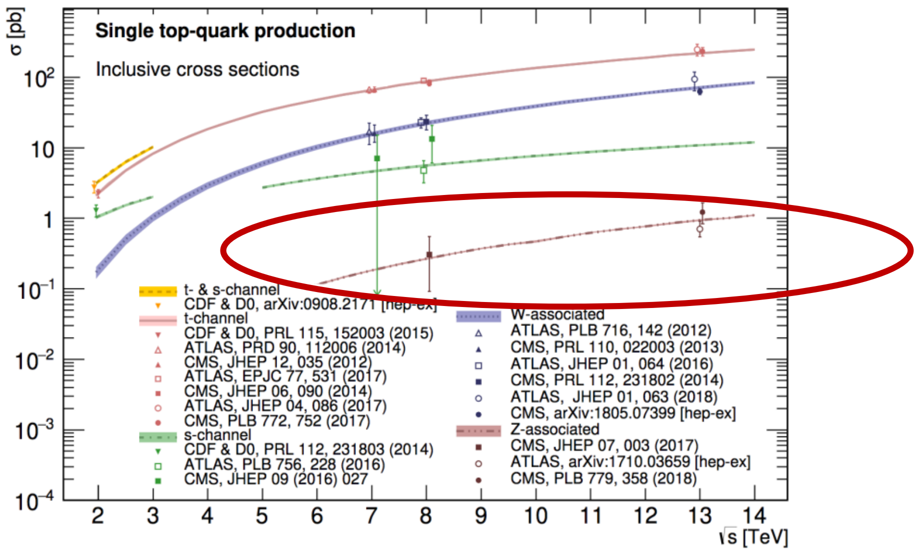
	ATLAS	CMS
Backgrounds from simulation	WZ normalisation from CR Normalisation uncertainties from cross section calculation	WZ constrained by the fit 30%uncertainty on all normalisations
Non prompt leptons	ttbar from MC, normalisation from CR. Z+jets from data, normalisation from CR. Z+jets MC part of the training	ttbar+Zjets, Fully data-driven : data-driven templates, normalisation free in the fit. Non-prompt not part of the training
Analysis strategies	Fit of NN in SR only, no separation of lepton flavours, Asymmetric p_T cuts on leptons =2 jets.	Simultaneous fit in SR and CR, 4 channels treated separately, Symmetric p_T cuts on leptons =2-3 jets.

In summary, there are different approaches followed,
but **the difference in expected significance probably** comes from

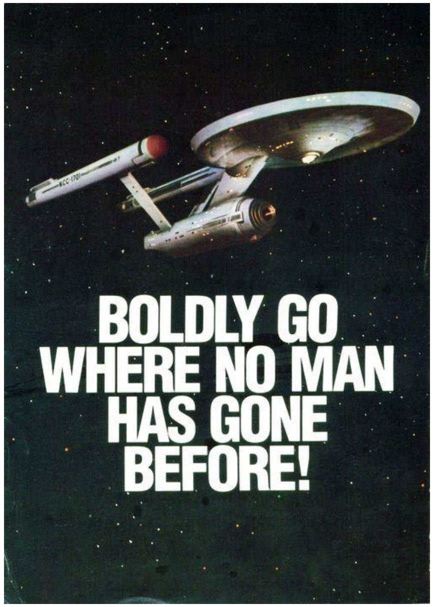
1. **contamination of non prompt leptons background in the signal region** (lepton ID performance and MVA discrimination).
2. **differences in MC generation (LO vs NLO)**.

Conclusion

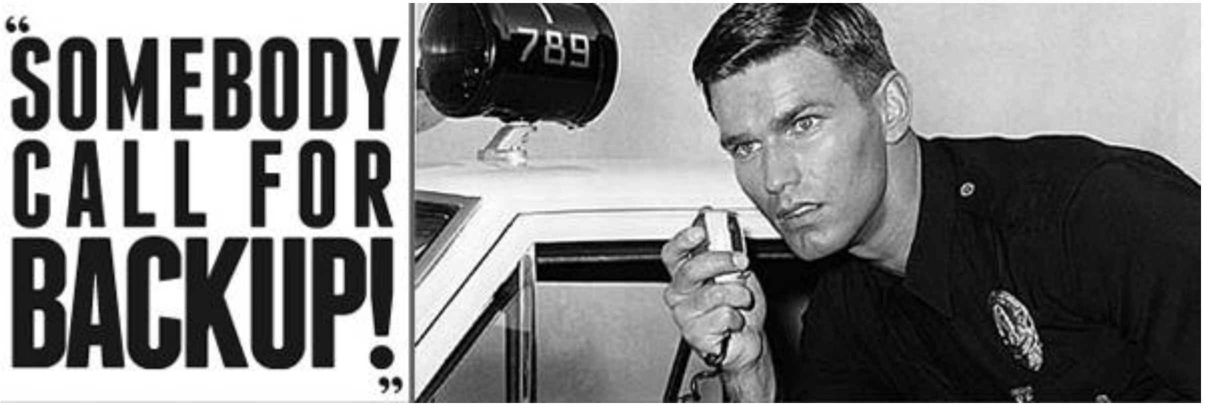
- Thanks to the high luminosity at the LHC, rare single top-quark processes can be reached.
- First evidence of the $t\gamma q$ and tZq processes have been announced by the ATLAS and CMS collaborations.
- **Observation** and **differential** measurements might be **reachable very soon** !
- Open up the paths to discoveries of new SM processes, constraining EFT couplings, and search for new physics !



Giammanco&Schwienhorst Rev. Mod. Phys. 90, 35001 (2018)



Backup



The Matrix Element Method

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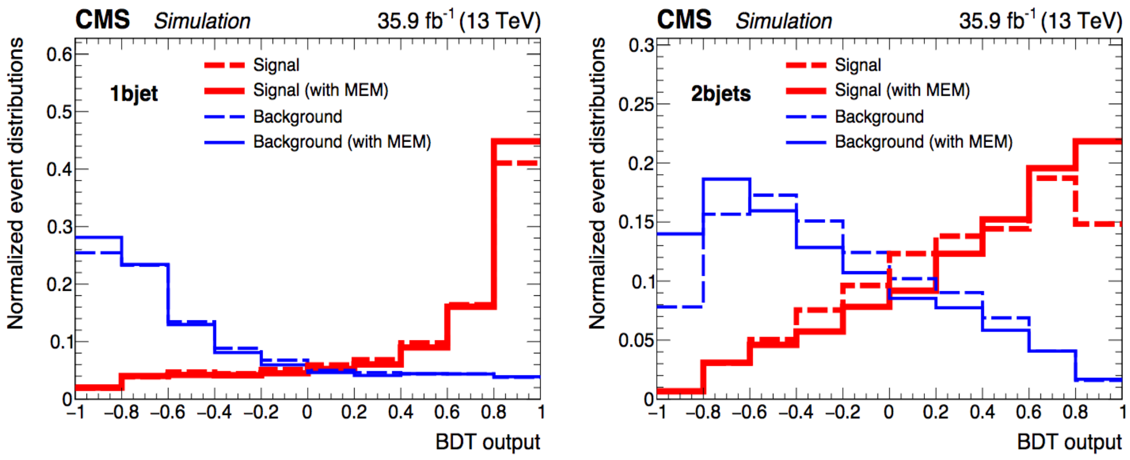
- Matrix Element Method,
  - Determines compatibility of the events with the signal hypothesis,
  - Used as an input to the BDT.

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k>1} p_k^\mu\right) \frac{f(x_1,\mu_F)f(x_2,\mu_F)}{x_1 x_2 s} \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 W(\Phi'|\Phi_\alpha),$$

- **Weight calculation**:
  - **Integration of phase space,**
  - **Accounting for PDF,**
  - **Matrix element calculation (diagrams),**
  - **Transfer function, to account for detector resolution.**

- Improvements of 20% on the discrimination.



$t\gamma q$ events yield

Process	Event yield
$t\bar{t}+\gamma$	1401 ± 131
$W\gamma$ + jets	$329\,^{+79}_{-77}$
$Z\gamma$ + jets	$232\,^{+59}_{-52}$
Misidentified photon	374 ± 74
$t\gamma$(s-,tW-channel)	$57\,^{+8}_{-9}$
$VV\gamma$	8 ± 3
Total background	$2401\,^{+180}_{-177}$
Expected signal	154 ± 24
Total SM prediction	$2555\,^{+182}_{-179}$
Data	2535

$t\gamma q$, data/MC cimparisons

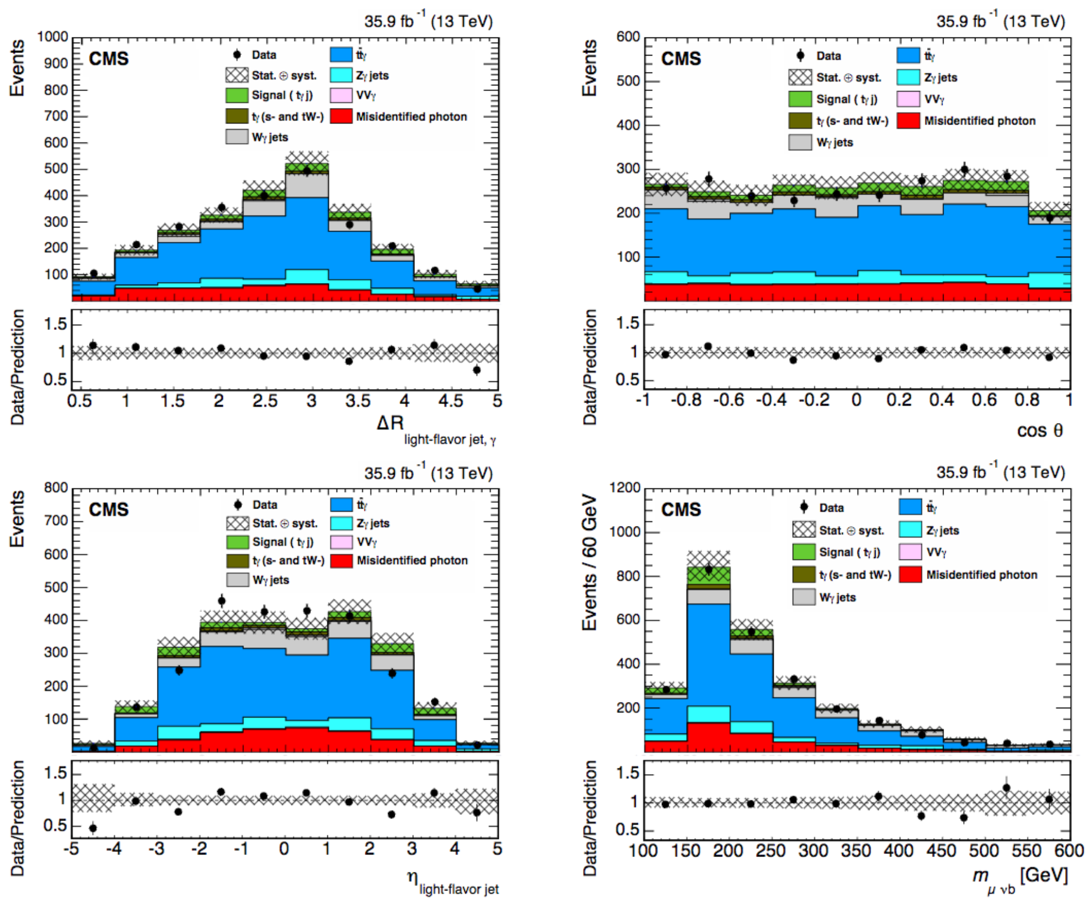
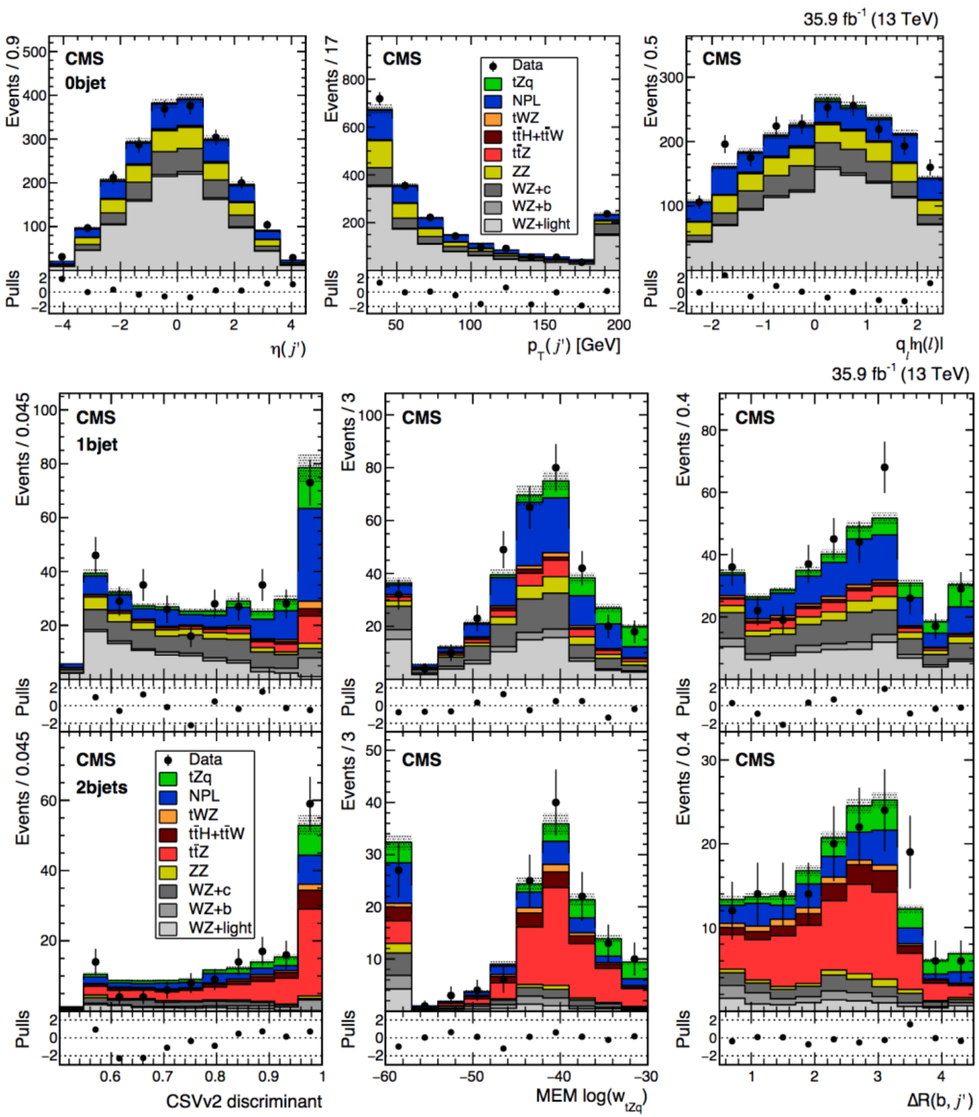


Figure 2: Distributions of some of the input variables to the BDT: $\Delta R(\text{light jet}, \gamma)$ (upper left), $\cos\theta$ (upper right), η of the light-flavor jet (lower left), and $m_{\mu\nu b}$ (lower right) after the final event selection in data (points), and the SM prediction (filled histograms). The hatched band shows the statistical and systematic uncertainties in the estimated signal and background yields, and the vertical bars on the points represent the statistical uncertainties of the data. The ratios of the data to the SM predictions are shown in the bottom panels.

tZq CMS, events yield

Process	eee	eeμ	e$\mu\mu$	$\mu\mu\mu$	All channels	$N^{\text{post-fit}} / N^{\text{pre-fit}}$
tZq	5.0 ± 1.5	6.6 ± 1.9	8.5 ± 2.5	12.3 ± 3.6	32.3 ± 5.0	—
$t\bar{t}Z$	3.7 ± 0.7	4.7 ± 0.9	6.1 ± 1.2	8.0 ± 1.5	22.4 ± 2.2	0.9 ± 0.2
$t\bar{t}W$	0.3 ± 0.1	0.3 ± 0.1	0.7 ± 0.2	0.6 ± 0.2	1.9 ± 0.3	1.0 ± 0.2
ZZ	4.8 ± 1.3	3.2 ± 0.9	9.0 ± 2.5	7.8 ± 2.2	24.7 ± 3.6	1.3 ± 0.3
WZ+b	3.0 ± 0.9	3.4 ± 1.1	4.6 ± 1.4	5.5 ± 1.7	16.6 ± 2.6	1.0 ± 0.2
WZ+c	9.0 ± 2.4	13.7 ± 3.7	18.0 ± 4.9	24.2 ± 6.5	64.8 ± 9.3	1.0 ± 0.2
WZ+light	12.2 ± 1.6	16.6 ± 2.0	22.4 ± 2.8	29.1 ± 3.4	80.3 ± 5.1	0.7 ± 0.1
$t\bar{t}H$	0.6 ± 0.2	0.9 ± 0.3	1.0 ± 0.3	1.5 ± 0.4	4.0 ± 0.6	1.0 ± 0.2
tWZ	1.0 ± 0.3	1.3 ± 0.4	1.7 ± 0.5	2.4 ± 0.7	6.5 ± 1.0	1.0 ± 0.2
NPL: electrons	19.2 ± 3.1	0.6 ± 0.1	17.9 ± 2.8	—	37.7 ± 4.2	—
NPL: muons	—	7.2 ± 2.3	31.1 ± 9.9	15.3 ± 4.9	53.6 ± 11.3	—
Total	58.8 ± 4.8	58.4 ± 5.5	121 ± 12	107 ± 10	345 ± 18	
Data	56	58	104	125	343	

tZq TOP-16-020



BDT variables : “These include the reconstructed **top quark mass** and distributions of variables reflecting the kinematics and **the angles of the recoiling jet**, of the **top quark**, and **of the Z boson**, as well as those of their decay products. “

tZq ATLAS, input to the NN

Table 2: Variables used as input to the neural network, ordered by their separation power.

Variable	Definition
$\|\eta(\mathrm{j})\|$	Absolute value of untagged jet η
$p_{\mathrm{T}}(\mathrm{j})$	Untagged jet p_{T}
m_t	Reconstructed top-quark mass
$p_{\mathrm{T}}(\ell^W)$	p_{T} of the lepton from the W-boson decay
$\Delta R(\mathrm{j}, Z)$	ΔR between the untagged jet and the Z boson
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of W boson
$p_{\mathrm{T}}(t)$	Reconstructed top-quark p_{T}
$p_{\mathrm{T}}(b)$	Tagged jet p_{T}
$p_{\mathrm{T}}(Z)$	p_{T} of the reconstructed Z boson
$\|\eta(\ell^W)\|$	Absolute value of η of the lepton coming from the W-boson decay

tZq ATLAS data/MC comparisons

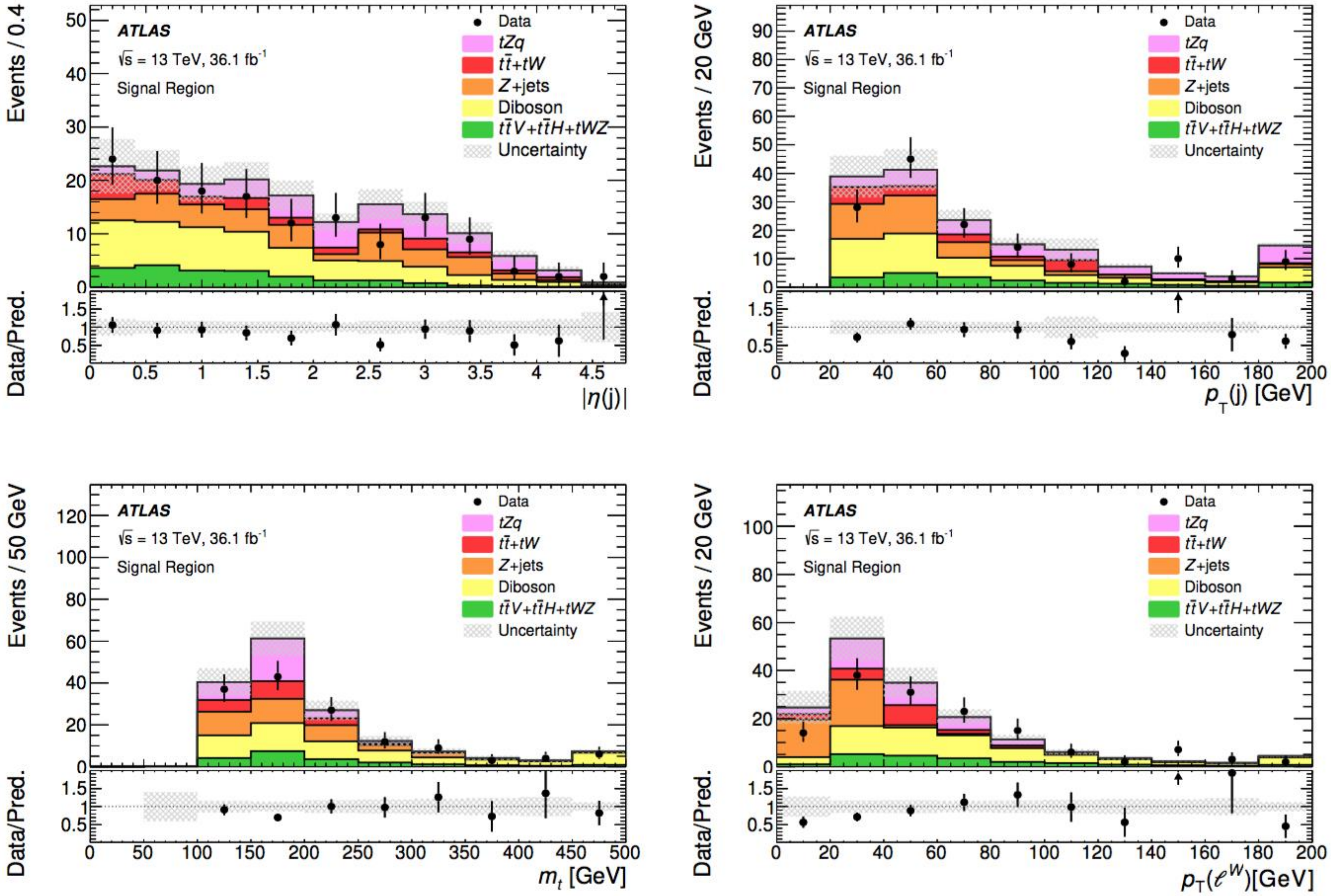


Figure 2: Comparison of the data and the signal+background model for the neural-network training variables with the highest separation power. Signal and backgrounds are normalised to the expected number of events. The $Z+\text{jets}$ background is estimated using a data-driven technique. The uncertainty band includes the statistical uncertainty and the uncertainties in the backgrounds derived in Section 6. The rightmost bin includes overflow events.

tZq ATLAS events yield

Table 4: Fitted yields in the signal region for the Asimov dataset and the data. The fitted numbers of events contain the statistical plus systematic uncertainties.

Channel	Number of events	
	Asimov dataset	Data
tZq	35 ± 9	26 ± 8
$t\bar{t} + tW$	18 ± 7	17 ± 7
$Z + \text{jets}$	37 ± 11	34 ± 11
Diboson	53 ± 13	48 ± 12
$t\bar{t}V + t\bar{t}H + tWZ$	20 ± 3	19 ± 3
Total	163 ± 12	143 ± 11