Search for rare top-quark decays at the LHC

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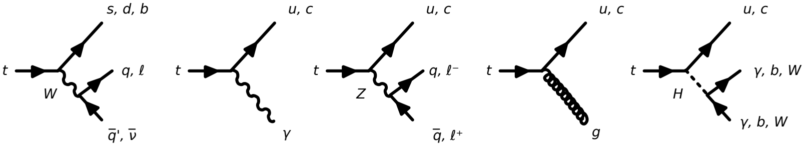
top quark decays



Dominant decay mode $t \to bW$
$BR(t \to bW)_{SM} = 9.98 \times 10^{-1}$
$BR(t \to sW)_{SM} = 1.64 \times 10^{-3}$
$BR(t \to dW)_{SM} = 7.85 \times 10^{-5}$

FCNC decays are suppressed by the GIM mechanism

maximum BR($t \to$ FCNC) in several models:

	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY	RS
$t \to cZ$	$\sim 10^{-14}$	$\sim 10^{-4}$	$\sim 10^{-6}$	$\sim 10^{-10}$	$\sim 10^{-7}$	$\sim 10^{-6}$	$\sim 10^{-5}$
$t \to cg$	$\sim 10^{-12}$	$\sim 10^{-7}$	$\sim 10^{-4}$	$\sim 10^{-8}$	$\sim 10^{-7}$	$\sim 10^{-6}$	$\sim 10^{-10}$
$t \to c\gamma$	$\sim 10^{-14}$	$\sim 10^{-9}$	$\sim 10^{-7}$	$\sim 10^{-9}$	$\sim 10^{-8}$	$\sim 10^{-9}$	$\sim 10^{-9}$
$t \to cH$	$\sim 10^{-15}$	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 10^{-5}$	$\sim 10^{-5}$	$\sim 10^{-9}$	$\sim 10^{-4}$

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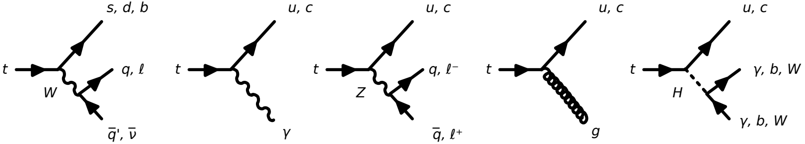
top quark decays



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FCNC decays are suppressed by the GIM mechanism

present experimental limits:

	LEP	HERA	Tevatron	LHC
BR($t \to qZ$)	7.8%	30% (tuZ)	3.2%	0.05%
BR($t \to qg$)	17%	13%	2.0×10^{-4} (ug) 3.9×10^{-3} (cg)	3.1×10^{-5} (ug) 1.6×10^{-4} (cg)
BR($t \to q\gamma$)	2.4%	0.47% ($tu\gamma$)	3.2%	1.6×10^{-4} ($u\gamma$) 1.8×10^{-3} ($c\gamma$)
BR($t \to qH$)	—	—	—	0.56%

will only cover the analyses with best sensitivity for each channel/detector

search for $t \to qZ$ (ATLAS)

JHEP 09 (2012) 139 $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.1$ fb^{-1}

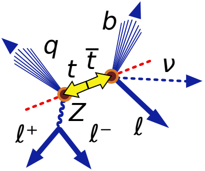
two orthogonal analyses:

- 3ID: 3 fully identified leptons (e, μ); main background from ZZ and WZ production
- 2ID+TL: 2 fully identified leptons (e, μ) and the third one is allowed to be a high quality inner detector track (TL); main background from jets faking TL

- $=3$ID ℓ
- $p_T^{\ell 1} > 25$ GeV
- $p_T^{\ell 2,3} > 20$ GeV

or

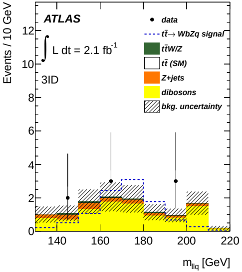
- $=2$ID ℓ + 1 TL
- $p_T^{ID} > 20$ GeV
- $p_T^{TL} > 25$ GeV



- 2 leptons with same flavour and opposite charges
- $|m_Z^{\mathrm{PDG}} - m_{\ell^+\ell^-}| < 15$ GeV
- ≥ 2 jets; $p_T > 25$ GeV; $|\eta^{j1,j2}| < 2.5$; (1 b-tagged in 2ID+TL)
- $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
- $|m_t^{\mathrm{FCNC,SM}} - 172.5$ GeV$| < 40$ GeV
- $|m_W - 80.4$ GeV$| < 30$ GeV

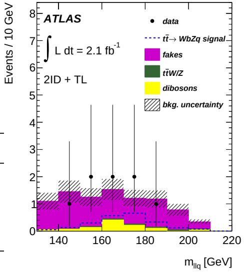
search for $t \to qZ$ (ATLAS)

	3ID	2ID+TL
ZZ and WZ	9.5 ± 4.4	1.0 ± $^{0.5}_{0.6}$
$t\bar{t}W$ and $t\bar{t}Z$	0.51 ± 0.14	0.25 ± 0.05
$t\bar{t}$, WW	0.07 ± 0.02	} 7.6 ± 2.2
Z+jets	1.7 ± 0.7	
Single top	0.01 ± 0.01	
2+3 fake leptons	0.0 ± $^{0.2}_{0.0}$	
Expected background	11.8 ± 4.4	8.9 ± 2.3
Data	8	8
Signal efficiency	(0.205 ± 0.024)%	(0.045 ± 0.007)%



main systematics:

- 3ID: *ZZ* and *WZ* simulation modelling
- 2ID+TL: fake-TL estimation

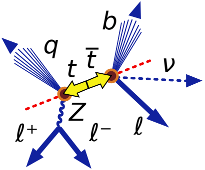


channel	observed	(-1σ)	expected	$(+1\sigma)$
3ID	0.81%	0.63%	0.95%	1.4%
2ID+TL	3.2%	2.15%	3.31%	4.9%
Combination	0.73%	0.61%	0.93%	1.4%

search for $t \to qZ$ (CMS)

PRL 112 (2014) 171802

$\sqrt{s} = 7 + 8$ TeV, $\mathcal{L} = 5 + 20$ fb^{-1}

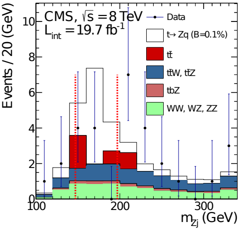


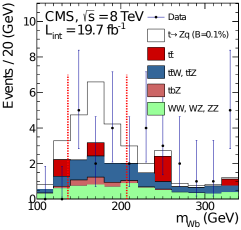
8 TeV:

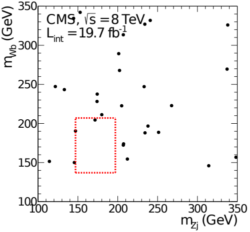
- =3 leptons ($p_T > 20$ GeV)
- 2 leptons with same flavour and opposite charges
- 78 GeV< $m_{\ell^+\ell^-}$ <102 GeV
- $E_T^{\text{miss}} > 30$ GeV
- ≥ 2 jets (($p_T > 30$ GeV, $|\eta| < 2.4$)
- ≥ 1 b-tagged jet
- $|m_t^{\text{SM}} - 172.5$ GeV$|$ <35 GeV
- $|m_t^{\text{FCNC}} - 172.5$ GeV$|$ <25 GeV

- event reconstruction assumes $m_{\ell\nu} = m_W$, $t^{\text{SM}} = \ell + \nu + b$-tagged jet, $t^{\text{FCNC}} = \ell^+ + \ell^- +$ light jet maximizing $\Delta\phi$ to t^{SM}.

search for $t \rightarrow qZ$ (CMS)







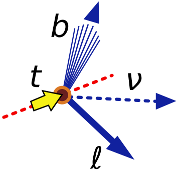
Process	Estimation from data	MC prediction
$t \rightarrow Zq$ ($B = 0.1\%$)	—	$6.4 \pm 0.1 \pm 1.3$
WZ		$0.9 \pm 0.1 \pm 0.3$
ZZ	$1.4 \pm 0.1 \pm 0.3$	< 0.1
Drell–Yan		< 0.1
$t\bar{t}$		$0.7^{+1.1}_{-0.4} \pm 1.2$
$t\bar{t}Z$	$1.7 \pm 0.8 \pm 0.4$	$1.1 \pm 0.1 \pm 0.8$
$t\bar{t}W$		$0.1 \pm 0.1 \pm 0.1$
tbZ		$0.3 \pm 0.1 \pm 0.2$
Total background	$3.1 \pm 0.8 \pm 0.8$	$3.2 \pm 1.2 \pm 1.5$
Observed events	1	—

$B(t \rightarrow Zq)$	8 TeV	7 TeV + 8 TeV
Expected upper limit	<0.10%	<0.09%
Observed upper limit	<0.06%	<0.05%
1 σ boundary	0.06–0.13%	0.06–0.13%
2 σ boundary	0.05–0.20%	0.05–0.18%

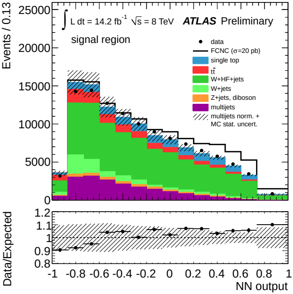
- main systematics for signal: renormalization/factorization scales, PDF, $\sigma^{SM}_{t\bar{t}}$

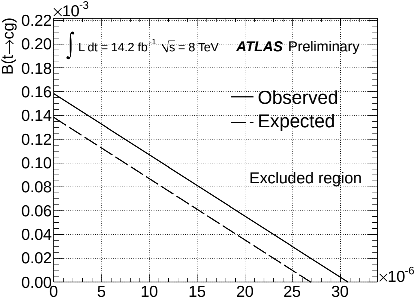
search for $qg \to t$ (ATLAS)

ATLAS-CONF-2013-063 $\sqrt{s} = 8$ TeV, $\mathcal{L} = 14.2$ fb^{-1}



- $t\bar{t}$ production with $t \to qg$ decay difficult to distinguish from multijet production
- search for single top production via FCNC (strong sector)
- = 1 lepton (>25 GeV), E_T^{miss}>30 GeV,
  1 jet (>30 GeV, =1 b-tagged), $m_T^W > 50$ GeV
- MVA method (neural-network with 13 variables) used to improve analysis





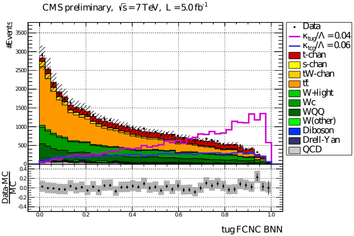
dominant systematics: b-tag, met, background modeling

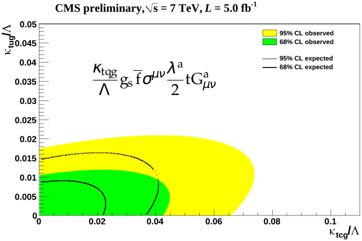
$\mathrm{BR}(t \to ug) < 3.1 \times 10^{-5}$ $\mathrm{BR}(t \to cg) < 1.6 \times 10^{-4}$

search for $qg \to t$ (CMS)

CMS-PAS-TOP-14-007 | $\sqrt{s} = 7$ TeV, $\mathcal{L} = 5$ fb^{-1}

- search for single top production via FCNC in t-channel topology
- $= \mu$ ($p_T > 15$ GeV)
- $= 2, 3$ jets ($p_T > 30$ GeV, $|\eta| < 4.7$)
- ≥ 1 b-tagged jet, ≥ 1 light jet
- different b-tagged jets and light jets CRs
- Bayesian neural-network with 4 variables used to reduce QCD
- Bayesian neural-network with 15 (20) variables used to define tug (tcg) region



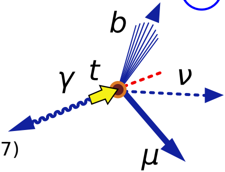


dominant systematics: PDF (9%), signal generator (5%)

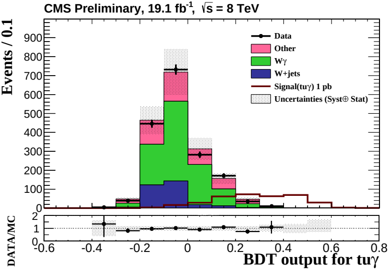
$BR(t \to ug) < 3.55 \times 10^{-4}$ (1.58×10^{-4}) $\qquad$ $BR(t \to cg) < 3.44 \times 10^{-3}$ (1.05×10^{-4})

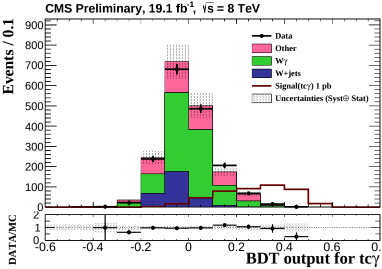
search for $t \to q\gamma$ (CMS)

CMS-PAS-TOP-14-003 $\sqrt{s} = 8$ TeV, $\mathcal{L} = 19.1$ fb^{-1}



- search for single top production via FCNC (QED)
- $= 1\mu$ ($p_T > 26$ GeV, $|\eta| < 2.1$)
- $= 1\gamma$ ($p_T > 50$ GeV, $|\eta| < 2.5$, $\Delta R(\mu, \gamma) > 0.7$)
- ≤ 1 b-tagged jet ($p_T > 30$ GeV, $|\eta| < 2.5$, $\Delta R(b, \gamma) > 0.7$)
- E_T^{miss}>30 GeV, $130 < m_t < 220$ GeV
- MVA method (BDT with 8 variables) used to improve analysis





dominant systematics: $W + \gamma$ and W+jets normalizations

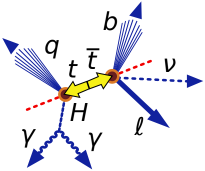
CL_s: BR($t \to u\gamma$) $< 1.6 \times 10^{-4}$ (2.8×10^{-4}) BR($t \to c\gamma$) $< 1.8 \times 10^{-3}$ (2.6×10^{-3})

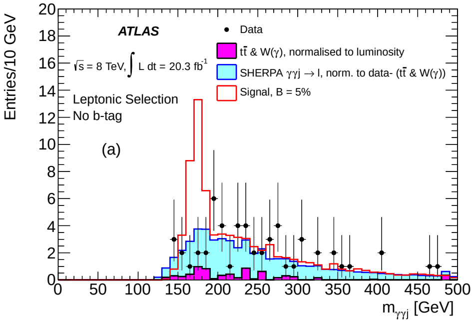
$\sim 28\%$ improvement if σ_{NLO} corrections are considered

search for $t \to qH$ (ATLAS)

JHEP 06 (2014) 008 $\sqrt{s} = 7$ TeV $\mathcal{L} = 4.7$ fb^{-1} + $\sqrt{s} = 8$ TeV $\mathcal{L} = 20.3$ fb^{-1}

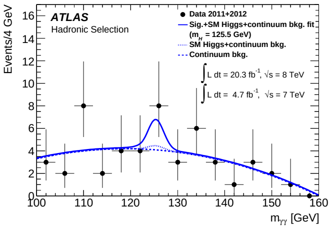
- ≥ 2 photons ($p_T^{\gamma 1} > 40$ GeV, $p_T^{\gamma 2} > 30$ GeV)
- two topologies searched for:
  - hadronic
    - =0 leptons
    - =4 jets (1 b-tagged)
    - 156 GeV$<m_{\gamma\gamma j}<$191 GeV
    - 130 GeV$<m_{jjj}<$210 GeV
  - leptonic (=1 lepton)
    - $m_T^W > 30$ GeV
    - $\geq$2 jets (1 b-tagged)
    - 156 GeV$<m_{\gamma\gamma j}<$191 GeV
    - 135 GeV$<m_{\ell\nu j}<$205 GeV

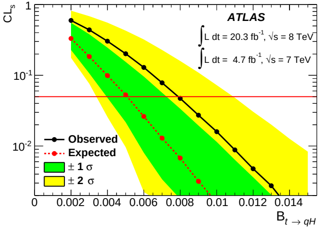




search for $t \to qH$ (ATLAS)

- 50 hadronic and 1 leptonic events selected
- maximum likelihood fit is performed





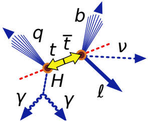
dominant systematics: photon ID, JES, ISR/FSR, *b*-tag

95% CL limits:

	observed	expected
BR($t \to cH$)	0.79%	0.51%

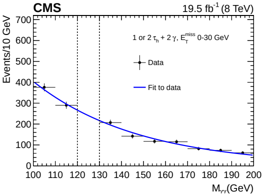
search for $t \to qH$ (CMS)

PRD 90 (2014) 112013 $\sqrt{s} = 8$ TeV $\mathcal{L} = 19.5$ fb^{-1} + $\sqrt{s} = 7$ TeV $\mathcal{L} = 5$ fb^{-1}

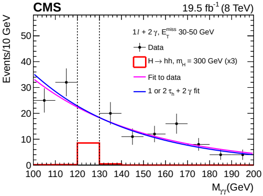


- $\geq 3\ell$ (e, μ, τ_{had}) or $= 1\ell + 2\gamma$ photons ($p_T^{\gamma 1} > 40$ GeV, $p_T^{\gamma 1} > 30$ GeV)

- multilepton events classified according to:
  - number of leptons (3, 4)
  - flavour and charge combinations
  - Z boson reconstructions ($75 < m_Z < 105$ GeV)
  - 5 E_T^{miss} bins (3ℓ), 4 E_T^{miss} bins (4ℓ)



- diphoton events ($120 < m_{\gamma\gamma} < 130$ GeV) classified according to:
  - lepton flavour
  - presence of a b-tagged jet
  - 4 E_T^{miss} bins



search for $t \to qH$ (CMS)

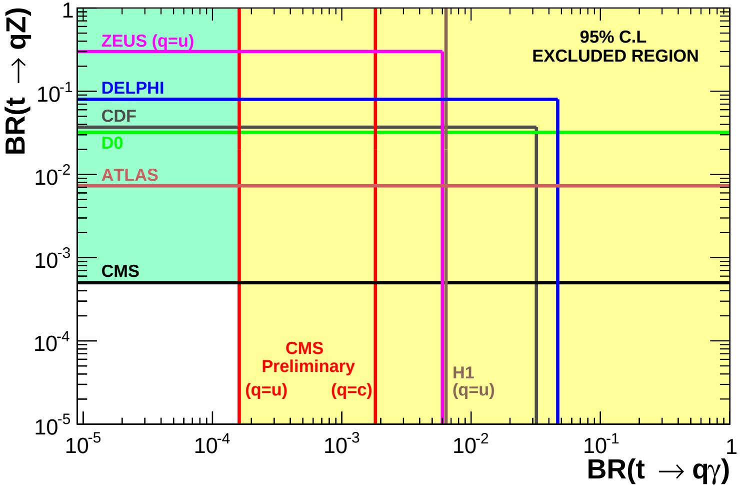
10 most sensitive search channels (signal for BR=1%):

Channel	E_T^{miss} (GeV)	N_b	Obs.	Exp.	Sig.
$\gamma\gamma\ell$	(50, 100)	≥ 1	1	2.3 ± 1.2	2.88 ± 0.39
	(30, 50)	≥ 1	2	1.1 ± 0.6	2.16 ± 0.30
	(0, 30)	≥ 1	2	2.1 ± 1.1	1.76 ± 0.24
	(50, 100)	0	7	9.5 ± 4.4	2.22 ± 0.31
	(100, ∞)	≥ 1	0	0.5 ± 0.4	0.92 ± 0.14
	(100, ∞)	0	1	2.2 ± 1.0	0.94 ± 0.17
$\ell\ell\ell$	(50, 100)	≥ 1	48	48 ± 23	9.5 ± 2.3
(OSSF1, below-Z)	(0, 50)	≥ 1	34	42 ± 11	5.9 ± 1.2
$\ell\ell\ell$	(50, 100)	≥ 1	29	26 ± 13	5.9 ± 1.3
(OSSF0)	(0, 50)	≥ 1	29	23 ± 10	4.3 ± 1.1

dominant systematics: diphoton background, $t\bar{t}$ and τ_{had} misidentification

Higgs boson decay mode		Upper limits on $\mathcal{B}(\mathrm{t} \to \mathrm{ch})$		
		Obs.	Exp.	68% CL range
$\mathcal{B}(\mathrm{h} \to \mathrm{WW}^*)$	$= 23.1\%$	1.58%	1.57%	(1.02–2.22)%
$\mathcal{B}(\mathrm{h} \to \tau\tau)$	$= 6.15\%$	7.01%	4.99%	(3.53–7.74)%
$\mathcal{B}(\mathrm{h} \to \mathrm{ZZ}^*)$	$= 2.89\%$	5.31%	4.11%	(2.85–6.45)%
Combined multileptons (WW^*, $\tau\tau$, ZZ^*)		1.28%	1.17%	(0.85–1.73)%
$\mathcal{B}(\mathrm{h} \to \gamma\gamma)$	$= 0.23\%$	0.69%	0.81%	(0.60–1.17)%
Combined multileptons + diphotons		0.56%	0.65%	(0.46–0.94)%

BR($t \to qZ$) vs BR($t \to q\gamma$)



HL-LHC sensitivities

- search for top quark FCNC decays can be one of the HL-LHC goals
- ATLAS and CMS sensitivities for top quark FCNC decays at $\sqrt{s} = 14$ TeV, 3 ab^{-1} was/is being studied
- exclusion limits improve by one order of magnitude

ATLAS

decay	7/8 TeV limit	HL-LHC sensitivity	
$t \to qZ$	5.8×10^{-4}	extrapolation	3.8×10^{-5} (ATL-PHYS-PUB-2012-001)
$t \to ug$	3.1×10^{-5}	extrapolation	2.1×10^{-6}
$t \to cg$	1.6×10^{-4}		1.4×10^{-5}
$t \to q\gamma$	—	extrapolation	3.8×10^{-5} (ATL-PHYS-PUB-2012-001)
$t \to qH$	8.3×10^{-3}	extrap / MC	1.5×10^{-4} (ATL-PHYS-PUB-2013-012)

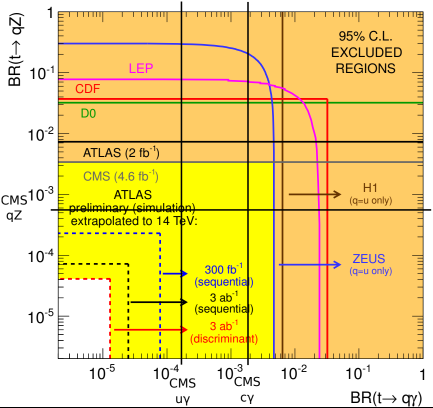
CMS

decay	7/8 TeV limit	HL-LHC sensitivity	
$t \to qZ$	5×10^{-4}	extrap	7×10^{-5} (CMS-PAS-FTR-13-016)
		MC	1×10^{-4}

summary

- ATLAS and CMS searches for top quark FCNC decays at 7 TeV and 8 TeV
- Z, γ, H, g channels covered
- no evidence for signal found
- 95% CL limits derived

- ATLAS and CMS sensitivities at 14 TeV, 3 ab^{-1} expected to improve by one order of magnitude



	LEP	HERA	Tevatron	LHC
BR($t \to qZ$)	7.8%	30% (tuZ)	3.2%	0.05%
BR($t \to qg$)	17%	13%	2.0×10^{-4} (ug) 3.9×10^{-3} (cg)	3.1×10^{-5} (ug) 1.6×10^{-4} (cg)
BR($t \to q\gamma$)	2.4%	0.47% ($tu\gamma$)	3.2%	1.6×10^{-4} ($u\gamma$) 1.8×10^{-3} ($c\gamma$)
BR($t \to qH$)	—	—	—	0.56%

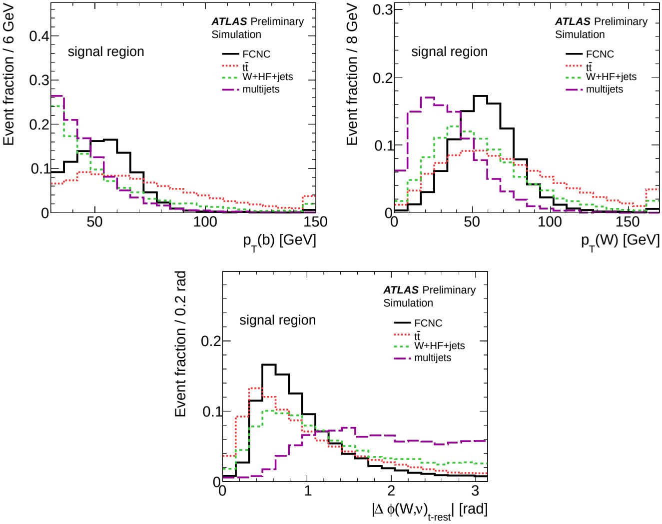
b a c k u p

Input variables of BNN used in the analysis

Table 3: Variables used as input to the neural network ordered by their importance, as estimated from the total correlation loss to the target caused by its removal.

Variable	loss of total correlation (%)	Variable	loss of total correlation (%)
$p_T(b)$	34	$\Delta\phi(\ell, W)$	6
$p_T(W)$	19	$\Delta\phi(b, \ell\nu b)$	5
$\Delta\phi(W, \nu)$ in the top quark rest frame	13	$\Delta R(\ell, \ell\nu b)$	5
Charge of the lepton $q(\ell)$	12	$\Delta\phi(W, \ell\nu b)$	4
$\eta(\ell)$	11	$\eta(\nu)$	4
$\Delta\phi(\ell, b)$	9	E_T^{miss}	4
$\eta(\ell\nu b)$	9		

search for $qg \to t$ (ATLAS)



Input variables of BNNs used in the analysis (1/2)

Variable	Description	tug BNN	tcg BNN
$p_T(b_1)$	p_T of the leading-b-jet (the b-tagged jet with the highest p_T) — hereinafter we use the notations "leading" and "second-leading" for jets correspondingly to their order in p_T, the decreasing one	V	V
$p_T(b_2)$	p_T of the second-leading b-jet		V
$p_T(j_1 j_2)$	a vector sum of p_T of the first and the second-leading jets	V	V
$p_T(\sum_{i \neq i_{best}} \vec{p}_T(j_i))$	a vector sum of p_T of all jets without the best jet. The notation "best jet" is used for the jet which gives the invariant mass of the top quark closest to the value of 172.5 GeV, which is used in the MC simulation	V	V
$p_T(j_L)$	p_T of the light-flavour jet (untagged jet with the highest value of $\|\eta\|$)	V	V
$p_T(\mu)$	transverse momenta of the muon		V
$p_T(W, b_1)$	p_T of the W boson and the leading-b-jet	V	V
$p_T(W)$	p_T of the W boson	V	V
E_T^{miss}	missing transverse energy (energy of the reconstructed neutrino)		V

Input variables of BNNs used in the analysis (2/2)

Variable	Description	tug BNN	tcg BNN
$\eta(\mu)$	η of the muon	V	V
$\eta(j_L)$	η of the light-flavour jet	V	V
$M(\sum_{i \neq i_{best}}(j_i))$	the invariant mass of all jets without the best one		V
$M(jW)$	the invariant mass of the W boson and all jets		
$M(W, b_1)$	the invariant mass of the W boson and the leading-b-jet	V	V
$M(\sum_i(j_i))$	the invariant mass of all jets	V	V
$\Delta R(j_1, j_2)$	equal to $\sqrt{(\eta(j_1) - \eta(j_2))^2 + (\varphi(j_1) - \varphi(j_2))^2}$	V	V
$\Delta R(\mu, j_2)$	equal to $\sqrt{(\eta(\mu) - \eta(j2))^2 + (\varphi(\mu) - \varphi(j2))^2}$		
$\Delta\varphi(\mu, E_T^{miss})$	azimuthal angle between the lepton and the reconstructed neutrino	V	V
$\cos(\theta_{\mu,j_L})\|_{top}$	the cosine of the angle between the lepton and the light flavour jet in the top quark rest frame, the top quark is reconstructed with the leading-b-jet [45]	V	V
$\cos(\theta_{\mu,W})\|_W$	the cosine of the angle between the lepton and the W boson in the W boson rest frame [46]	V	V
$\cos(\theta_{\mu,j_1})\|_{top}$	the cosine of the angle between the lepton and the first jet in the top quark rest frame		V
$Q(\mu)$	a charge of the lepton	V	V

Input variables of BDT used in the analysis

- photon transverse momentum,
- b-jet transverse momentum,
- muon transverse momentum,
- angular separation between the photon and the muon, $\Delta R(\mu, \nu)$,
- angular separation between the photon and the b-jet, $\Delta R(b\text{−jet}, \gamma)$,
- CSV discriminant value for the b-tagged jet,
- jet multiplicity,
- cosine of the angle between the reconstructed top quark and the photon.

other analyses

ATLAS:

- arXiv:1504.04605: $BR(t \to uH) < 1\%$.

CMS:

- CMS-PAS-TOP-12-021: $BR(t \to ug) < 0.56\%$, $BR(t \to cg) < 7.12\%$, $BR(t \to uZ) < 0.51\%$ and $BR(t \to cZ) < 11.40\%$.