



TOP-LHC-FRANCE  
May 2017



# Rare Single-Top Processes

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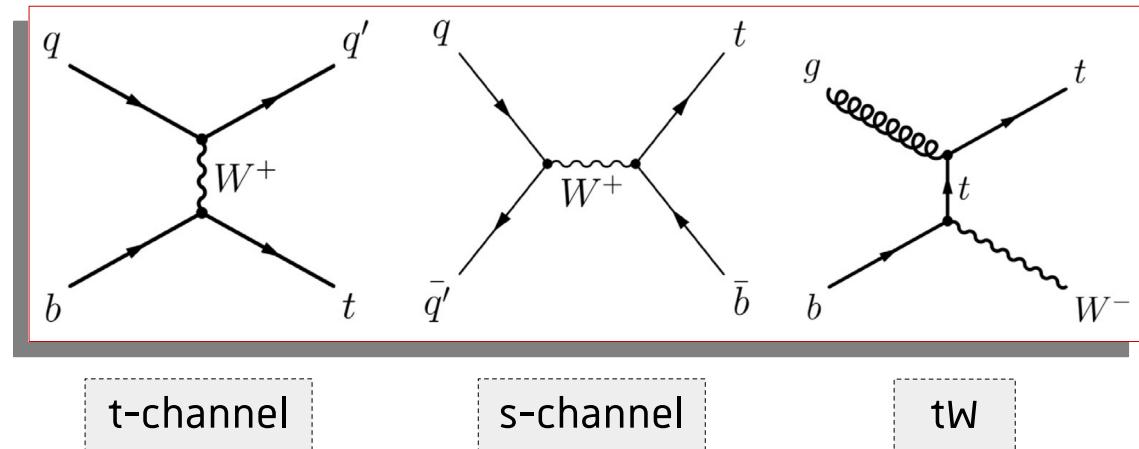
**Nicolas Tonon** (IPHC Strasbourg)

on behalf of CMS & ATLAS collaborations



- 1 Motivations
- 2 Searches for single top production in the s-channel
- 3 Searches for single top + Z
- 4 Searches for Anomalous Couplings/FCNC
- 5 Conclusion

- 3 SM production modes :

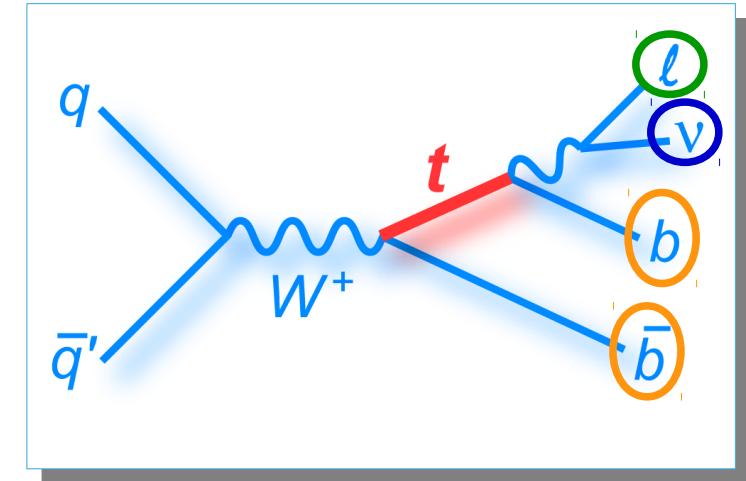


- Rare single top processes → **low cross-sections** & large backgrounds
  - e.g. : { - s-channel production  
-  $t\gamma q$ ,  $tZq$ ,  $tHq$   
-  $tWZ$   
- FCNC
- Interesting environment to look for SM deviations
  - Anomalous couplings, FCNC → **Possible gateway to BSM physics**
  - Much less constrained than first 2 generations & b-quark
- Such processes will constitute **backgrounds to future searches**

# Search in the s-channel

- Evidence, not yet observed !
- Final state : {

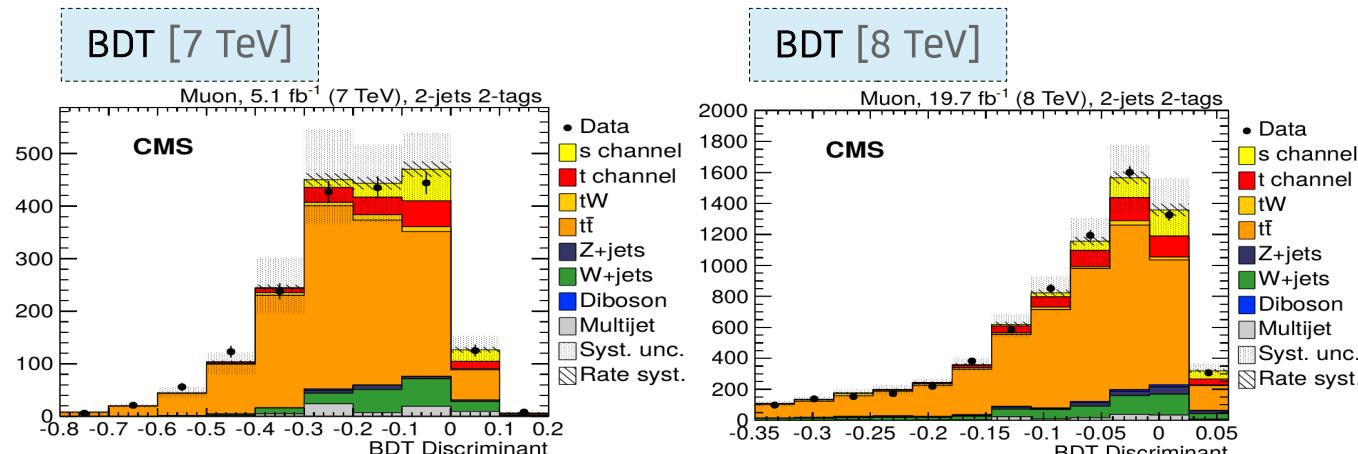
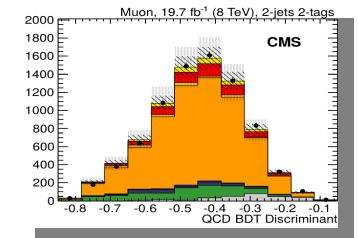
  - Isolated muon / electron
  - 2 b-tagged jets
  - MET



Energy	Process	Cross section [pb]
Tevatron (1.96 TeV)	$t$	$2.10 \pm 0.13$
	$s$	$1.05 \pm 0.06$
	$Wt$	$0.25 \pm 0.03$
LHC (7 TeV)	$t$	$65.9^{+2.1}_{-0.7}$ (scale) $^{+1.5}_{-1.7}$ (PDF)
	$s$	$4.56 \pm 0.07$ (scale) $^{+0.18}_{-0.17}$ (PDF)
	$Wt$	$15.6 \pm 0.4$ (scale) $\pm 1.1$ (PDF)
LHC (8 TeV)	$t$	$87.2^{+2.8}_{-1.0}$ (scale) $^{+2.0}_{-2.2}$ (PDF)
	$s$	$5.55 \pm 0.08$ (scale) $\pm 0.21$ (PDF)
	$Wt$	$22.2 \pm 0.6$ (scale) $\pm 1.4$ (PDF)
LHC (13 TeV)	$t$	$216.99^{+6.62}_{-4.64}$ (scale) $\pm 6.16$ (PDF)
	$s$	$10.3 \pm 0.4$
	$Wt$	$71.1 \pm 3.8$

- Main backgrounds :
- t-channel & tW production
- $t\bar{t}$
- $W/Z + jets$
- Diboson
- Multijet backgrounds ← Data

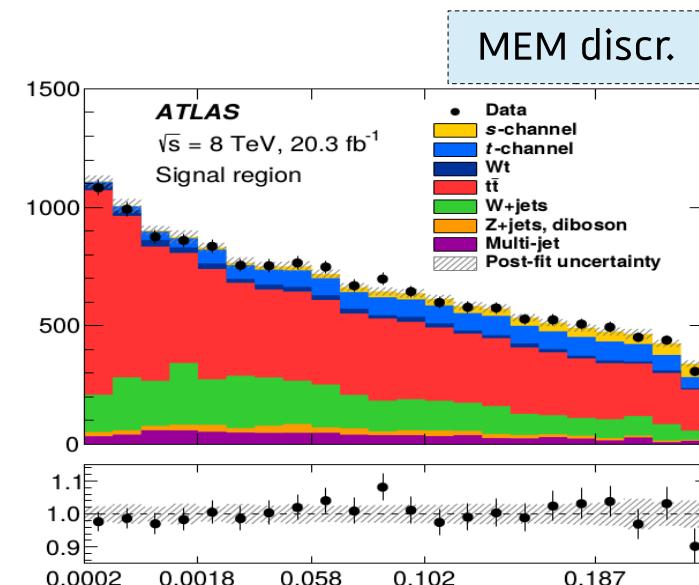
- Combined fit to 7 TeV (muon channel) and 8 TeV (muon & electron channels) data results
- 3 independent regions ( $\neq$  numbers of light & b-tagged jets)
- Multijet background :
  - 7 TeV → Norm. estimated from fit to  $m_{TW}$
  - 8 TeV → Cut on **dedicated QCD-BDT discriminant**  
→ Norm. estimated from fit to discriminant
- Signal extraction : Simultaneous fit to a signal vs background BDT discriminant (in all 3 regions)



Observed significance → **2.5  $\sigma$**  (1.1  $\sigma$  expected)

$$\sigma_s = 13.4 \pm 7.3 \text{ (stat + syst)} \text{ pb}$$

- Previous ATLAS result based on same dataset using **BDT** gave  $1.3\sigma$  observed significance
- Muon & electron channels
- + Improved by using a **Matrix Element Method (MEM)** discriminant
- ↗ Also  $\approx 50\%$  improvement due to latest calibrations, optimization & better simulations
- Signal extraction: Simultaneous fit to **MEM discriminant** (signal region) & **lepton charge** (control region – constrain WZ+jets)

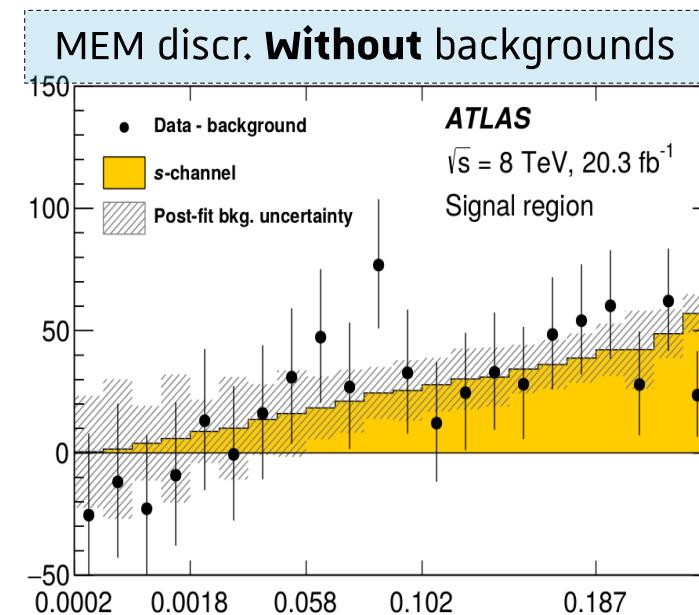


Observed significance  $\rightarrow 3.2\sigma$  ( $3.9\sigma$  expected)

$$\sigma_s = 4.8 \pm 0.8(\text{stat.})^{+1.6}_{-1.3}(\text{syst.}) \text{ pb}$$



[ATLAS Collar., Phys. Lett. B756 (2016) 228-246]



# Searches for tZq

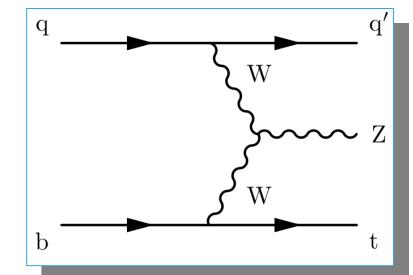
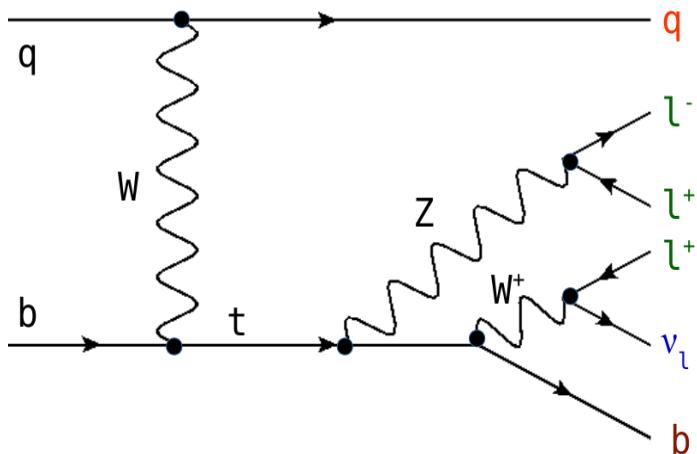


IPHC WORK



- Analyses at 8 TeV & 13 TeV (pre-approved)
- Predicted by SM, expect its observation in near future
- Same **FCNC final state** & sensitive to WWZ trilinear coupling

- Final state :
- 3 leptons ( $\mu/e^-$ )
  - 1 b-tagged jet
  - 1-2 light jets
  - MET



- Main backgrounds :
- WZ + jets, ZZ
  - ttZ, ttW, ttH
  - DY, tt>, WW  $\leftrightarrow$  « Fakes » **← Data**

# Search for tZq at CMS [8 TeV]

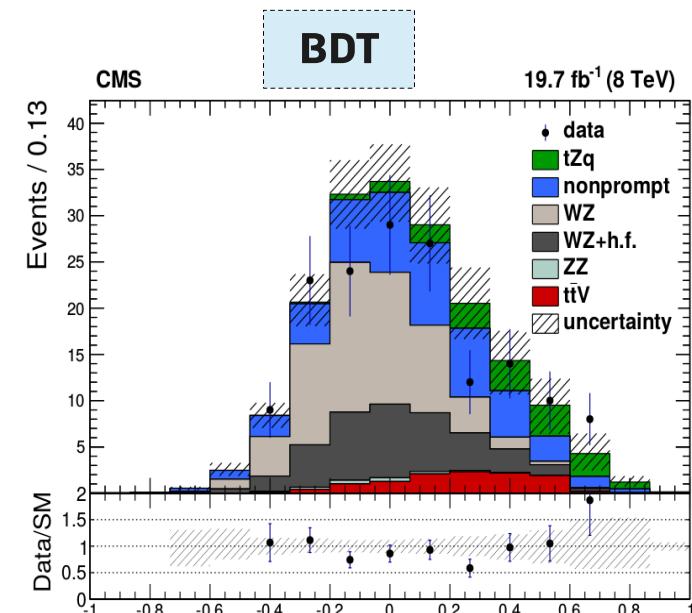
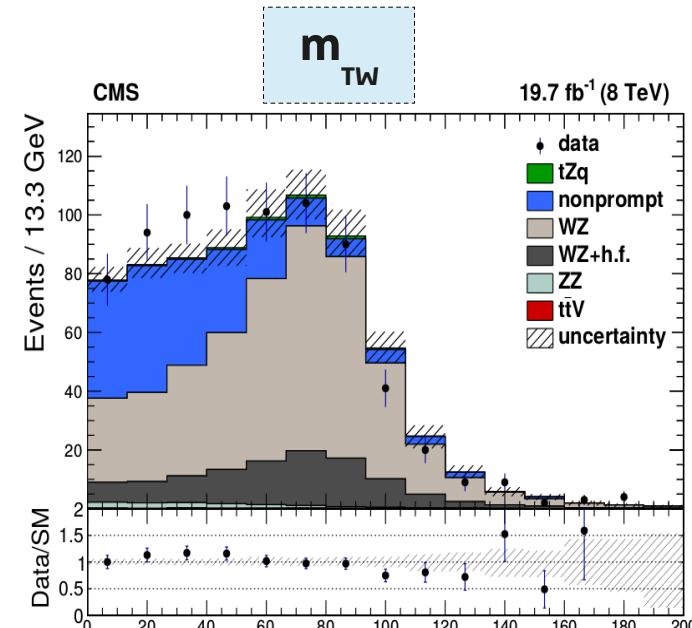
- Simultaneous fit in 2 regions :
  - Signal region → BDT
  - WZ-enriched Control region →  $m_{TW}$
- « Fake » backgrounds estimated from data :
  - Distributions obtained in enriched region (inverted iso cut)
  - Normalizations left free in the fit

Observed significance →  $2.4\sigma$  ( $1.8\sigma$  expected)

Channel	Cross section (fb)
eee	$0^{+9}$
ee $\mu$	$11^{+13}_{-10}$
$\mu e e$	$24^{+19}_{-16}$
$\mu \mu \mu$	$5^{+9}_{-5}$
Combined fit	$10^{+8}_{-7}$



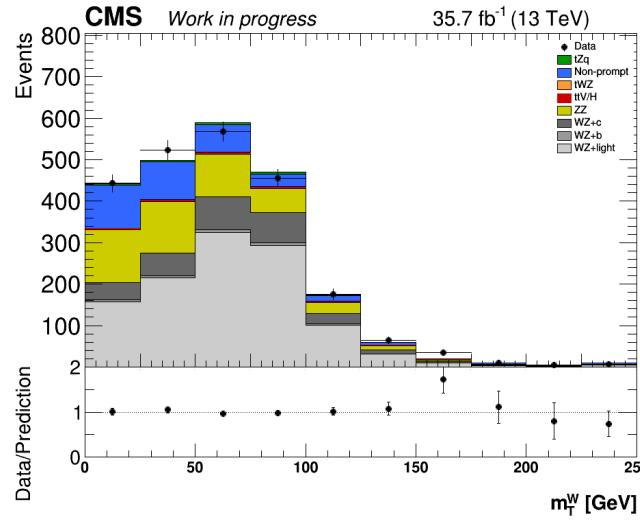
[CMS-TOP-12-039]



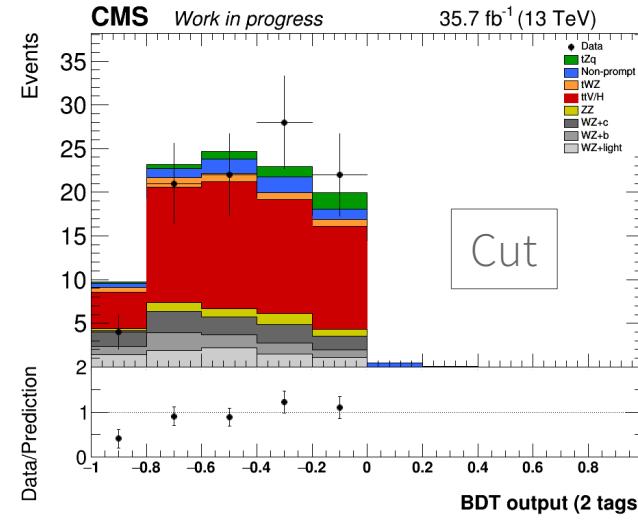


- Not approved, being finalized
- + Adding a ttZ Control region with dedicated **BDT-ttZ**  
→ Fitted simultaneously with the 2 other regions

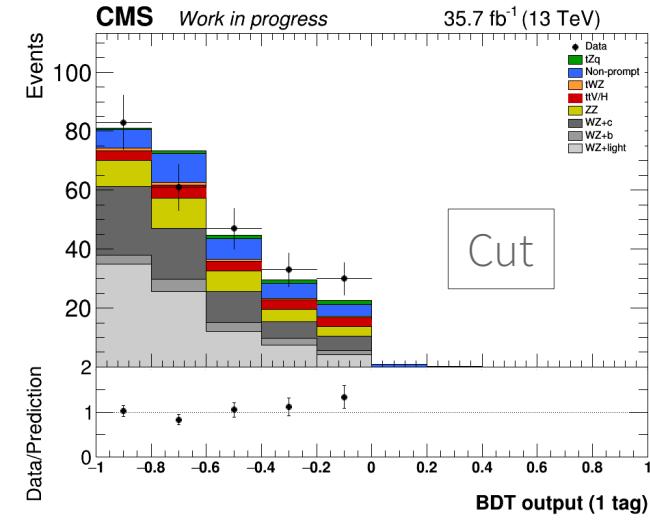
**CR WZ -  $m_{TW}$**



**CR ttZ - BDTttZ**



**SR tZq - BDT**



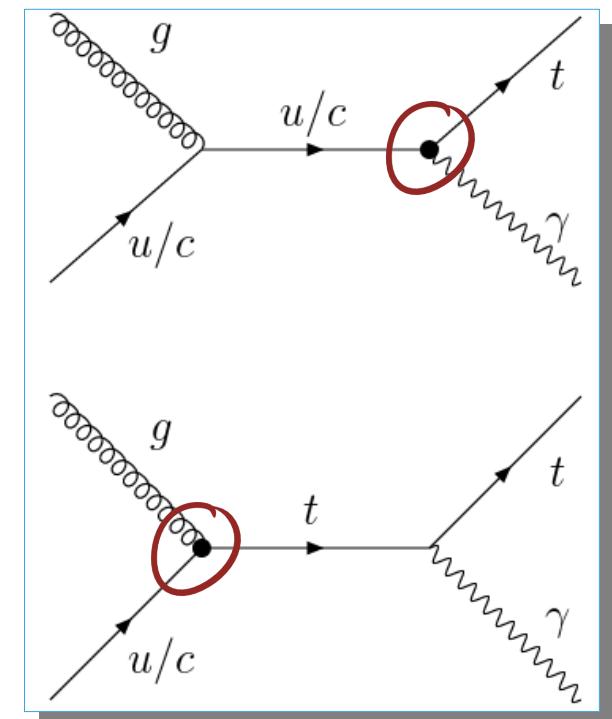
Postfit templates from the 3 regions (after MaxLikelihood Fit with ttZ as signal)

# Searches for FCNC

- Flavor-Changing Neutral Currents forbidden at tree-level in SM & suppressed at higher orders [GIM Mechanism]

> In SM, can only appear through quantum loop corrections  
with  $\mathcal{B}(t \rightarrow Xq) \approx 10^{-17} - 10^{-12}$

▪ Many BSM models predict FCNC enhancement  
up to  $\mathcal{B}(t \rightarrow Xq) \approx 10^{-3}$  [1]



FCNC observation would be  
unambiguous proof of new physics !

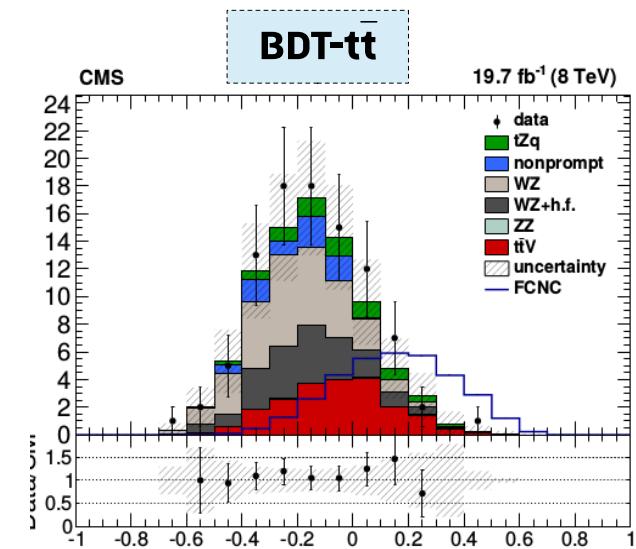
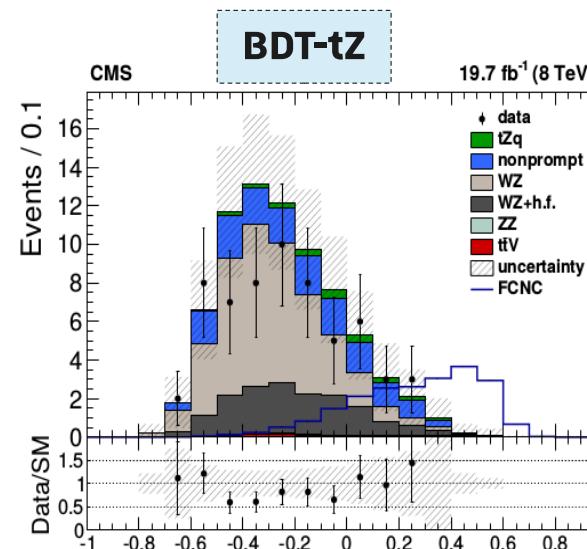
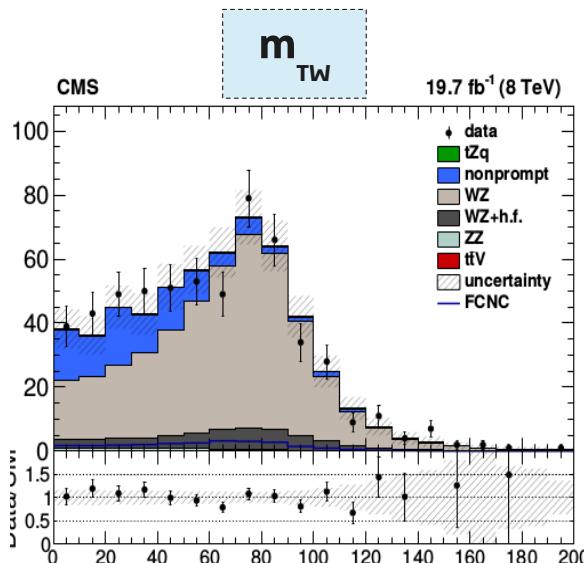
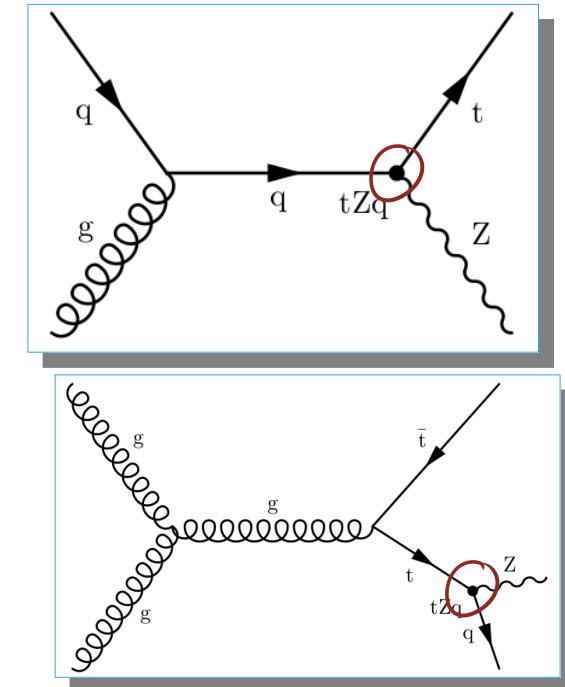


[1] J.A. Aguilar-Saavedra, Acta. Phys. Pol. B 35, 2695 (2004)

- Common framework with SM analysis
- Simultaneous fit in 2 regions :
  - Signal region 'tZ'
  - Signal region 'tt'
  - WZ-enriched Control region

→ BDT-tZ  
 → BDT-tt  
 → m<sub>TW</sub>

Branching fraction	Expected	68% CL range	95% CL range	Observed
$\mathcal{B}(t \rightarrow Zu) (\%)$	0.027	0.018 – 0.042	0.014 – 0.060	0.022
$\mathcal{B}(t \rightarrow Zc) (\%)$	0.118	0.071 – 0.222	0.049 – 0.484	0.049

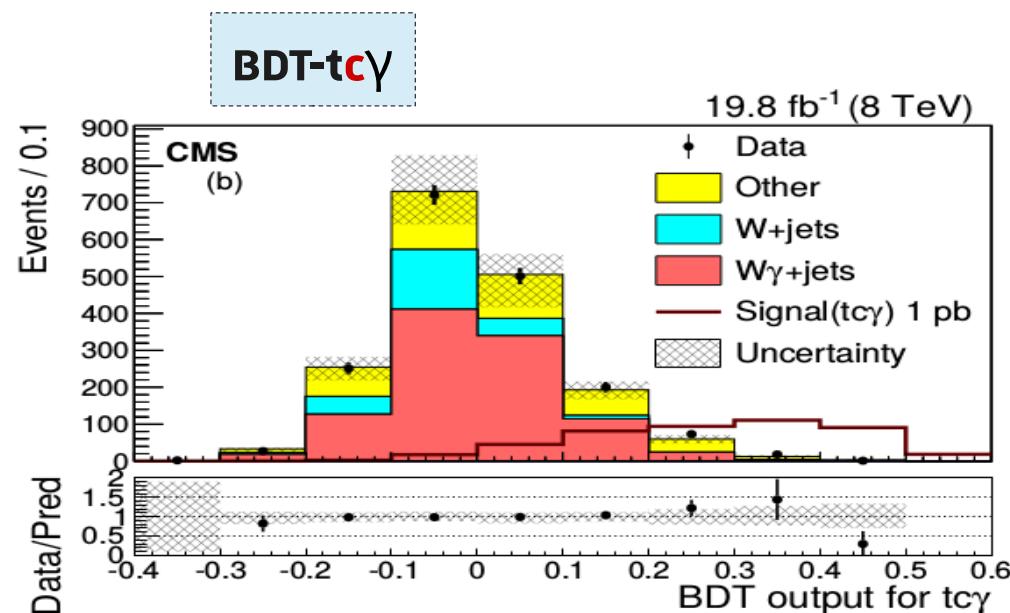
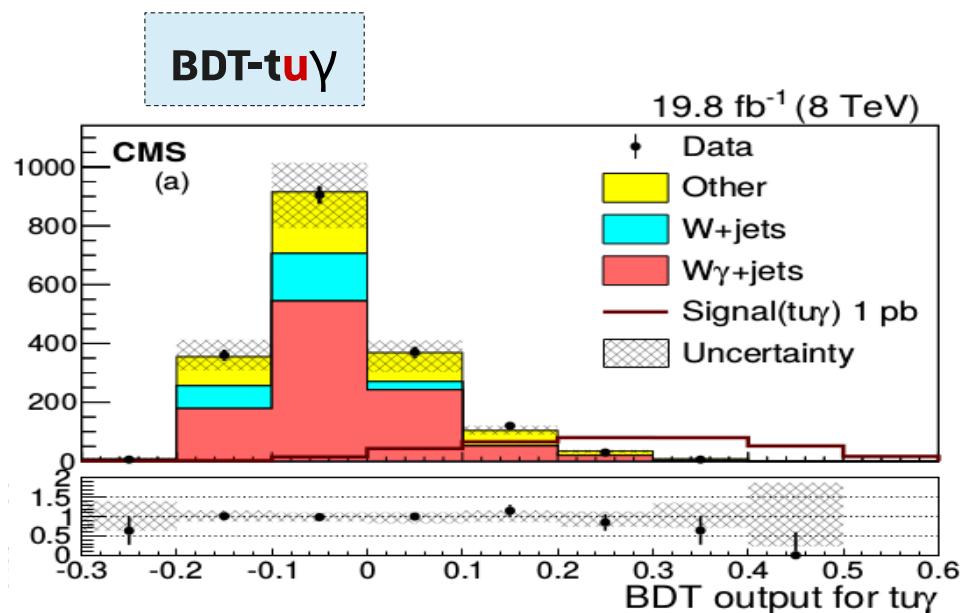
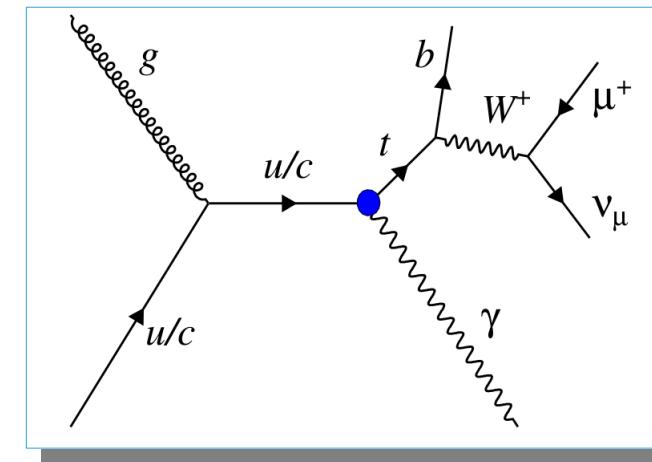


# Search for $t\gamma q$ at CMS

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- Muon decay channel only
- $W+jets$  &  $W\gamma+jets$  estimated from fit to a **dedicated Neural Network (NN)** output
- Use **separate BDTs** for  $t u \gamma$  &  $t c \gamma$  signals to exploit differences

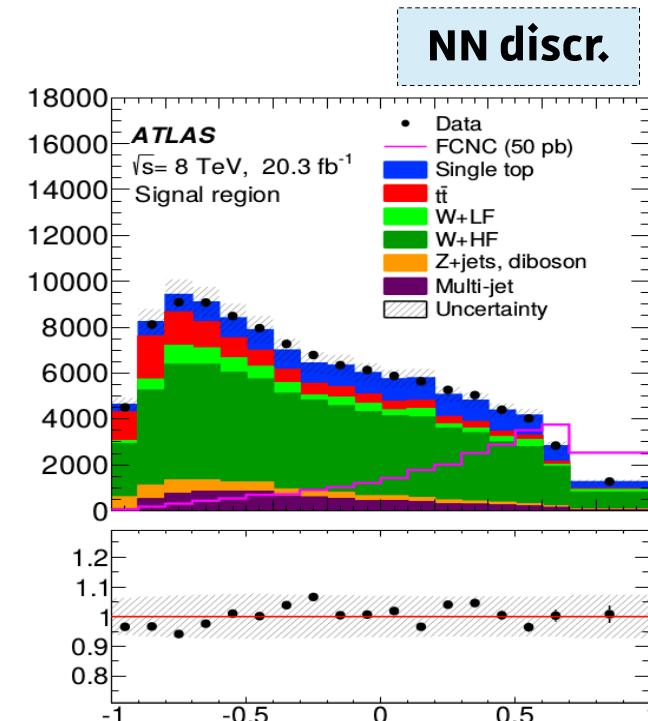
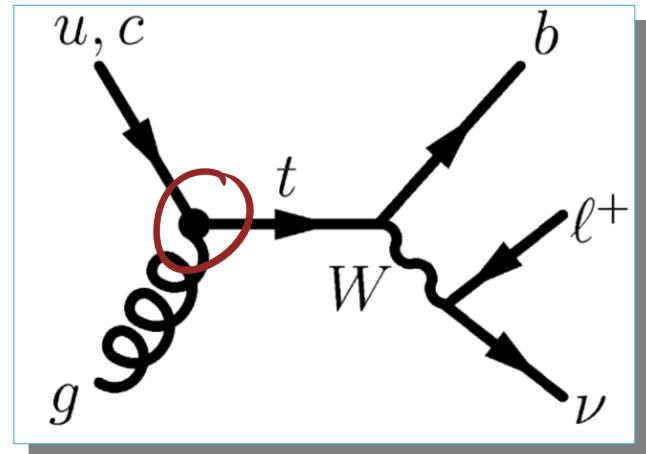
→ **Fit to BDT** discriminant in signal region



# Search for $qg \rightarrow t$ at ATLAS

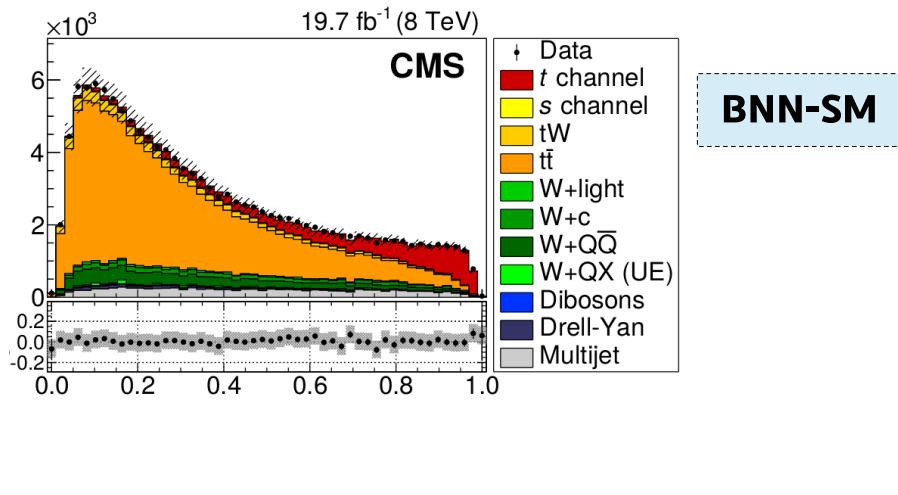
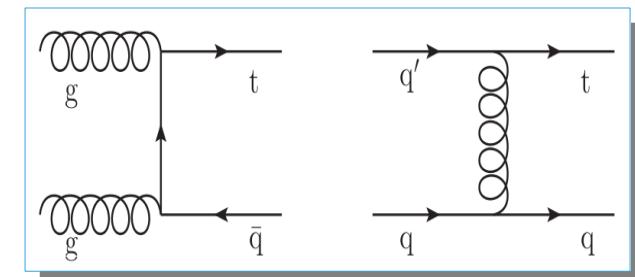
13

- $t \rightarrow qg$  overwhelmed by multijet backgrounds  
→ Look only for **anomalous production**  
(Muon & electron decay channels)
- Multijet background shape :
  - Electron  $\leftarrow$  MC simulation
  - Muon  $\leftarrow$  Data enriched in multijet (invert iso cut, etc.)
- Multijet norm. from **fit to MET** in Signal region (no MET cut)
- Signal characteristics :
  - Top decay products  $\approx$  back-to-back (transverse plane)
  - W decay products have small angles
  - Top charge asymmetry greater than in SM
- Signal extraction : Fit to a **NN classifier** in Signal region



[ATLAS Collar., Eur. Phys. J. C (2016) 76:55]

- Combined results of 7 TeV & 8 TeV searches for **Anomalous Wtb Couplings** & **FCNC** in **t-channel** single top production [muon channel]
- Use several **Bayesian Neural Networks** (BNN)
- Cut on dedicated **BNN-QCD** to reject multijet backgrounds
- BNN-SM** separates t-channel events from all other SM processes

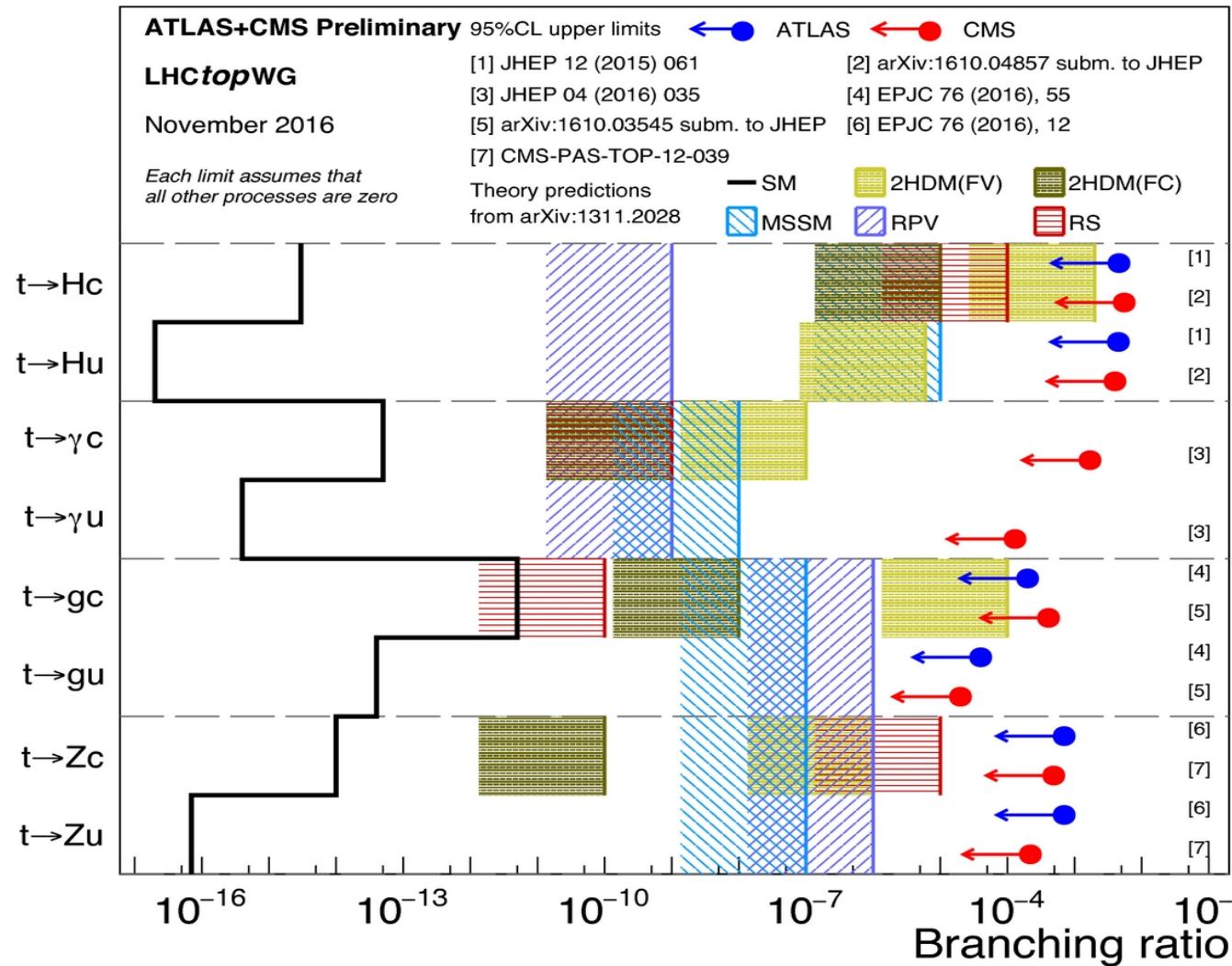


$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu \left( f_V^L P_L + f_V^R P_R \right) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{\sigma^{\mu\nu} \partial_\nu}{M_W} \left( f_T^L P_L + f_T^R P_R \right) t + \text{h.c.},$$

- { 3 BNNs to estimate individual Anom. Couplings
- 2 BNNs to estimate **tug** & **tcg** (FCNC)

(Most general, lowest-dimension, CP-conserving Lagrangian for Wtb vertex)

- No sign of FCNC yet
- Some channels will soon reach sufficient precision to start rejecting BSM models



- Rare Single top processes possess interesting features, both for **testing the SM** predictions & searching for new physics by **probing anomalous couplings**
  - All results in **good agreement** with the SM until now
  - **Approaching sufficient sensitivity** to start investigating some BSM models predictions
  - Upcoming data will turn some analysis into **precision measurements**, and will make possible to look for even rarer processes
- More promising analysis to come ! ( $tHq \rightarrow$  top yukawa sign, etc.)

# BACKUP

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- Region definitions [N jets – M tags] :

- 2 jets – 2 tags → Signal extraction
- 3 jets – 2 tags → Constrain ttbar
- 2 jets – 1 tag → Constrain W-jets

*(N jets with  $p_T > 40$ , M jets passing the b-tagging requirement)*

Events with at least one muon were selected by the online trigger 9, requiring  $p_T > 17 \text{ GeV}$  at 7 TeV,  $p_T > 24 \text{ GeV}$  at 8 TeV,  $|\eta| < 2.1$ , and lepton isolation criteria. Similarly, for electrons at 8 TeV, the corresponding values are  $p_T > 27 \text{ GeV}$  and  $|\eta| < 2.5$ .

Source	Uncertainty (%)				
	$\mu, 7 \text{ TeV}$	$\mu, 8 \text{ TeV}$	$e, 8 \text{ TeV}$	$\mu + e, 8 \text{ TeV}$	$7+8 \text{ TeV}$
Statistical	34	15	14	10	11
$t\bar{t}$ , single top quark normalization	29	15	14	12	14
W/Z+jets, diboson normalization	23	11	13	12	12
Multijet normalization	9	3	5	2	2
Lepton efficiency	14	1	2	1	3
Hadronic trigger	5	—	—	—	1
Luminosity	10	5	6	4	6
JER & JES	66	39	29	34	18
b tagging & mistag	34	15	14	14	16
Pileup	6	11	7	9	7
Unclustered $E_T$	5	8	2	6	5
$\mu_R, \mu_F$ scales	54	34	31	30	28
Matching thresholds	43	11	12	7	17
PDF	12	8	7	7	9
Top quark $p_T$ reweighting	3	5	7	6	6
Total uncertainty	115	64	54	55	47

Process	Uncertainty (%)
$t\bar{t}$	10
W+jets	20
Z +jets	20
Diboson	30
tW	15
t channel	10
Multijet, $\mu, 7 \text{ TeV}$	30, 100, 100
Multijet, $\mu, 8 \text{ TeV}$	30, 10, 30
Multijet, $e, 8 \text{ TeV}$	20, 5, 25

- Signal region :

- Electron:  $pT > 30, |\eta| < 2.47$  ( $1.37 < |\eta| < 1.52$  excluded)
- Muon :  $pT > 30, |\eta| < 2.5$
- Jets :  $pT > 40$  (leading) &  $> 30$  (second),  $|\eta| < 2.5$ , both b-tagged
- MET  $> 35$ , mTW  $> 30$
- Veto on add. Jet with  $pT > 25$  &  $|\eta| < 2.5$

Process
Single-top <i>s</i> -channel
Single-top <i>t</i> -channel
Assoc. <i>Wt</i> production
<i>t</i> <i>̄</i> production
<i>W+jets</i>
<i>Z+jets &amp; diboson</i>
Multi-jet
Total expectation
Data

Type	$\pm \Delta\sigma/\sigma [\%]$
Data statistics	16
MC statistics	12
Jet energy resolution	12
<i>t</i> -channel generator choice	11
<i>b</i> -tagging	8
<i>s</i> -channel generator scale	7
<i>W+jets</i> normalization	6
Luminosity	5
<i>t</i> -channel normalization	5
Jet energy scale	5
PDF	3
Lepton identification	2
Electron energy scale	1
<i>t</i> <i>̄</i> generator choice	1
Lepton trigger	1
Charm tagging	1
Other	< 1
Total	34

- Signal region :

- Electron:  $p_T > 20$ ,  $|\eta| < 2.5$
- Muon :  $p_T > 20$ ,  $|\eta| < 2.4$
- 2 leptons compatible with Z decay, veto add. loose lepton
- Jets :  $p_T > 30$ ,  $|\eta| < 2.4$   
 $(tZq-SM : |\eta| < 4.5 \text{ because light jet is forward})$
- tZq-SM :  $m_{TW} > 10$
- tZq-FCNC : MET  $> 40$  &  $m_{TW} > 10$

Systematic source
Z+jets, $t\bar{t}$
Muon misidentification
Electron misidentification
$Z p_T$
WZ+l jets norm.
WZ+l jets matching
WZ+l jets scale
WZ+hf jets norm.
WZ+hf jets matching
WZ+hf jets scale
tZq
tZq scale
ZZ
Single top
$t\bar{t}V$
Trigger
Lepton selection
JES
JER
Uncertainty $p_T^{\text{miss}}$
b tagging
Pileup
PDF
tZ-FCNC scale
Luminosity

- Signal region :

- Muon :  $pT > 26, |\eta| < 2.1$
- Veto add. muon with  $pT > 10, |\eta| < 2.5$  (+iso)
- Veto electron with  $pT > 20, |\eta| < 2.5,$
- Photon :  $pT > 50, |\eta| < 2.5$  ( $1.44 < |\eta| < 1.56$  excluded)
- Jets :  $pT > 30, |\eta| < 2.5$
- MET  $> 30$
- $\Delta R(\mu, \gamma) > 0.7$  &  $\Delta R(b\text{ jet}, \gamma) > 0.7$

- W+jets CR :

- Require photons w/ wide EM showers
- No b-tagged jets

Type	Source	$t\bar{u}\gamma$ (%)	$t\bar{c}\gamma$ (%)
Rate	Integrated luminosity	1.8	4
	Background normalization ( $W + \text{jets}$ )	5.6	3
	Background normalization ( $W\gamma + \text{jets}$ )	2.5	1.1
	Other background normalizations	<1	1
Rate+Shape	Trigger efficiency	2.2	0.4
	Pileup effects	7	2.3
	Lepton identification and isolation	<1	4.4
	Photon identification and isolation	1.9	4.5
	Photon energy scale	<1	3.1
	b tagging and mistag efficiency	1.1	4
	Jet energy scale	2.9	2.2
	Jet energy resolution	2.1	3.4
	PDF	3.1	<1
	Scale	1	2.4
	Top quark mass	2.5	1

- Signal region :

- Electron :  $pT > 25, |\eta| < 2.47$  ( $1.37 < |\eta| < 1.52$  excluded)
- Muon :  $pT > 25, |\eta| < 2.5$
- Preliminary jet sel. :  $pT > 25, |\eta| < 2.5$
- After further sel : require  $pT > 30$  & b-tagged
- MET $> 30$ , mTW $> 50$

Process	Source
Single top	Normalisation & MC statistics
$t\bar{t}$	Multi-jets normalisation and modelling
$W+LF$	Luminosity
$W+HF$	Lepton identification
Z+jets	Electron energy scale
Multi-jet	Electron energy resolution
Total expected	Muon momentum scale
Data	Muon momentum resolution
	Jet energy scale
	Jet energy resolution
	Jet reconstruction efficiency
	Jet vertex fraction scale
	$b$ -tagging efficiency
	$c$ -tagging efficiency
	Mistag acceptance
	$E_T^{\text{miss}}$ modelling
	PDF
	Scale variations
	MC generator (NLO subtraction method)
	Parton shower modelling
	All systematic uncertainties

- Signal region :

- Muon :  $pT > 20$  (7TeV),  $pT > 26$  (8TeV),  $|\eta| < 2.1$
- Veto add. lepton with  $pT > 10$ ,  $|\eta| < 2.5$
- 2 or 3 jets :  $pT > 30$ ,  $|\eta| < 4.7$ , leading jet  $pT > 40$  (8TeV)
- $\geq 1$  b-tagged jet,  $\geq 1$  light jet (tight WP)
- MET  $> 30$ , mTW  $> 50$

- Upper limits on AC :

- $|f_{LV}| > 0.98$
- $|f_{RV}| < 0.16$
- $|f_{LT}| > 0.057$
- $-0.049 < f_{RT} < 0.048$

The FCNC tcg and tug interactions can be written in a model-independent form with the following effective Lagrangian [1]:

$$\mathcal{L} = \frac{\kappa_{tqg}}{\Lambda} g_s \bar{q} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G_{\mu\nu}^a, \quad (3)$$

Process
$t$ channel
$s$ channel
tW
$t\bar{t}$
W+jets
Dibosons
Drell-Yan
Multijets
Total
Data