

# Single top production measurements at the LHC: other channels

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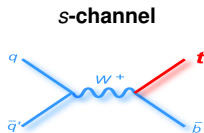
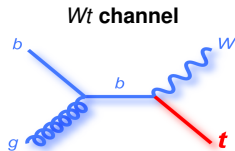
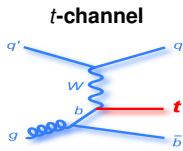
**“Top2015 - 8th International Workshop on Top Quark Physics”**  
Ischia, Italy, 14-18/09/2015



- ▶ Why is the single top quark so interesting?
- ▶ Single top-quark production in the  $Wt$  channel at 8 TeV
  - ▶ Inclusive cross-section measurements in CMS and ATLAS and the LHC combination
  - ▶ Fiducial cross-section measurement in ATLAS
- ▶ Single top-quark production in the  $s$  channel at 8 TeV
  - ▶ Inclusive cross-section limits in CMS and ATLAS
  - ▶ New single top-quark production in the  $s$ -channel in ATLAS
- ▶ CKM matrix element ( $|V_{tb}|$ ) determination
- ▶ Conclusions

# Why is the single top quark so interesting?

Single top-quark production via electroweak interaction, involving a  $Wtb$  vertex



NLO+NNLL with  
 $m_t = 172.5$  GeV

$\sqrt{s}$ (pb)	$\sigma$ (t-channel)	$\sigma$ ( $Wt$ )	$\sigma$ (s-channel)
8 TeV	$87.8 \pm 3.4$ Phys. Rev. D 83, 091503(R) (2011)	$22.4 \pm 1.5$ Phys. Rev. D 82, 054018 (2010)	$5.6 \pm 0.2$ Phys. Rev. D 81, 054028 (2010)

✓ Measurements of the single top production provide a **test of SM predictions**:

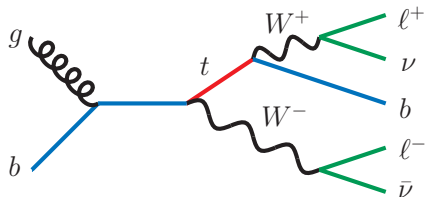
- ▶ Production cross-section and direct determination of the quark mixing matrix element  $|V_{tb}|$   
→ Test of unitarity of the CKM matrix
- ▶ Probe of the  $b$ -quark structure function

✓ Powerful **probe for physics beyond the SM (BSM)** related to EWSB:

- ▶ Resonances ( $W', H+, B'$ ), vector-like quarks, anomalous couplings.

✓ Significant **background** in search for Higgs and several expected BSM processes

## $Wt$ associated production: generic selection



### Dilepton $Wt$ signature

- ✓ Two oppositely charged isolated leptons ( $e\mu, ee, e\mu$ )
- ✓ One high  $p_T$  and central  $|\eta|$   $b$ -jet
- ✓ Missing transverse energy ( $E_T^{miss}$ ) from the two neutrinos

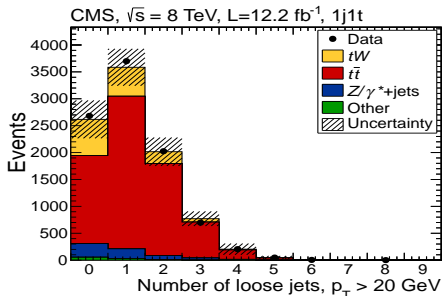
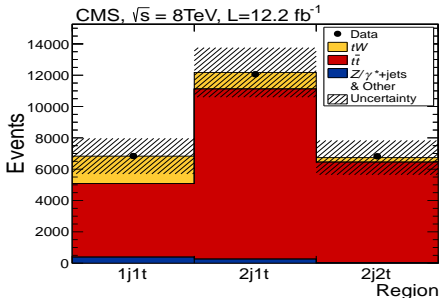
- ▶ Events are divided into analysis regions by jet and  $b$ -tag multiplicity
- ▶ Large contribution from the top pair production, dominant background  
→ > 70% in the signal region (1-jet tagged as  $b$ -jet)
- ▶ Multivariate analysis based on Boosted Decision Trees (BDT) is used to separate the  $Wt$  signal from the backgrounds

► **Specific selection** - dilepton channel ( $e\mu$ ,  $ee$ ,  $\mu\mu$  channels)

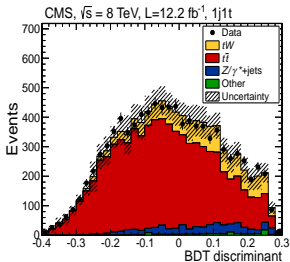
- Leptons with  $p_T > 20$  GeV
- 1 or 2 central jets, 1  $b$ -tagged,  $p_T > 30$  GeV &  $|\eta| < 2.5$   
→ **Looser jets** also considered with  $p_T > 20$  GeV &  $|\eta| < 4.9$
- $E_T^{miss} > 50$  GeV &  $m_{\ell\ell} > 20$  GeV & for same-flavour channels exclude around  $Z$ -boson mass

► **Analysis strategy**

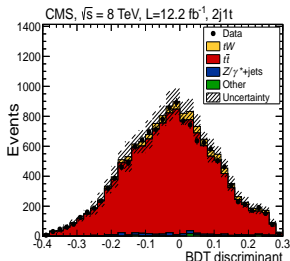
- 1 signal region with 1-jet  $b$ -tagged (1j1t)
- 2 control regions enriched in  $t\bar{t}$ : 2 jets with either one (2j1t) or two  $b$ -tagged (2j2t).
- Three BDT discriminants: 13 highest-ranking variables.
  - Most powerful variables:  $n^o$  of loose jets &  $p_T$  of the system of leptons, jets and  $E_T^{miss}$  ( $p_T^{sys}$ )



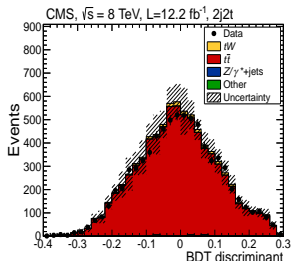
1-jet 1-tag signal region  
( $\sim 16\%$  of  $Wt$ )



2-jet 1 b-tagged control region  
( $\sim 6\%$  of  $Wt$ )



2-jet 2 b-tagged control region  
( $\sim 3\%$  of  $Wt$ )



- ▶ The inclusive  $Wt$  production cross-section is measured from a simultaneous binned likelihood fit of the BDT distributions.
  - ▶ The 2-jets control regions constrain the  $t\bar{t}$  background uncertainties and the  $b$ -tagging uncertainties.

$\sigma_{Wt} = 23.4 \pm 5.4$  pb (23%)  
Significance:  $6.1\sigma$  ( $5.4\sigma$  exp.)

## OBSERVATION of the $Wt$ channel

Dominant uncertainties (in  $t\bar{t}$  simulation):

- ME/PS matching ( $\sim 14\%$ )
- renormalization/factorization scale ( $\sim 12\%$ )

# $Wt$ cross-section: LHC combination @ 8 TeV

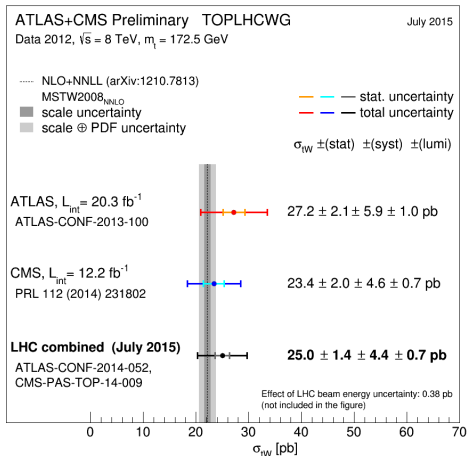
Combination of  $Wt$  cross-section measurements by ATLAS and CMS using BLUE

Source	Uncertainty	
	(%)	(pb)
Data statistics	5.5%	1.4
Simulation statistics	1.8%	0.5
Luminosity	2.7%	0.7
Theory modeling	15.8%	4.0
Background normalization	2.3%	0.6
Jets	5.3%	1.3
Detector modeling	4.9%	1.2
Total systematics (excl. lumi)	17.5%	4.4
Total systematics (incl. lumi)	17.7%	4.4
Total uncertainty	18.6%	4.7

LHC combination:

$$\sigma_{Wt} = 25.0 \pm 4.7 \text{ pb}$$

(total unc. 19%)



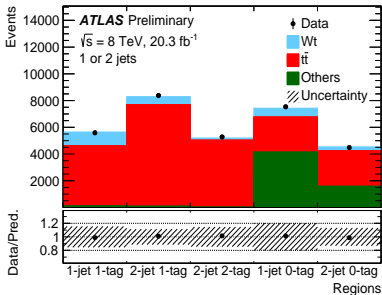
\* combination uses a preliminary ATLAS result in the  $e\mu$  channel (ATLAS-CONF-2013-100)

# NEW! ATLAS: $Wt$ @ 8 TeV - dilepton channel

TOPQ-2012-20 @ 20.3 fb<sup>-1</sup>

## ► Specific selection

- Leptons with  $p_T > 25$  GeV
- One or two central jets with  $p_T > 20$  GeV & at least one  $b$ -tagged jet
- Only for  $ee$  and  $\mu\mu$ : reject events with  $81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$
- Set of requirements on  $E_T^{\text{miss}}$  &  $|\eta^{\text{sys}(\ell,j)}| < 2.5$

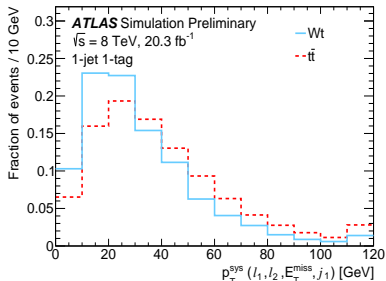


- 1 signal region with 1-jet  $b$ -tagged (1-jet 1-tag)
- 2 regions enriched in  $t\bar{t}$ : 2 jets with either one (2-jet 1-tag) or both  $b$ -tagged (2-jet 2-tag)
- 2 regions enriched in other BGs.: 1-jet 0-tag & 2-jet 0-tag

## ► Three BDT discriminants into the cross-section fit:

13 (1-jet 1-tag) & 16 (2-jet  $b$ -tagged) variables

- Most powerful variables:  $p_T^{\text{sys}}(\ell_1, \ell_2, E_T^{\text{miss}}, j_1)$ ,  $\Delta R(\ell_1, j_1)$  &  $m(\ell_1, j_2)$





# NEW! ATLAS: $Wt$ inclusive cross-section @ 8 TeV

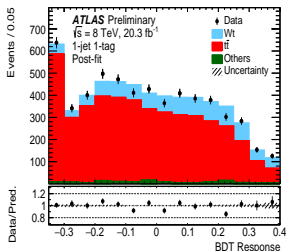
TOPQ-2012-20 @ 20.3 fb<sup>-1</sup>

- The inclusive  $Wt$  production cross-section is measured from a simultaneous profile likelihood fit to the three BDT classifiers

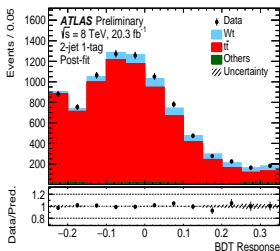
$$\sigma_{Wt} = 23.0 \pm 1.3 \text{ (stat.)}^{+3.2}_{-3.5} \text{ (syst.)} \pm 1.1 \text{ (lumi.) pb}$$

Total uncer.  $^{+16}_{-17}\%$  Significance:  $7.7\sigma$  ( $6.9\sigma$  exp.)

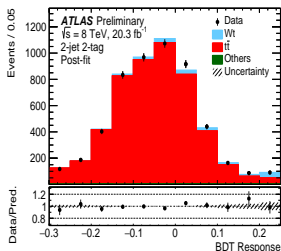
1-jet 1-tag ( $\sim 20\%$  of  $Wt$ )



2-jet 1-tag ( $\sim 10\%$  of  $Wt$ )



2-jet 2-tag ( $\sim 3\%$  of  $Wt$ )



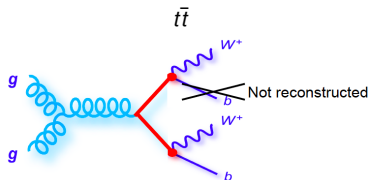
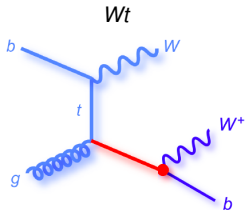
Dominant uncertainties:

ISR/FSR ( $\sim 9\%$ ), jet uncertainties ( $\sim 10\%$ ), BG. normalisation ( $\sim 10\%$ )

# NEW! ATLAS: $Wt + t\bar{t}$ fiducial cross-section @ 8 TeV

TOPQ-2012-20 @ 20.3 fb<sup>-1</sup>

- ▶ In the 5-flavour number scheme,  $Wt$  process overlaps and interferes with  $t\bar{t}$  at NLO
- ▶ **Fiducial acceptance** → physics objects constructed using stable particles to approximate the  $Wt$  detector acceptance:
  - ▶ Fiducial selection: Exactly 2 leptons with  $p_T > 25$  GeV and  $\eta < 2.5$ , exactly one  $b$ -tagged jet with  $p_T > 20$  GeV,  $E_T^{miss} > 20$  GeV
    - ▶ Particle-level jets matched with nearby  $b$ -hadrons ( $p_T > 5$  GeV) using the ghost tagging method
  - ▶ Includes  $Wt$  events
  - ▶ Includes  $t\bar{t}$  events for which one of the  $b$  quark was not reconstructed



- ▶ **Benefits of a fiducial measurement:**
  - ▶ Separation of experimental and theoretical uncertainties
  - ▶ Reduce the dependence on the theory assumptions

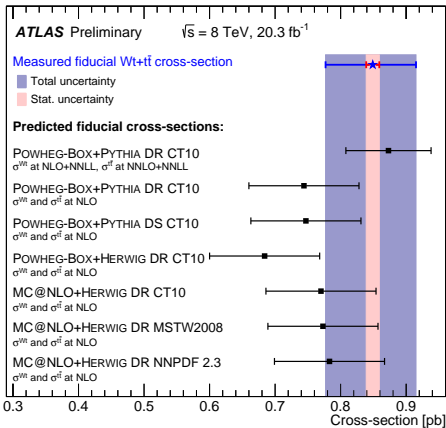
# NEW! ATLAS: $Wt + t\bar{t}$ fiducial cross-section @ 8 TeV: results

TOPQ-2012-20 @ 20.3 fb<sup>-1</sup>

- ▶ Selected  $Wt$  and  $t\bar{t}$  events are split into two categories: in-fiducial and out-of-fiducial
- ▶ Fraction of in-fiducial events: 81% for  $Wt$  and 53% for  $t\bar{t}$

Fiducial cross-section is measured by fitting the sum of the  $Wt$  and  $t\bar{t}$  contributions to data in the 1-jet 1-tag region.

Comparison of measured fiducial cross-section with theoretical predictions



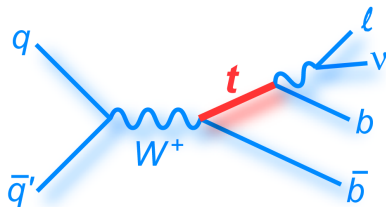
$$\sigma_{fid} = 0.85 \pm 0.01 \text{ (stat.) } \begin{matrix} +0.06 \\ -0.07 \end{matrix} \text{ (syst.) } \pm 0.02 \text{ (lumi.) pb}$$

(Total uncer. 8%)

Dominant uncertainties:

ISR/FSR ( $\sim 4.2\%$ ), jet uncertainties ( $\sim 5.2\%$ )

## s-channel: generic selection



Semileptonic s-channel signature:

- ✓ One isolated and high  $p_T$  lepton ( $e, \mu$ )
- ✓ Two jets with high  $p_T$  and central  $|\eta|$  originating from  $b$ -quarks
- ✓ Missing transverse energy ( $E_T^{miss}$ ) from the neutrino

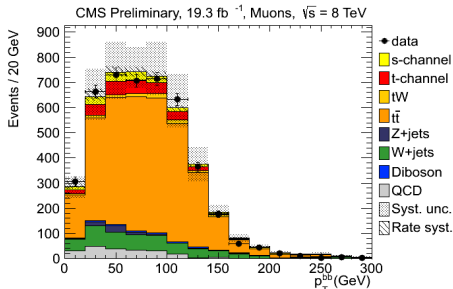
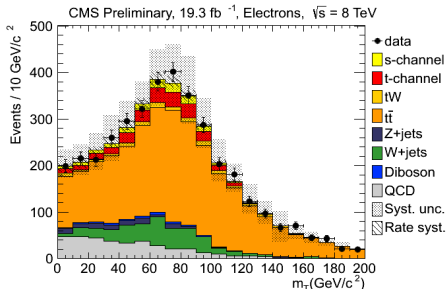
- ▶ The most challenging single top-quark process at the LHC  
→ low cross-section and difficult to separate from backgrounds
- ▶ Main backgrounds: top pair production and  $W$ +jets
- ▶ Multivariate analyses based in two techniques: Boosted Decision Trees (BDT) and Matrix Element (ME) Method

## ► Specific selection:

- Single isolated lepton:  $e$  ( $\mu$ ) with  $p_T > 24$  (27) GeV
- 2 central jets, 2  $b$ -tagged,  $p_T > 40$  GeV (other jets only if  $p_T > 30$  GeV)

## ► Analysis strategy

- One signal region (2-jet 2  $b$ -tag) and one control region enriched in  $t\bar{t}$  (3-jet 2  $b$ -tag)
- Four BDT discriminants: Each region is separated in electron and muon channel
  - 10 (11) highest ranking variables for the  $e$  ( $\mu$ ) channels
  - Most powerful: transverse  $W$  boson mass ( $m_T$ ) in  $e$  ch. & vector sum of  $p_T$  of the 2  $b$ -tagged jets ( $p_T^{bb}$ ) in  $\mu$  ch.

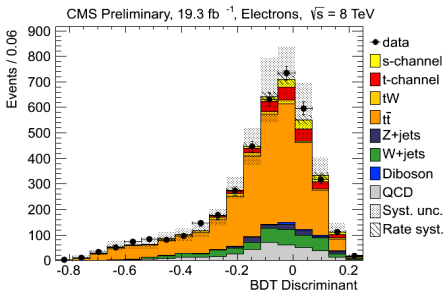


- ▶ The s-channel production cross-section is measured from a binned maximum-likelihood fit to the four BDT classifiers
- ▶ 3-jets, 2-tags regions allow to constrain the  $t\bar{t}$  and  $W$  + jets BG.

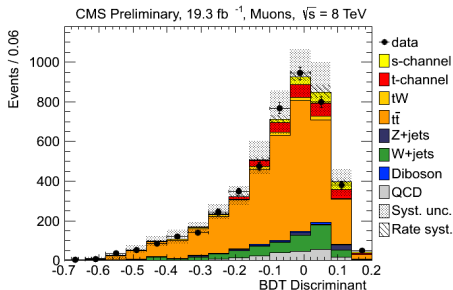
$\sigma_s = 6.2 \pm 8.0 \text{ pb}$  with  $0.7\sigma$  (exp.  $0.9\sigma$ )  
 At 95 % CL. cross-section limit: 11.5 pb

Dominant uncertainties:  
 - Factorization/renormalization scales ( $\sim 83\%$ )

2-jet 2-tag,  $e + \text{jets}$  ( $\sim 3.6\%$  of s-channel)



2-jet 2-tag,  $\mu + \text{jets}$  ( $\sim 3.9\%$  of s-channel)



# NEW! ATLAS: s-channel @ 8 TeV - using ME method (1)

ATLAS-CONF-2015-47 @ 20.3 fb<sup>-1</sup>

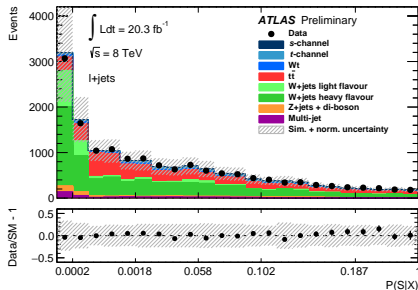
## Specific selection

- ▶ Single isolated lepton with  $p_T > 30$  GeV &  $\eta < 2.5$ 
  - ▶ Veto events containing additional leptons with  $p_T > 5$  GeV
- ▶ 2 central jets, 2  $b$ -tagged,  $p_T > 40(30)$  GeV for 1<sup>st</sup> (2<sup>nd</sup>) jet
  - ▶ Veto events involving additional jets with  $p_T < 25$  GeV
- ▶  $E_T^{miss} > 35$  GeV &  $m_T^W > 30$  GeV

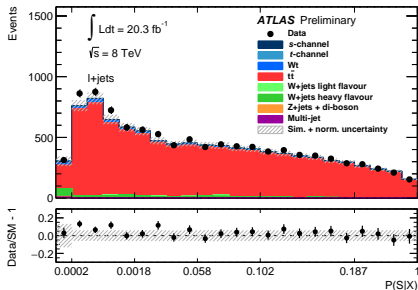
## Analysis strategy

- ▶ 1 signal region (2-jet 2  $b$ -tag) & 1 validation region for  $t\bar{t}$  & 1 control region to constrain  $W$ +jet BG.

$W$  + jets region



$t\bar{t}$  region



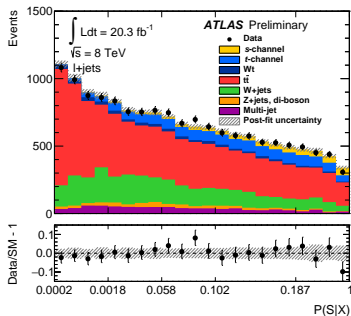
$$P(S|X) = \frac{\sum_i \alpha_{S_i} P(X|S_i)}{\sum_i \alpha_{S_i} P(X|S_i) + \sum_j \alpha_{B_j} P(X|B_j)} \rightarrow \text{probability for a measured event } (X) \text{ to be a signal event } (S)$$

# NEW! ATLAS: $s$ -channel @ 8 TeV - using ME method (2)

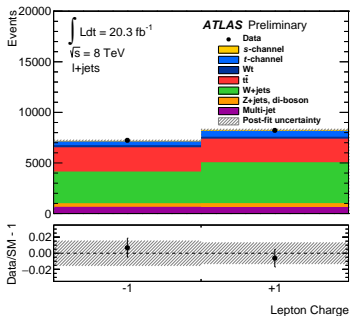
ATLAS-CONF-2015-47 @ 20.3 fb<sup>-1</sup>

- ▶ The ME Method is used to separate the signal from the background
  - ▶ ME discriminant is extracted using theoretical calculations to compute a per-event signal probability.

2-jet 2-tag ( $\sim 4.3\%$  of  $s$ -channel)



$W$  + jets region



- ▶  $s$ -channel cross-section from **binned maximum likelihood fit of the ME discriminant in the signal region**
  - ▶ the lepton charge in the  $W$  + jets control region is included into the fit to constrain the  $W$ +jets BG.



# NEW! ATLAS: s-channel evidence @ 8 TeV - Results

ATLAS-CONF-2015-47 @ 20.3 fb<sup>-1</sup>

$$\sigma_s = 4.8 \pm 1.1 \text{ (stat.)}_{-2.0}^{+2.2} \text{ (syst.) pb}$$

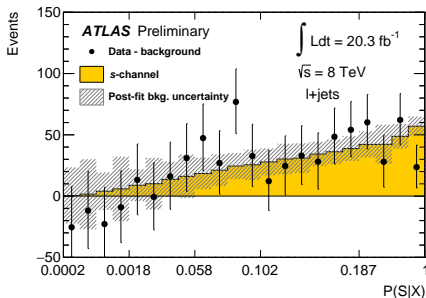
Significance: 3.2 $\sigma$  (exp. 3.9 $\sigma$ )



Consistent with SM expectation:

$$\sigma_{s\text{-ch.}}^{\text{theory}} = 5.61 \pm 0.22 \text{ pb}$$

Type	$\pm\Delta\sigma/\sigma$ [%]
Data statistics	22.1
MC statistics	17
Jet energy resolution	17
<i>t</i> -channel generator	15
<i>s</i> -channel generator scale	11
<i>b</i> -tagging	11
W+jets normalization	9
Luminosity	7
<i>t</i> -channel normalization	7
Jet energy scale	6
PDF	3
Lepton identification	3
<i>t</i> $\bar{t}$ generator	2
Electron energy scale	2
Lepton trigger	2
Charm tagging	2
Other	< 1
Total	49



**First EVIDENCE**  
of the s-channel production at LHC

# $|V_{tb}|$ measurements

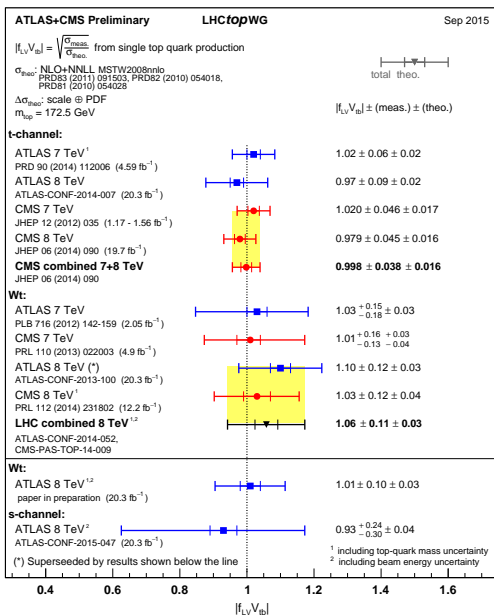
- ▶ Direct determination of the quark mixing matrix element  $|V_{tb}|$ :
  - ▶ Opportunity to test the unitarity of the CKM matrix
  - ▶ Deviations from the SM are potentially sensitive to new physics or radiative corrections through anomalous coupling contributions
- ▶ Measure  $|V_{tb}|$  assuming left-handed SM-like W-t-b coupling and  $|V_{tb}| \gg |V_{ts}|, |V_{td}|$ :

$$|V_{tb} \cdot f_{LV}|^2 = \frac{\sigma^{obs.}}{\sigma^{theory}} \quad \text{with } f_{LV} = 1 \text{ in SM}$$

- ▶ Summary of the  $|V_{tb}|$  measurements and limits in the  $Wt$  and s-channel:

Channel	Experiment	Reference	$ V_{tb} \cdot f_{LV} $	Limit at 95 % C.L.
$t$ -channel	CMS	JHEP06 (2014) 090	$0.98 \pm 0.05$ (5%)	
$Wt$	ATLAS	ATLAS-CONF-2013-100	$1.10 \pm 0.12$ (11%)	$ V_{tb}  > 0.72$
$Wt$	CMS	PRL 112 (2014) 231802	$1.03 \pm 0.13$ (12%)	$ V_{tb}  > 0.78$
$Wt$	ATLAS & CMS	ATLAS-CONF-2014-052	$1.06 \pm 0.11$ (10%)	$ V_{tb}  > 0.79$
$Wt$	ATLAS	TOPQ-2012-20	$1.01 \pm 0.10$ (10%)	$ V_{tb}  > 0.80$
s-channel	ATLAS	ATLAS-CONF-2015-47	$0.93^{+0.24}_{-0.30}$ ( $\sim 32\%$ )	$ V_{tb}  > 0.4$

# Summary of $|V_{tb}|$ measurements at 7 & 8 TeV

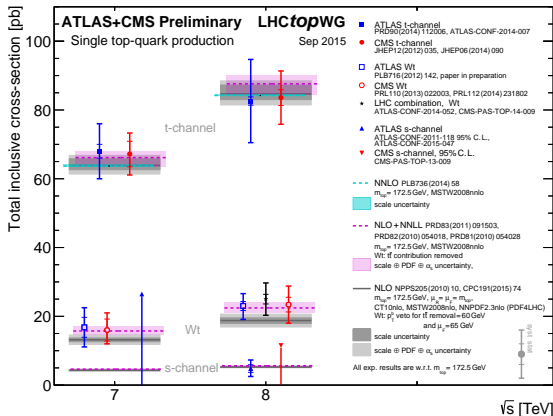


# Conclusions

- ▶ LHC experiments delivered many results in single top final states with Run-1 data
  - ▶ Single top-quark production has been **observed** in association with a  $W$  boson by ATLAS & CMS
    - ▶ The  $Wt$  cross-section has been **measured** with a precision of **23% in CMS & 17% in ATLAS**
  - ▶ First fiducial cross-section measurement by ATLAS in the  $Wt$  fiducial acceptance
  - ▶ First **evidence** of the  $s$ -channel by ATLAS

All measurements are so far consistent with the SM predictions

- ▶ No sign of new physics has been found yet



BACKUP

# ATLAS: $Wt$ cross-section @ 8 TeV - only $e\mu$ channel

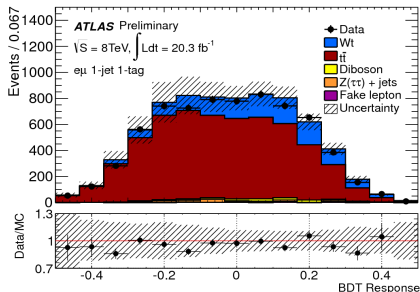
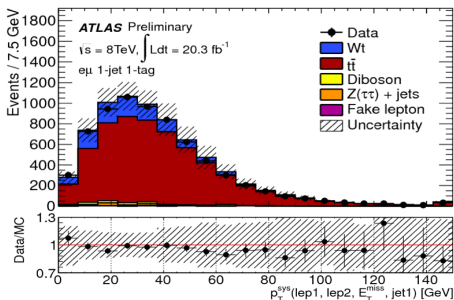
ATLAS-CONF-2013-100 @ 20.3 fb<sup>-1</sup>

## Specific selection - only $e\mu$ channel

- Leptons with  $p_T > 25$  GeV & 1 or 2 central jets, 1  $b$ -tagged,  $p_T > 30$  GeV

## Analysis strategy

- One enriched signal region (1-jet 1  $b$ -tag) and one control region (2-jets  $\geq$  1-tag)
- Two BDT discriminants: 19 highest-ranking variables for 1-jet 1-tag and 20 for the 2-jet  $\geq$  1-tag



## The $Wt$ cross-section is measured from a maximum likelihood fit to BDT classifiers.

- 2-jet control region constrains the  $t\bar{t}$  background uncertainties
- Impact of systematic uncertainties is evaluated using ensembles of pseudo-experiments

$\sigma_{Wt} = 27.2 \pm 5.8$  pb ( $\sim 21\%$ )  
Significance:  $4.2\sigma$  ( $4.0\sigma$  exp.)

modeling ( $\sim 8\%$ ) and  $b$ -tagging ( $\sim 9\%$ )

# ATLAS: s-channel @ 8 TeV - using BDT

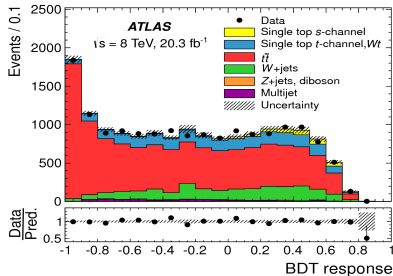
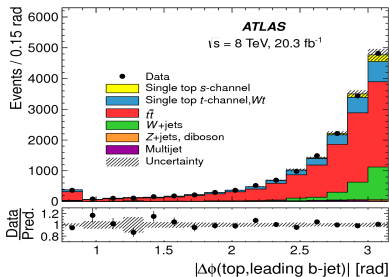
PLB 740 (2015) 118 @ 20.3 fb<sup>-1</sup>

## Specific selection:

- Single isolated lepton with  $p_T > 30$  GeV
- 2 central jets, 2  $b$ -tagged,  $p_T > 30$  GeV (other jets only if  $p_T < 25$  GeV)

## Analysis strategy

- One signal region (**2-jet 2  $b$ -tag**) and two control regions to validate the BG. modeling.
- One BDT discriminant: 19 highest-ranking variables
  - Most powerful:  $\Delta\phi$  between top from 2<sup>nd</sup>  $b$ -jet and 1<sup>st</sup>  $b$ -jet & lepton  $p_T + E_T^{miss}$



- s-channel cross-section  $\rightarrow$  **binned maximum likelihood fit to BDT distribution.**
  - Impact of **systematic uncertainties** is evaluated using **ensembles of pseudo-experiments**

$\sigma_s = 5.0 \pm 4.3$  pb with  $1.3\sigma$  ( $1.4\sigma$  exp.)  
At 95 % CL. cross-section limit: 14.6 pb

Dominant uncertainties:

-  $E_T^{miss}$  scale ( $\sim 80\%$ )