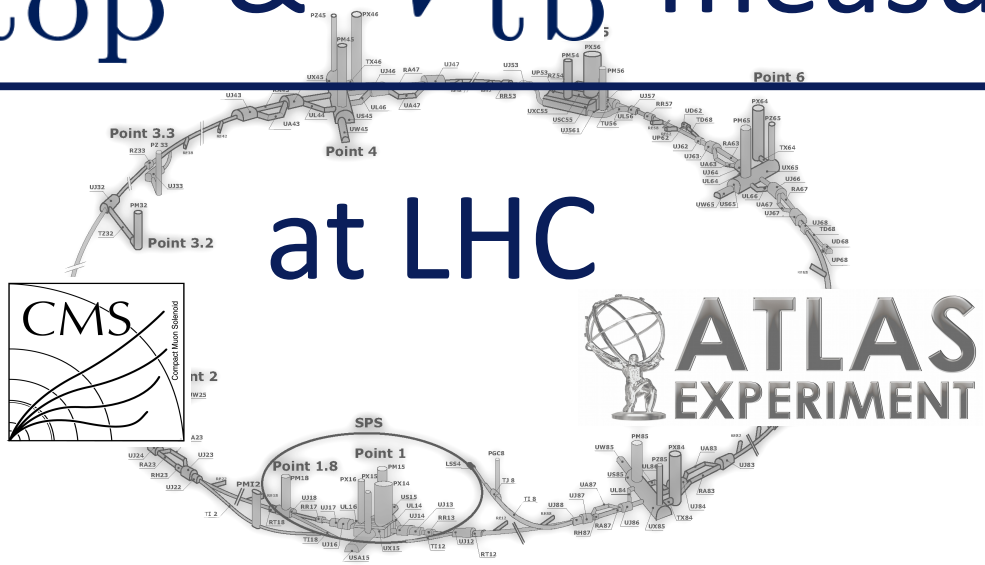
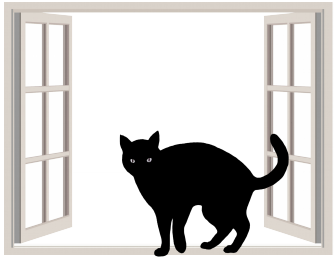
$\sigma_{\text{single-top}}$ & V_{tb} measurements at LHC



13 TeV

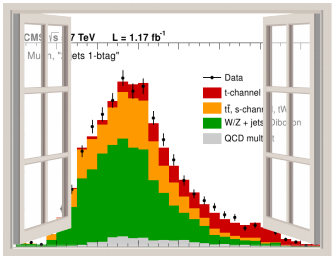


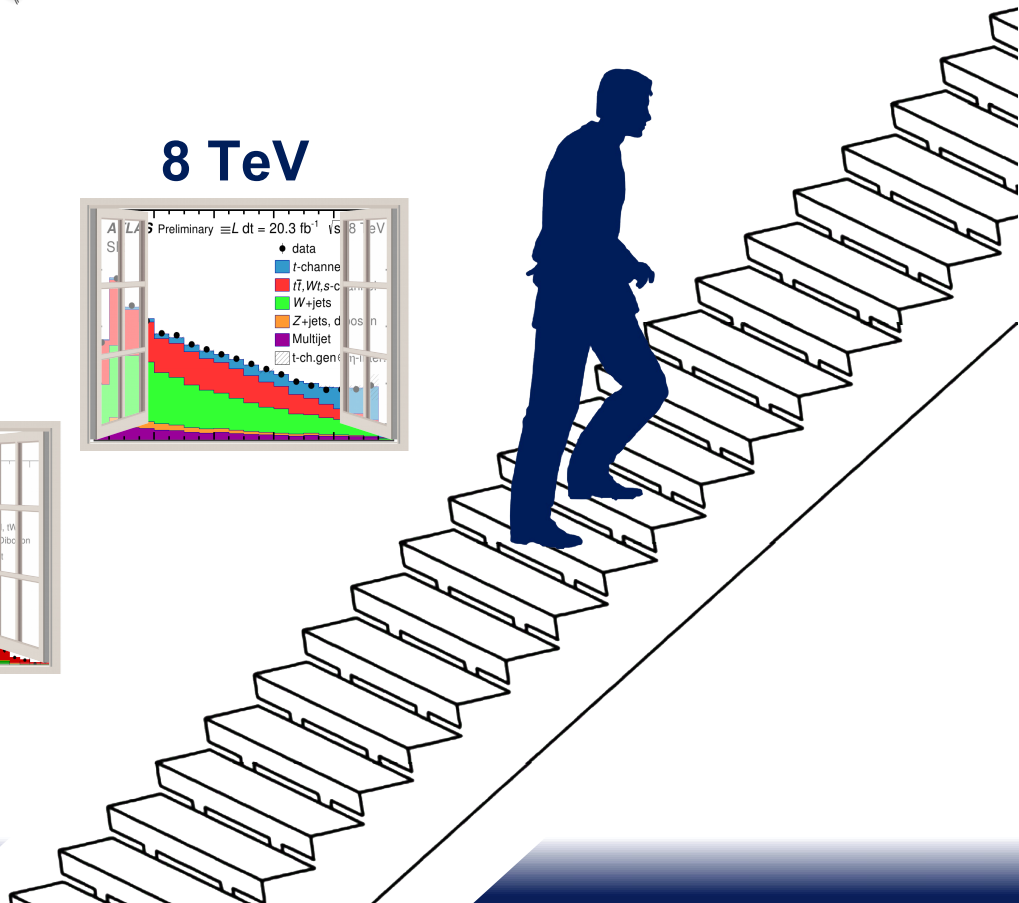
Matthias Komm

on behalf of the ATLAS & CMS collaborations

8 TeV

7 TeV





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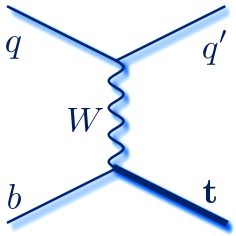
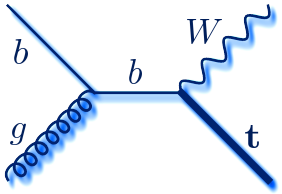
Outline

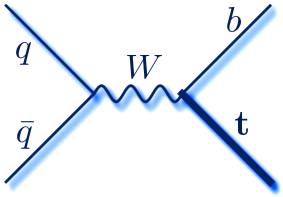
- single top overview



t-channel

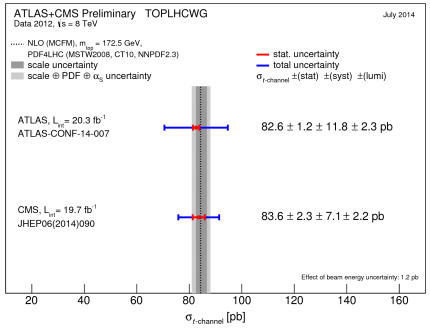


tW-channel

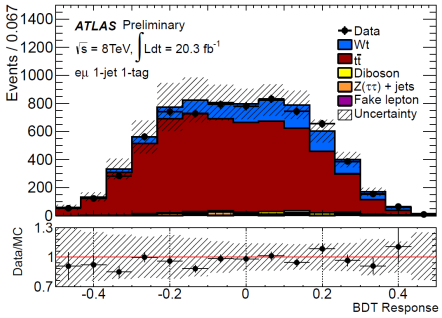


s-channel

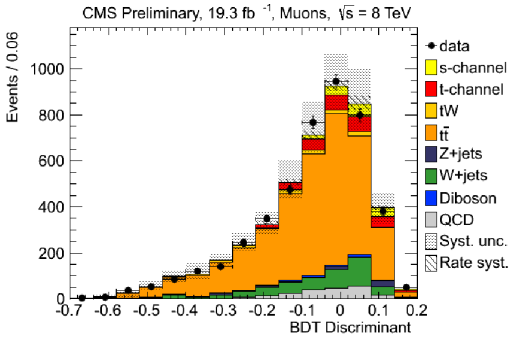
- single top measurements at **8 TeV**



t-channel



tW-channel

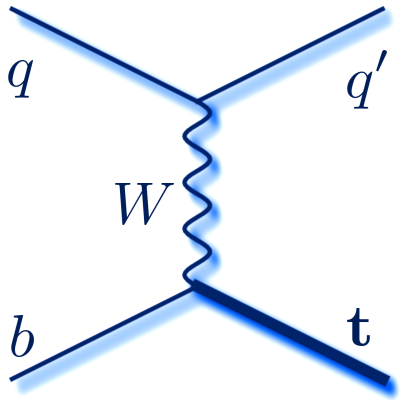


s-channel

- summary
  - single top cross section
  - V_{tb} measurements

Overview: Production

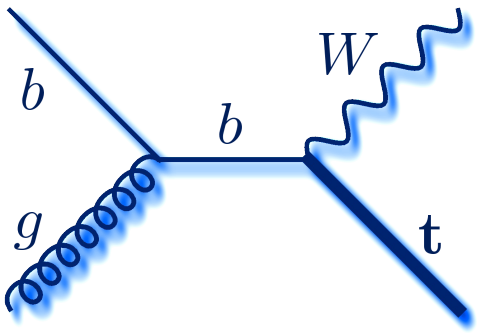
approximate NNLO using MSTW2008 NNLO PDF & $m_{\mathrm{top}} = 173\ \mathrm{GeV}$



t-channel

- $\sigma^{(7\ \mathrm{TeV})} = 65.9^{+2.1}_{-0.7}(\mathrm{scale})^{+1.5}_{-1.7}(\mathrm{PDF})\ \mathrm{pb}$
- $\sigma^{(8\ \mathrm{TeV})} = 87.2^{+2.8}_{-1.0}(\mathrm{scale})^{+2.0}_{-2.2}(\mathrm{PDF})\ \mathrm{pb}$

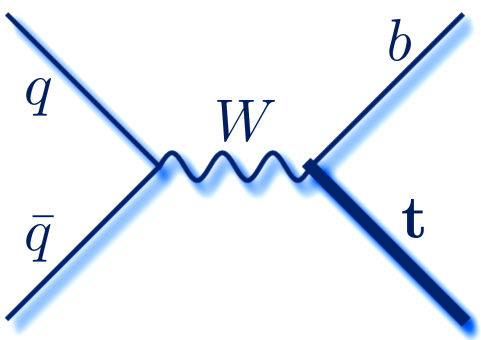
  $\Rightarrow$ dominant single top production process at LHC
- first differential & property measurements have already been performed (not this talk)



tW-channel

- $\sigma^{(7\ \mathrm{TeV})} = 15.6 \pm 0.4(\mathrm{scale}) \pm 1.1(\mathrm{PDF})\ \mathrm{pb}$
- $\sigma^{(8\ \mathrm{TeV})} = 22.2 \pm 0.6(\mathrm{scale}) \pm 1.4(\mathrm{PDF})\ \mathrm{pb}$
- first observation at LHC (inaccessible at Tevatron)
- interferes with $t\bar{t}$-production at NLO:

  unified description possible as $WWbb$ final state with 1 or 2 resonant tops



s-channel

- $\sigma^{(7\ \mathrm{TeV})} = 4.56 \pm 0.07(\mathrm{scale})^{+0.18}_{-0.17}(\mathrm{PDF})\ \mathrm{pb}$
- $\sigma^{(8\ \mathrm{TeV})} = 5.55 \pm 0.08(\mathrm{scale}) \pm 0.21(\mathrm{PDF})\ \mathrm{pb}$

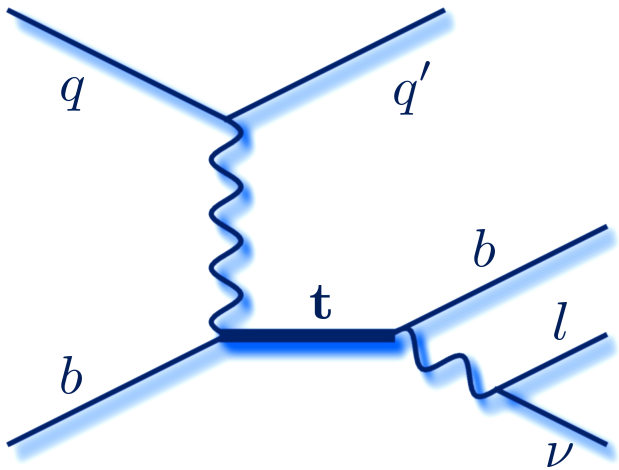
  $\Rightarrow$ challenging at LHC
- sensitive to new physics, e.g. non-SM mediators (W',...)

cross sections: N. Kidonakis, Phys.Part.Nucl.45:714,2014
WWbb production: F. Cascioli et. al., arXiv:1312.0546 [hep-ph]

8 TeV: t-channel cross section

ATLAS-CONF-2014-007
CMS: JHEP06 (2014) 090

- event selection at ATLAS (CMS)



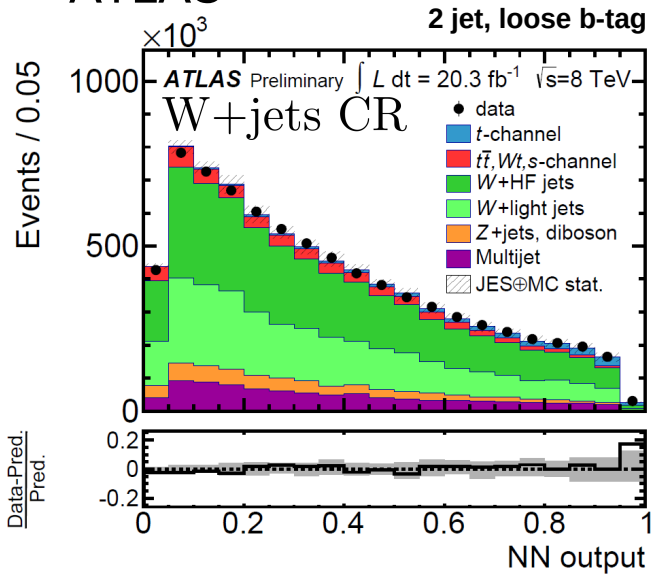
- single & isolated **muon** $p_{\mathrm{T}} > 25(26)\ \mathrm{GeV},\ |\eta| < 2.5(2.1)$ or **electron** $p_{\mathrm{T}} > 25(30)\ \mathrm{GeV},\ |\eta| < 2.47(2.5)$
- **jets**: $p_{\mathrm{T}} > 30(40)\ \mathrm{GeV},\ |\eta| < 4.5(4.5)$
- **b-tagging:** MVA (3rd track significance)
- signal region: 2 jets & 1 b-tagged, 1 lepton, $\not{E}_{\mathrm{T}}$

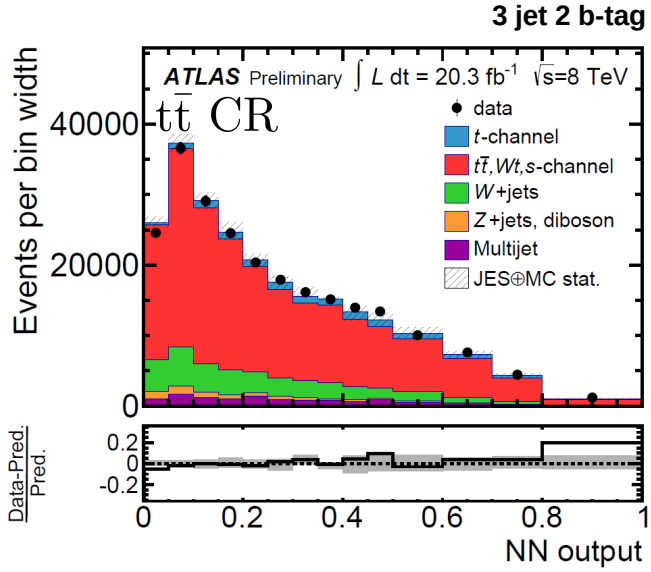
- analysis strategies
  - data-driven QCD multijet background estimation
  - top quark reconstruction
  - signal extraction: binned likelihood fit
    - ATLAS: **neutral network** (NN) $\Rightarrow$ fiducial cross section & extrapolated total cross section
    - CMS: η of **spectator jet** (non b-tagged) $\Rightarrow$ cross section & $t/\bar{t}$ ratio
  - extraction of $|V_{\mathrm{tb}}|$

Validation

ATLAS-CONF-2014-007
CMS: JHEP06 (2014) 090

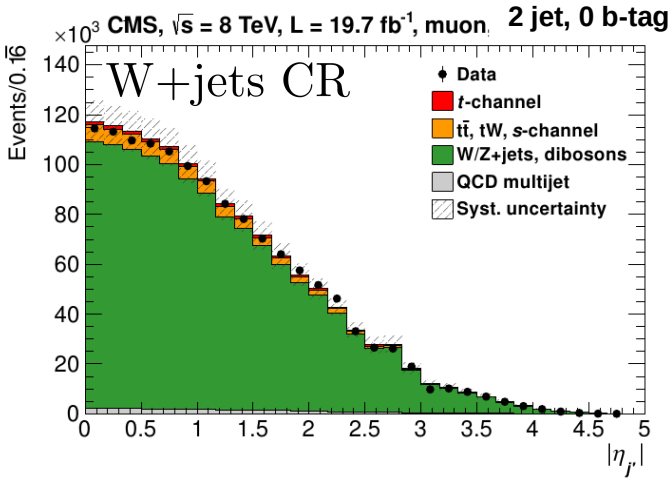
➢ ATLAS

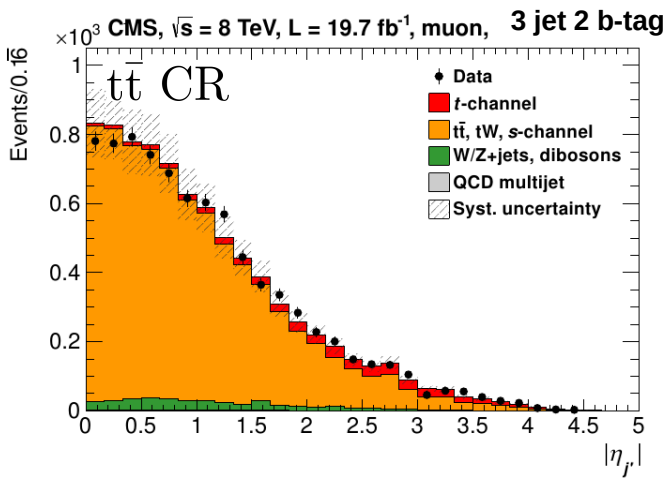




- QCD multijet shape:
  electron: **"lepton-jet"** method
  muon: **inverted selections**
- QCD yield: $\not{E}_{\mathrm{T}}$ - fit
- QCD rejection: $\not{E}_{\mathrm{T}} > 30\ \mathrm{GeV}$, $m_{\mathrm{T}}(W) > 50\ \mathrm{GeV}$

➢ CMS





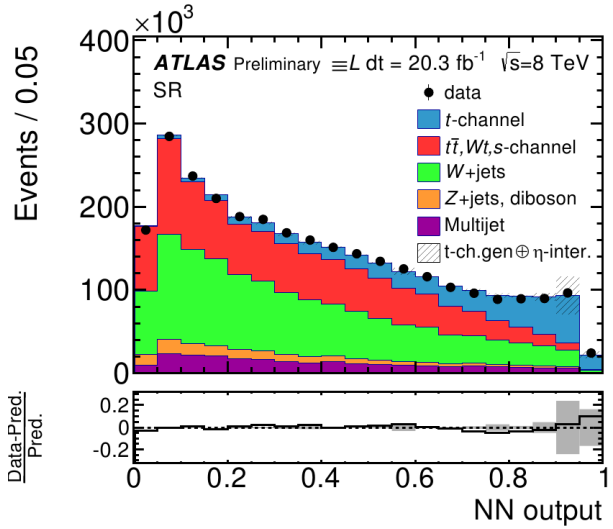
- QCD multijet shape:
  loosened lepton isolation
- QCD yield: $\not{E}_{\mathrm{T}}/m_{\mathrm{T}}(W)$-fit
- QCD rejection:
  electron: $\not{E}_{\mathrm{T}} > 45\ \mathrm{GeV}$
  muon: $m_{\mathrm{T}}(W) > 50\ \mathrm{GeV}$

t-channel: Result

ATLAS-CONF-2014-007

- ATLAS: t-channel fiducial & total cross section at 8 TeV

neutral network output



input variables

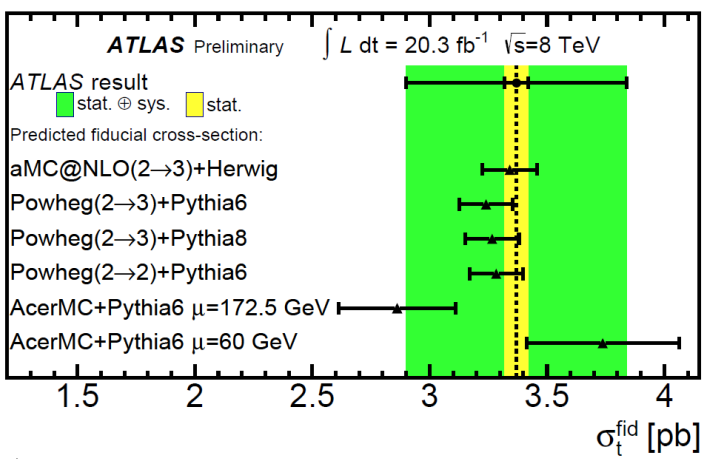
$|\eta_{\mathrm{lj}}|,\ m_{\mathrm{top}},\ m_{\mathrm{jb}},$
$m_{\mathrm{T}}(W),\ m_{\mathrm{lb}},\ \eta_W,$
$\cos\theta^{\mathrm{top}}(l,j),\ H_{\mathrm{T}},$
$\not{E}_{\mathrm{T}},\ \Delta R(t,l),\ p_{\mathrm{T}}^{W},$
$\eta_{\mathrm{top}},\ \eta_b,\ p_{\mathrm{T}}^{\mathrm{top}}$

systematic sources

Source	$\Delta\sigma_{\mathrm{fid}}/\sigma_{\mathrm{fid}}$ [%]
Data statistics	±1.5
MC statistics	±1.1
Multijet normalisation	+2.3 -1.4
Other background normalization	±0.8
JES η intercalibration	±7.9
JES physics modelling	±3.0
Lepton uncertainties	±2.9
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	±3.0
b-tagging efficiency	±3.5
Jet energy resolution	±1.7
t-channel generator	±7.9
W+jets generator	±1.4
PDF	±1.1
Total Systematic	±14
Total	±14

($< 0.5\%$ systematics not shown)

measurement



→ future t-channel measurements may give input to generators

$$\sigma_{\text{t-channel}}^{\text{fiducial}} = 3.37 \pm 0.05(\text{stat.}) \pm 0.47(\text{syst.}) \pm 0.09(\text{lumi.})\ \text{pb}$$

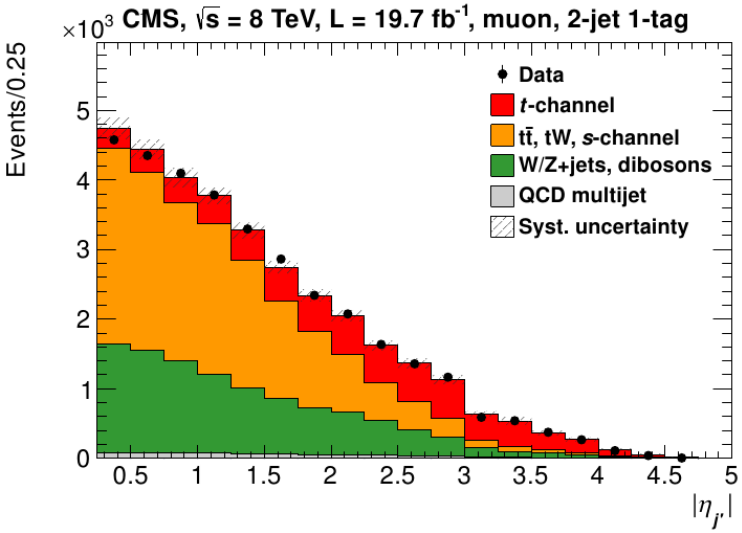
$$\sigma_{\text{t-channel}} = 82.6 \pm 1.2(\text{stat.}) \pm 12.0(\text{syst.})\ \text{pb} = 82.6 \pm 12.1\ \text{pb} \quad \left[\sigma_{\text{t-ch.}}^{\text{SM}} = 87.2 \pm 3.6\ \text{pb}\right]$$

t-channel: Result (2)

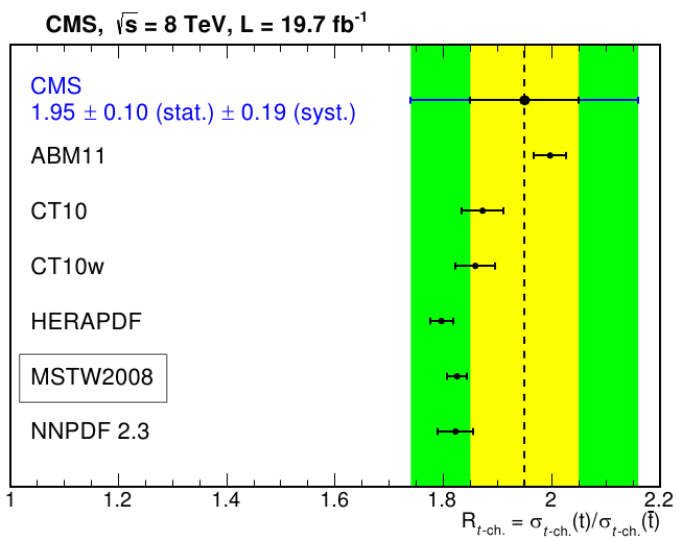
CMS: JHEP06 (2014) 090

- CMS: t-channel cross section & $t/\bar{t}$ ratio at 8 TeV

η of specator jet in SR



ratio measurement



systematic sources

Uncertainty source	$\sigma_{t\text{-ch.}}$ (%)	$R_{t\text{-ch.}}$ (%)
Statistical uncertainty	$\pm$ 2.7	$\pm$ 5.1
JES, JER, MET, and pileup	$\pm$ 4.3	$\pm$ 1.1
b-tagging and mis-tag	$\pm$ 2.5	$\pm$ 0.2
Lepton reconstruction/trig.	$\pm$ 0.6	$\pm$0.3
QCD multijet estimation	$\pm$ 2.3	$\pm$1.9
W+jets, $t\bar{t}$ estimation	$\pm$ 2.2	$\pm$ 3.0
Other backgrounds ratio	$\pm$ 0.3	$\pm$ 0.6
Signal modeling	$\pm$ 5.7	$\pm$ 6.1
PDF uncertainty	$\pm$ 1.9	$\pm$ 6.2
Simulation sample size	$\pm$ 0.7	$\pm$ 1.2
Luminosity	$\pm$ 2.6	—
Total systematic	$\pm$ 8.9	$\pm$ 9.6
Total uncertainty	$\pm$ 9.3	$\pm$ 10.9
Measured cross section	83.6 $\pm$ 7.8 pb	1.95 $\pm$ 0.21

measurement

$$\sigma_{\text{t-channel}} = 83.6 \pm 2.3(\text{stat.}) \pm 7.4(\text{syst.})\ \text{pb}$$
$$= 83.6 \pm 7.8\ \text{pb} \quad \left[\sigma^{\text{SM}}_{\text{t-ch.}} = 87.2 \pm 3.6\ \text{pb}\right]$$
$$\sigma(t)/\sigma(\bar{t}) = 1.95 \pm 0.10(\text{stat.}) \pm 0.19(\text{syst.})$$
$$= 1.95 \pm 0.21 \quad \left[R^{\text{SM}}_{t/\bar{t}} = 1.84 \pm 0.11\right]$$

Limits on CKM element V_{tb}

ATLAS-CONF-2014-007
CMS: JHEP06 (2014) 090

$$\left[\sigma^{\mathrm{SM}}_{\mathrm{t-ch.}} = 87.2 \pm 3.6\ \mathrm{pb}\right]$$

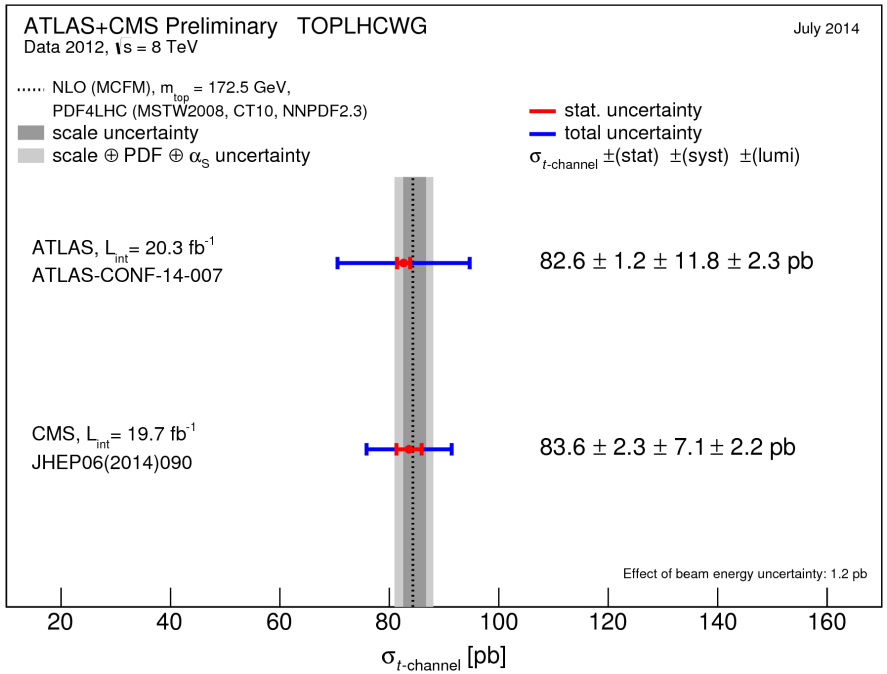
- calculation
  - assume $\mathcal{B}(t \to bW) \approx 100\%$
  - "strength" of top production vertex $\sigma(pp \to t, j) \propto V_{\mathrm{tb}}^2$

$$\Rightarrow |V_{\mathrm{tb}} \cdot f_{\mathrm{L}}| = \sqrt{\frac{\sigma_{\mathrm{measured}}}{\sigma^{\mathrm{SM}}_{\mathrm{theory}}}}$$

(f_{L} = left-handed "form factor"; $f_{\mathrm{L}}^{\mathrm{SM}} \equiv 1$)

without assumptions on number of quark generation & no unitarity constraint

- result



ATLAS

$$|V_{\mathrm{tb}}| = 0.97^{+0.06}_{-0.07}(\mathrm{exp.}) \pm 0.06(\mathrm{theo.})$$

$$|V_{\mathrm{tb}}| > 0.78\ @95\%\mathrm{CL}$$

CMS

$$|V_{\mathrm{tb}}| = 0.98 \pm 0.05(\mathrm{exp.}) \pm 0.02(\mathrm{theo.})$$

<u>7+8 TeV t-channel combination</u>

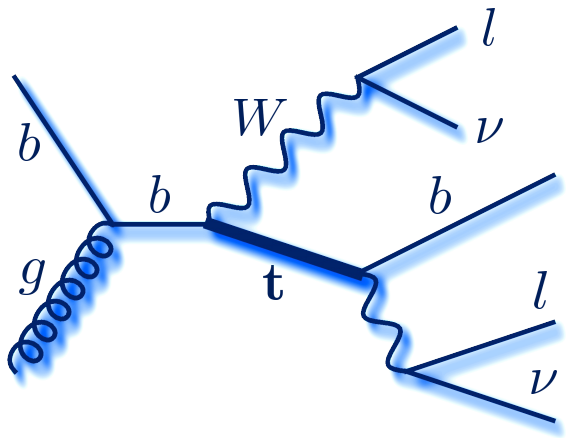
$$|V_{\mathrm{tb}}| = 0.998 \pm 0.038(\mathrm{exp.}) \pm 0.016(\mathrm{theo.})$$

$$|V_{\mathrm{tb}}| > 0.92\ @95\%\mathrm{CL}$$

8 TeV: tW-channel observation

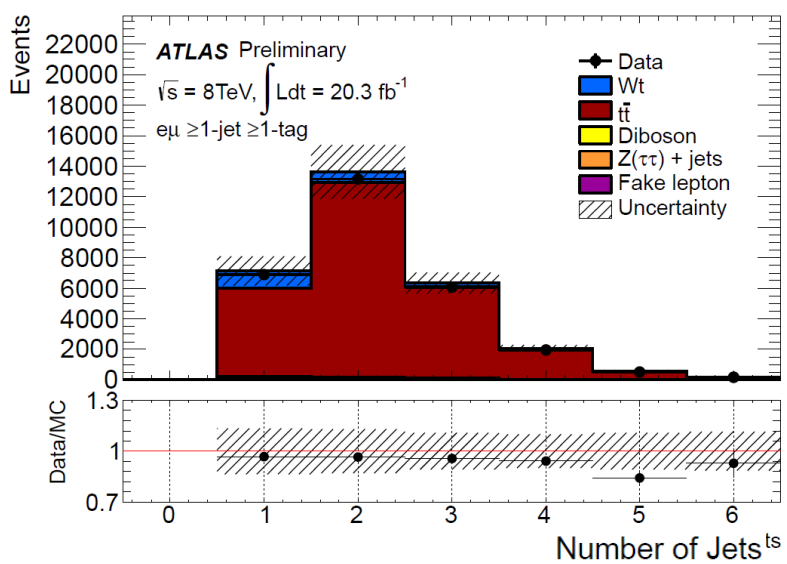
ATLAS-CONF-2013-100
CMS: PRL 112 (2014)

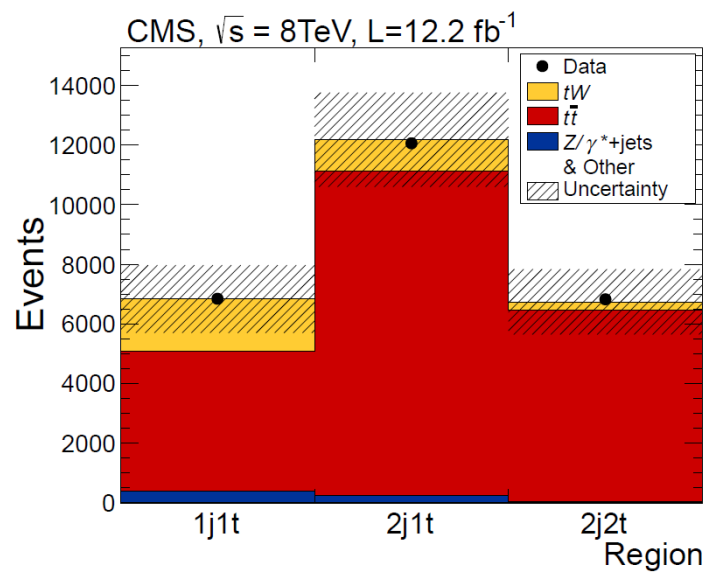
- event selection at ATLAS (CMS)



- "**diagram removal**" scheme to define process at NLO (alternative "diagram subtraction" scheme evaluated as systematic)
- iso. **muons**: $p_{\mathrm{T}} > 25(20)\ \mathrm{GeV},\ |\eta| < 2.5(2.4)$
- iso. **electrons**: $p_{\mathrm{T}} > 25(20)\ \mathrm{GeV},\ |\eta| < 2.47(2.5)$
- **jets**: $p_{\mathrm{T}} > 30(30)\ \mathrm{GeV},\ |\eta| < 2.5(2.4)$ & MVAs for **b-tagging**
- signal region: 2 oppositely charge leptons, 1 b-tagged jet, $\not{E}_{\mathrm{T}}$

- analysis strategies
  - small cross section vs. $t\bar{t}$ background, QCD multijet contribution negligible



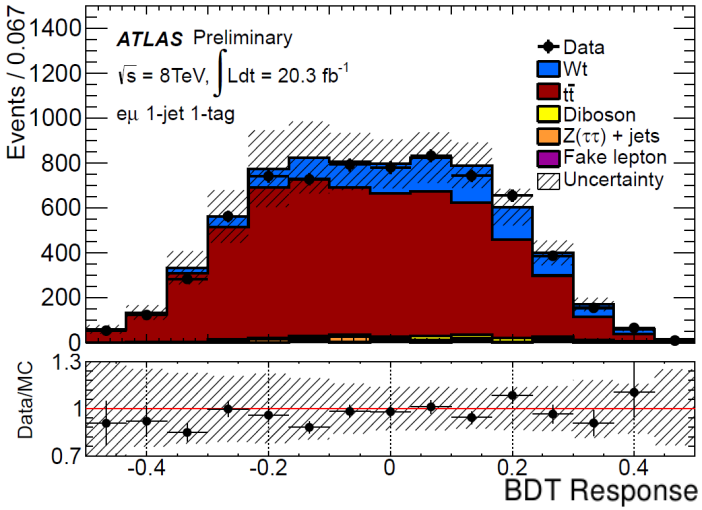


dedicated MVA utilized in both analyses

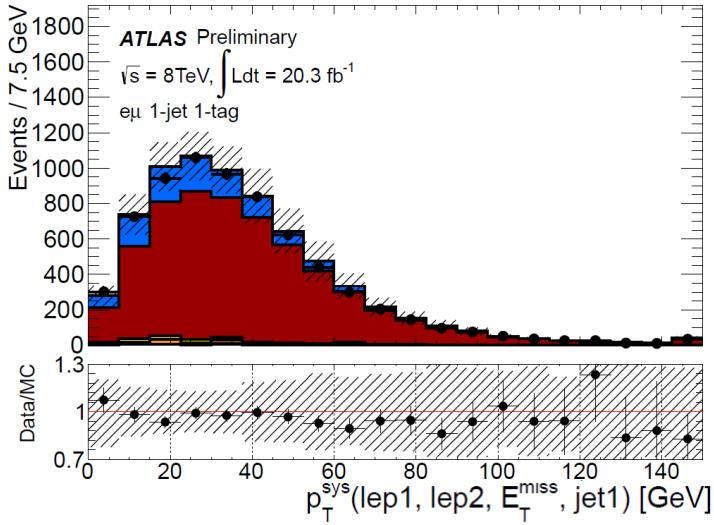
MVA outputs

ATLAS-CONF-2013-100
CMS: PRL 112 (2014)

- ATLAS:

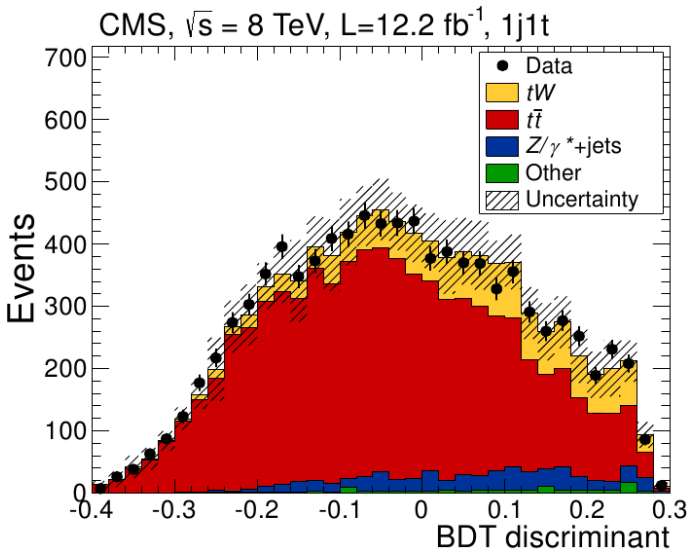


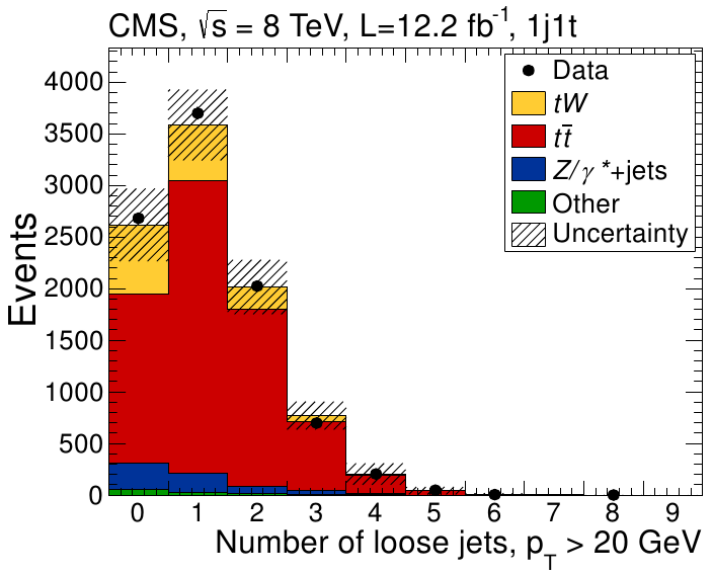
most discriminating variable



- 2 BDTs trained: 19 (20) input variables for 1 (2) jet exclusive category with 1 b-tag
- some input variables: $\Sigma p_{\mathrm{T}}^{i}$, $\Delta p_{\mathrm{T}}^{i,j}$, $\Delta\phi^{i,j}$, $m^{i,j}$, thrust, centrality, ...

- CMS

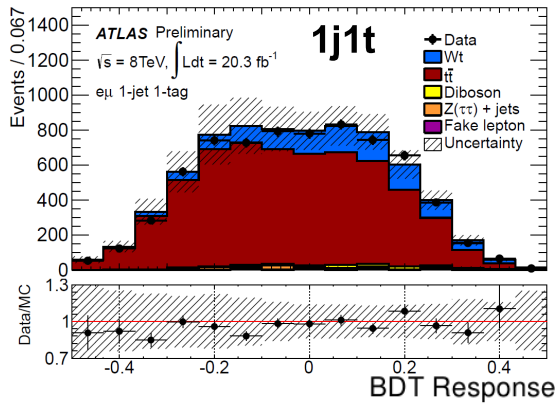


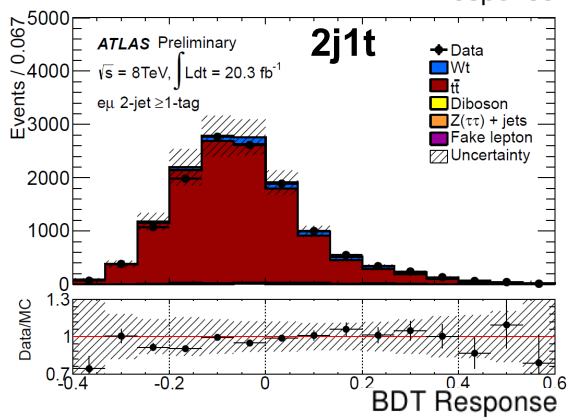


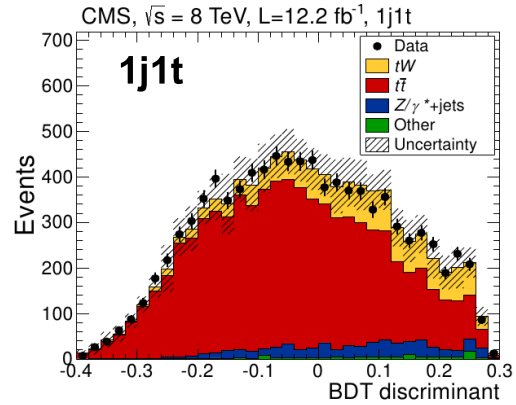
- 13 input variables: #loose jets, #loose central jets, #loose b-tagged jets, centrality, p_{T}^{sys}, ...

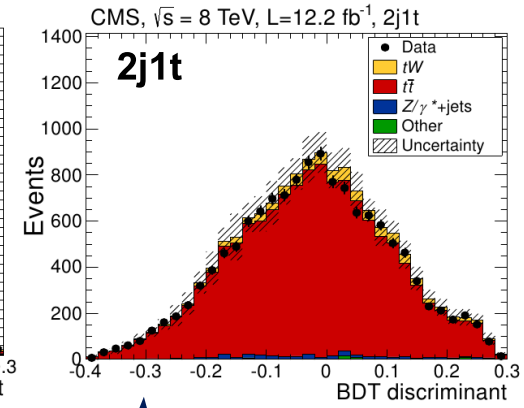
tW-channel: Fit & Result

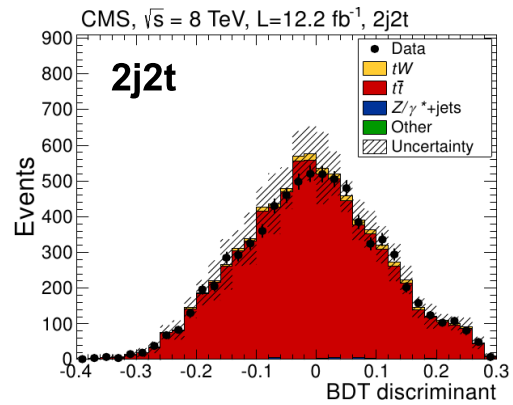
ATLAS-CONF-2013-100
CMS: PRL 112 (2014)
comb.: CMS PAS TOP-14-009











2 $t\bar{t}$-control regions allow in-situ constraint of b-tagging efficiency

$$\left[\sigma_{\mathrm{tW}}^{(\mathrm{theo.})} = 22.2 \pm 1.5\ \mathrm{pb}\right]$$

ATLAS

major systematic uncertainties:
$tW, t\bar{t}$ modeling, flavor tagging, b-jet scale

$$\sigma_{\mathrm{tW}} = 27.2 \pm 2.8(\mathrm{stat.}) \pm 5.4(\mathrm{syst.})\ \mathrm{pb}$$
$$|V_{\mathrm{tb}}| = 1.10 \pm 0.12 \qquad |V_{\mathrm{tb}}| > 0.72\ @95\%\mathrm{CL}$$

$$\sigma_{\mathrm{tW}}^{\mathrm{ATLAS+CMS}} = 25.0 \pm 4.7\ \mathrm{pb} \quad |V_{\mathrm{tb}}| > 0.79$$

CMS

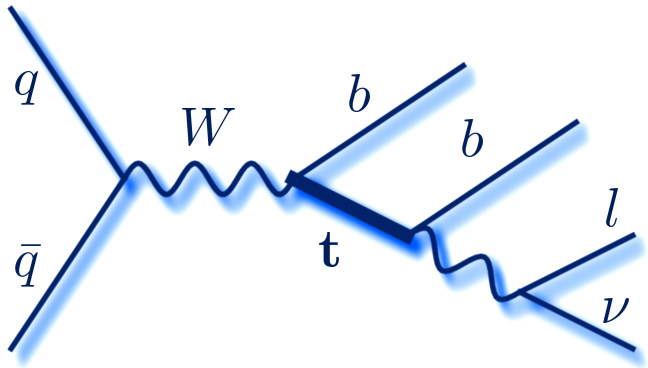
major systematic uncertainties:
ME/PS matching, Q^2, μ_F^2 scale, top mass

$$\sigma_{\mathrm{tW}} = 23.4 \pm 5.4\ \mathrm{pb}$$
$$|V_{\mathrm{tb}}| = 1.03 \pm 0.13 \qquad |V_{\mathrm{tb}}| > 0.78\ @95\%\mathrm{CL}$$

8 TeV: s-channel search

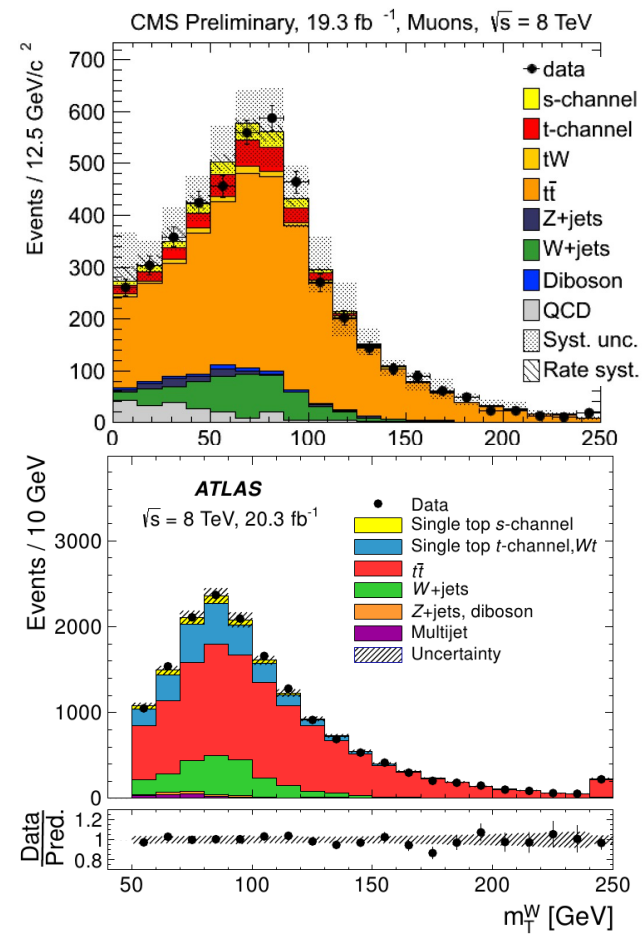
ATLAS: PLB 740 (2015)
CMS PAS TOP-13-009

- event selection at ATLAS (CMS)



- single & isolated **muon** $p_{\mathrm{T}} > 30(26)\ \mathrm{GeV},\ |\eta| < 2.5(2.1)$ or **electron** $p_{\mathrm{T}} > 30(30)\ \mathrm{GeV},\ |\eta| < 2.47(2.5)$
- **jets**: $p_{\mathrm{T}} > 30(40)\ \mathrm{GeV},\ |\eta| < 2.5(2.5)$ & **b-tagging**
- signal region: 2 jets & both b-tagged, 1 lepton, $\not{E}_{\mathrm{T}}$

- analysis strategies
  - CMS
    - data-driven QCD estimation using $m_{\mathrm{T}}(W)/\not{E}_{\mathrm{T}}$
    - 2 BDTs (e & μ) for signal + 2 BDTs for $W{+}\mathrm{jets}/t\bar{t}$
    - signal estimation using simultaneous maximum likelihood fit in 2j2t (SR) & 3j2t ($t\bar{t}$ CR)
  - ATLAS
    - data-driven QCD estimation with matrix method
    - special selection & reconstruction: e.g. best top $\equiv l + \nu + j_i$ closest to $172.5\ \mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{j,best\ top}} > 50\ \mathrm{GeV}$
    - likelihood fit to single BDT

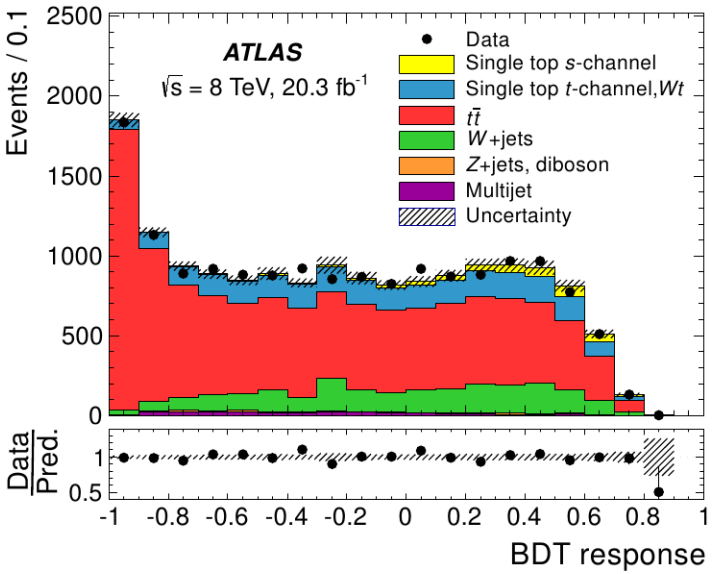


s-channel: BDTs & Result

ATLAS: PLB 740 (2015)
CMS PAS TOP-13-009

$$\left[\sigma^{(\text{theo.})}_{\text{s-channel}} = 5.55 \pm 0.22 \text{ pb}\right]$$

➢ ATLAS



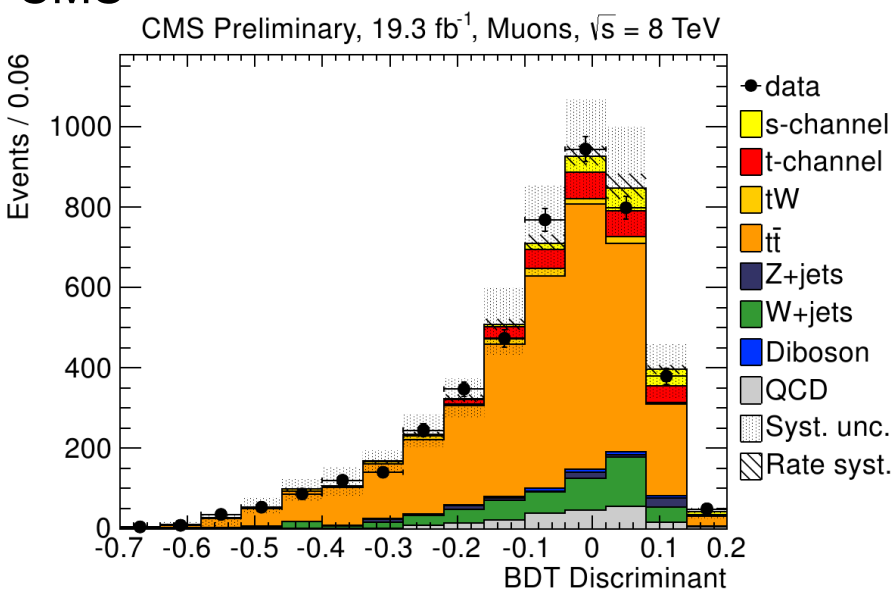
- major systematic uncertainties:
  jet energy scale, $\not{E}_{\mathrm{T}}$ scale, simulation statistics, ...
- result

  $\sigma_{\text{s-channel}} = 5.0 \pm 4.3 \text{ pb}$

  observed (expected) limit: $1.3\sigma(1.4\sigma)$

  $\sigma_{\text{s-channel}} < 14.6 \text{ pb @95\%CL}$

➢ CMS



- major systematic uncertainties:
  Q^2, μ_F^2 scale, jet energy scale, ME/PS matching, ...
- result

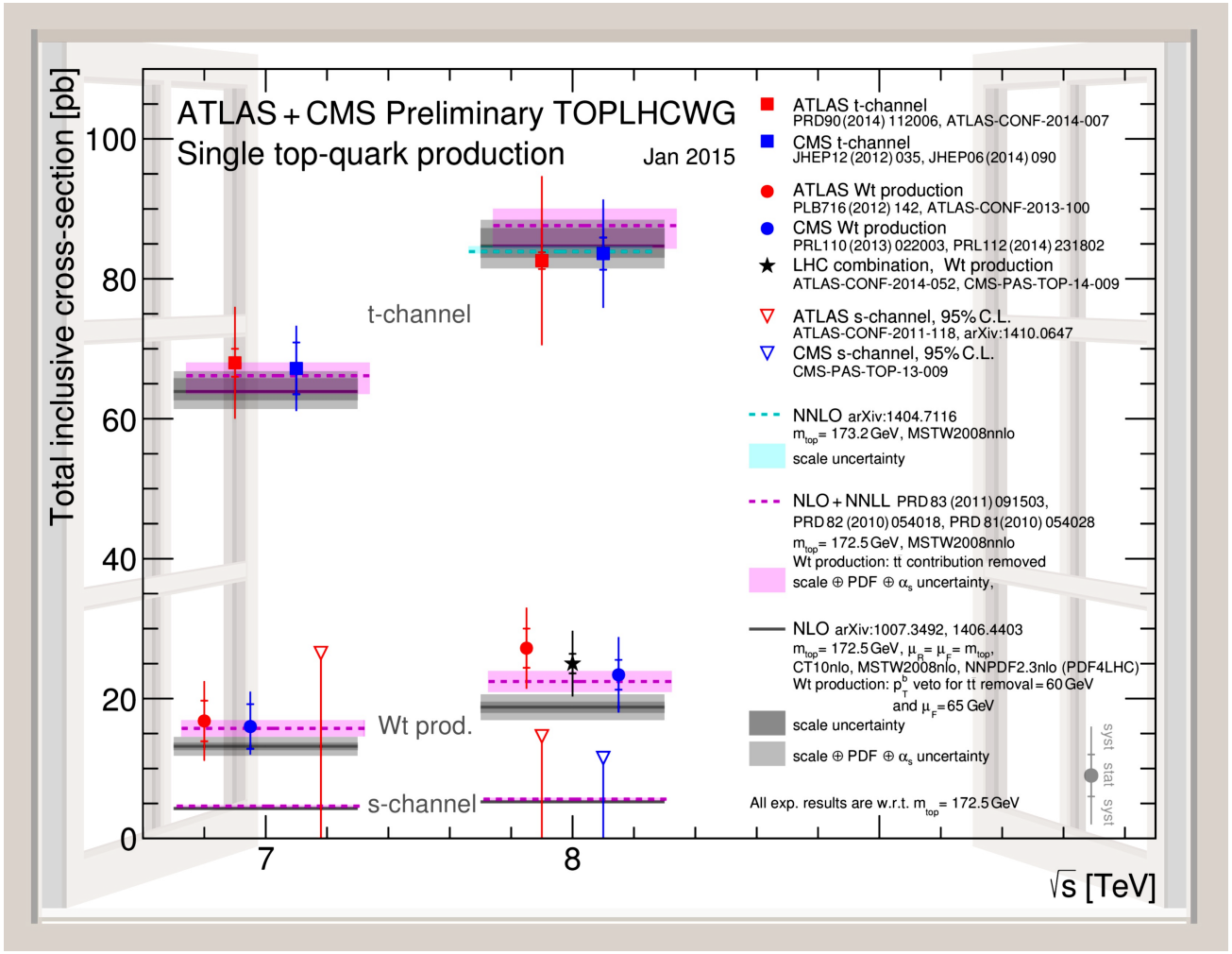
  $\sigma_{\text{s-channel}} = 6.2 \pm 8.0 \text{ pb}$

  observed (expected) limit: $0.7\sigma(0.9\sigma)$

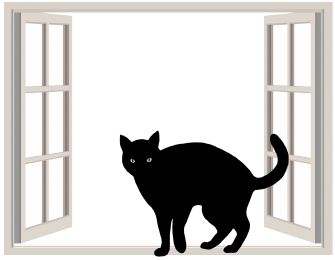
  $\sigma_{\text{s-channel}} < 11.5 \text{ pb @95\%CL}$

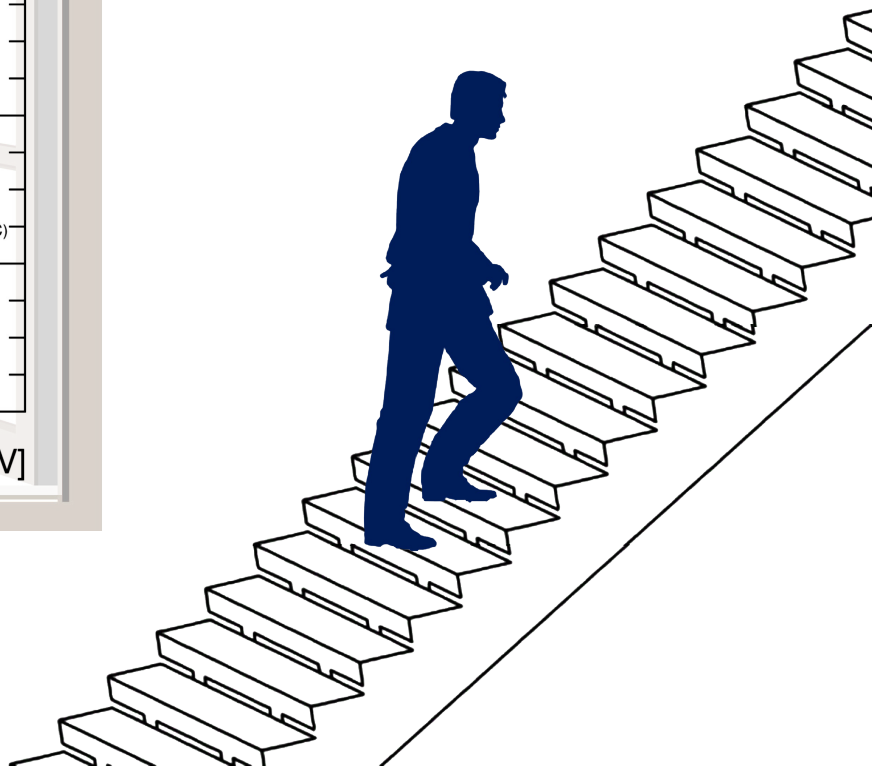
Summary: $\sigma_{\text{single-top}}$

7+8 TeV



13 TeV

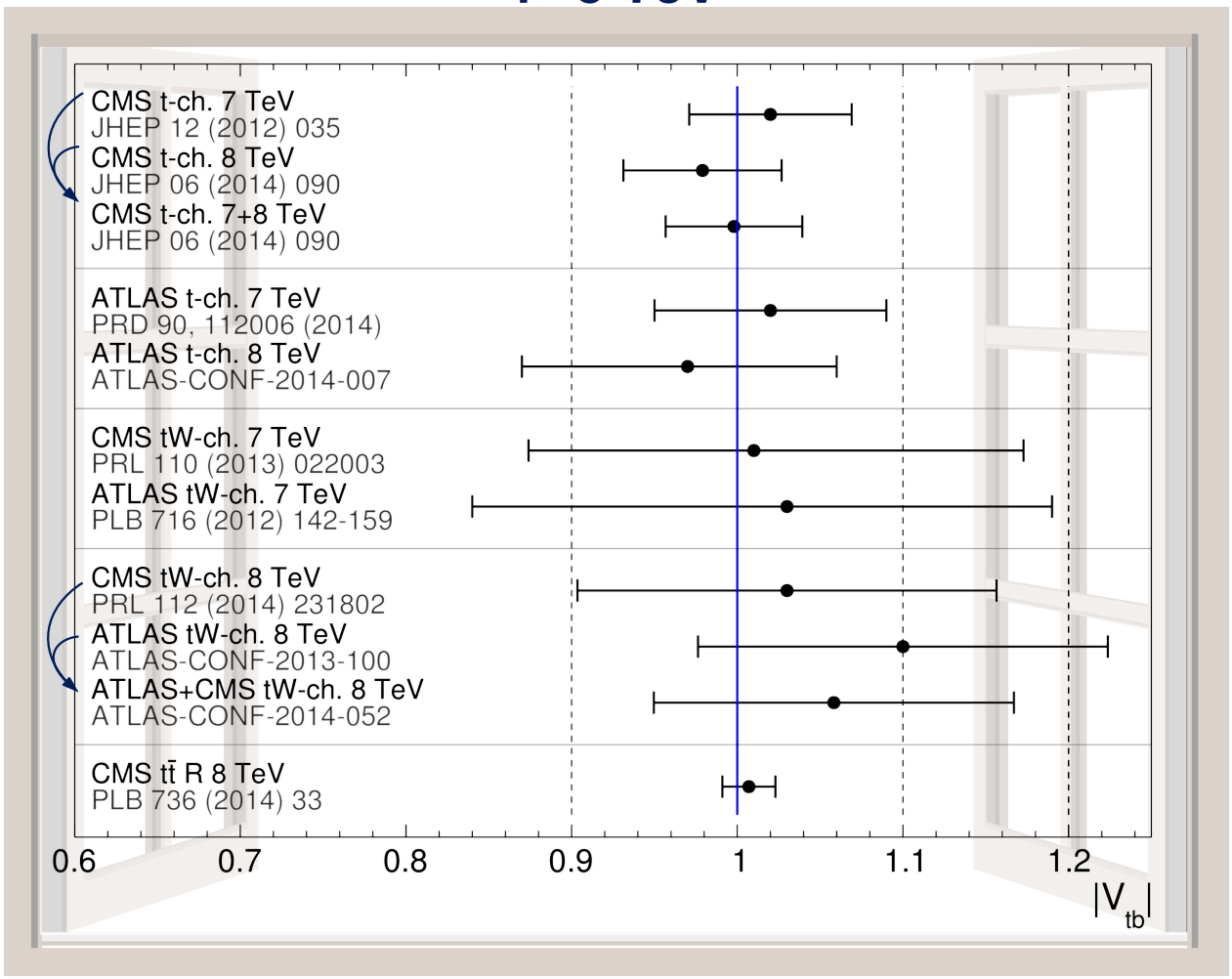




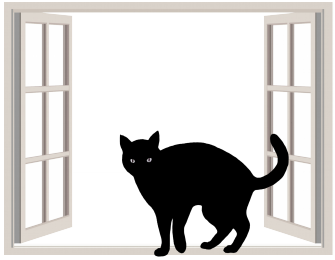
- got a good view at single top production at 7+8 TeV
- analyses performed targeting **all channels**:
  - precise **t-channel** measurements
  - first observation of **tW-production**
  - search for **s-channel**

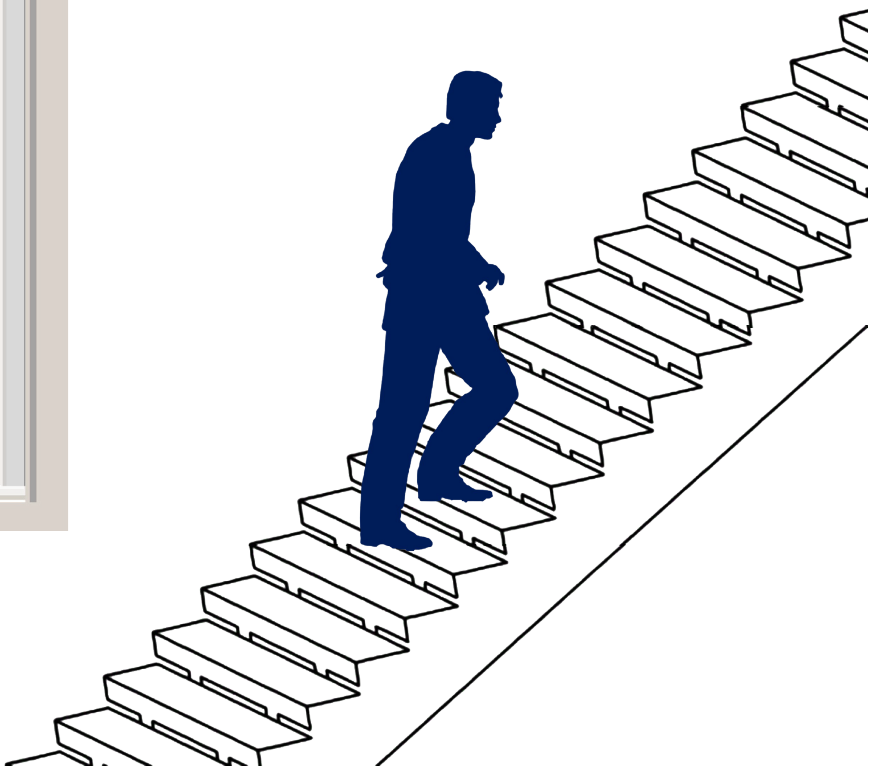
Summary: V_{tb} measurements

7+8 TeV



13 TeV





- got a good view at V_{tb} as well through single top production via **t- & tW-channels**
- most precise determination of V_{tb} through $\mathbf{R} = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$ measurement in $t\bar{t}$ (assumes 3 generations & unitarity)

Backup

ATLAS: 8 TeV t-channel

ATLAS-CONF-2014-007

- NN input variables

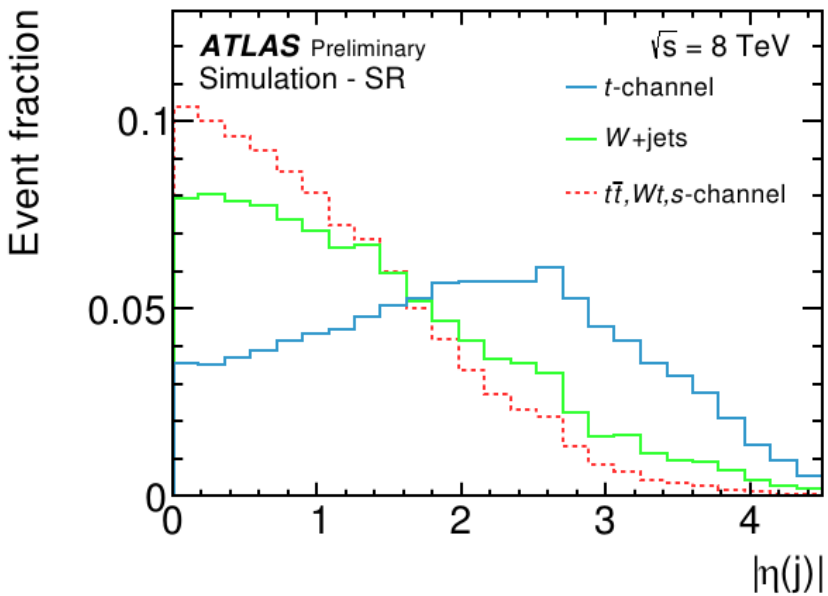
Variable	Definition
$\lvert\eta(j)\rvert$	pseudorapidity of the light quark (untagged) jet (j)
$m(\ell\nu b)$	top-quark mass reconstructed from the charged lepton, neutrino and b-quark jet
$m(jb)$	invariant mass of the tagged (b) and light quark jet (j)
$m_{\mathrm{T}}(W)$	transverse mass of the reconstructed W boson
$m(\ell b)$	invariant mass of the lepton (ℓ) and the tagged jet (b)
$\eta(l\nu)$	pseudorapidity of the reconstructed W-boson
$\cos\Theta(\ell, j)_{\ell\nu b\,\mathrm{r.f.}}$	cosine of the angle θ between the charged lepton and the light quark (untagged) jet (j) in the rest frame of the reconstructed top quark
$H_T(l, \mathrm{jets}, E_{\mathrm{T}}^{\mathrm{miss}})$	scalar sum of the transverse momenta of the jets, the charged lepton and the missing transverse momentum
$E_{\mathrm{T}}^{\mathrm{miss}}$	transverse missing momentum
$\Delta R(\ell\nu b, \ell)$	ΔR of the reconstructed top quark and the charged lepton
$p_{\mathrm{T}}(\ell\nu)$	transverse momentum of the reconstructed W-boson
$\eta(\ell\nu b)$	pseudorapidity of the reconstructed top quark
$\eta(b)$	pseudorapidity of the b-quark jet (b)
$p_{\mathrm{T}}(\ell\nu b)$	transverse momentum of the reconstructed top quark

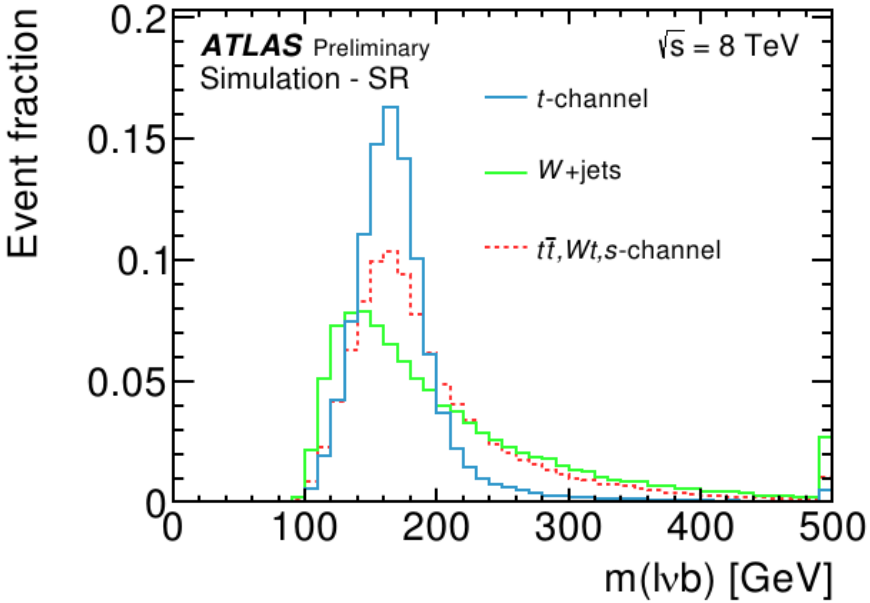
- setup:
  - NeuroBayes (three-layer feed-forward with Bayesian regularization in training)
  - additional bias node
  - 50:50 background to signal events

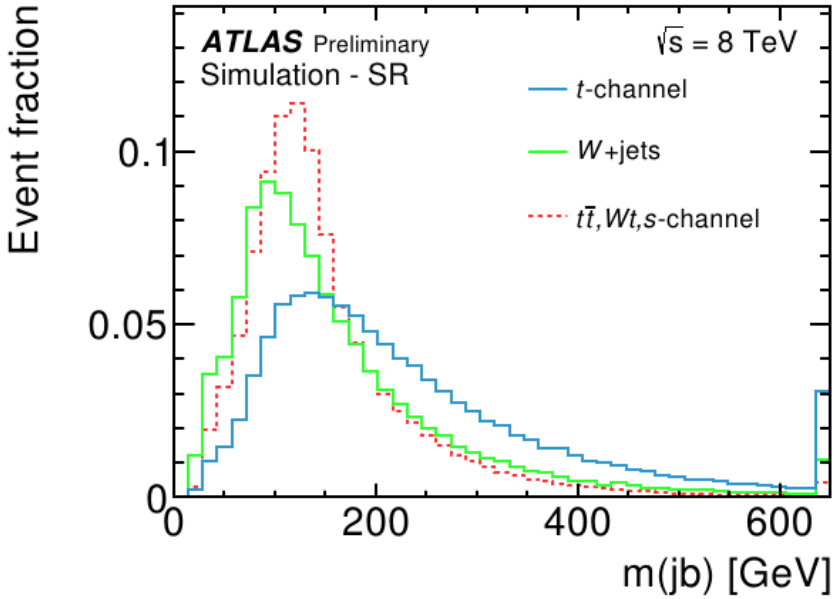
ATLAS: 8 TeV t-channel

ATLAS-CONF-2014-007

- the three most discriminating variables







ATLAS: 8 TeV t-channel

ATLAS-CONF-2014-007

- fiducial region definition

Object	Cut
Electrons	$p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$
Muons	$p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$
Jets	$p_T > 30$ GeV and $\lvert\eta\rvert < 4.5$
	$p_T > 35$ GeV, if $2.75 < \lvert\eta\rvert < 3.5$
Lepton (ℓ), Jets (j_i)	$\Delta R(\ell, j_i) > 0.4$
E_T^{miss}	$E_T^{miss} > 30$ GeV
Transverse W-boson mass	$m_T(W) > 50$ GeV
Lepton (ℓ), jet with the highest p_T (j_1)	$p_T(\ell) > 40\text{ GeV}\left(1 - \frac{\pi - \lvert\Delta\phi(j_1,\ell)\rvert}{\pi - 1}\right)$

ATLAS: tW-channel MVAs

ATLAS-CONF-2013-100

1 jets events

Variable	Description
p_T^{sys} variables	p_T of the vectorial sum of physics objects
p_T^{sys} (lep1,lep2,E_T^{miss},jet1)	p_T^{sys} of leptons, E_T^{miss} and jet1
p_T^{sys} (lep1,lep2,jet1)	p_T^{sys} of leptons and jet1
p_T-related variables	
Δp_T ((lep1,lep2),(E_T^{miss},jet1))	Difference in p_T between the system of leptons and that of E_T^{miss} and jet
Δp_T (lep1,E_T^{miss})	Difference in p_T between lep1 and E_T^{miss}
$\sum E_T$	Visible event transverse energy
H_T (lep1,lep2,E_T^{miss},jet1)	Scalar sum of the p_T of all objects
Angular correlations	
$\Delta\phi$ ((lep1,lep2),jet1)	$\Delta\phi$ between the vector sum of leptons and jet1
ΔR ((lep1,lep2),jet1)	ΔR between the vector sum of leptons and jet1
$\Delta\phi$ (lep1,jet1)	$\Delta\phi$ between lep1 and jet1
$\Delta\phi$ (E_T^{miss},jet1)	$\Delta\phi$ between E_T^{miss} and jet1
Centrality (lep1,lep2)	$(p_T(\text{lep1}) + p_T(\text{lep2}))/(p(\text{lep1}) + p(\text{lep2}))$
Thrust	Thrust of all leptons and jets
η (lep1,lep2)	Pseudo-rapidity of the vector sum of leptons
m or m_T variables	Mass or transverse mass of the vectorial sum of objects
m_T (lep2,E_T^{miss})	m_T of lep2 and E_T^{miss}
m (lep1,lep2,jet1)	m of leptons and jet1
m (lep1,jet1)	m of lep1 and jet1
Object kinematics	
E_T^{miss}	Missing transverse momentum
E_T (jet1)	jet1 transverse energy
η (lep2)	lep2 pseudo-rapidity

2 jet events

Variable	Description
p_T^{sys} variables	p_T of the vectorial sum of physics objects
p_T^{sys} (jet1,jet2)	p_T^{sys} of both jets
p_T^{sys} (lep1,lep2)	p_T^{sys} of both leptons
p_T^{sys} (lep1,lep2,E_T^{miss},jet1)	p_T^{sys} of leptons, E_T^{miss} and jet1
p_T^{sys} (lep1,E_T^{miss},jet2)	p_T^{sys} of lep1, E_T^{miss} and jet2
p_T-related variables	
Δp_T ((lep1,lep2),(E_T^{miss},jet1))	Difference in p_T between the system of leptons and the system of E_T^{miss} and jet1
Δp_T (jet1,E_T^{miss})	Difference in p_T between jet1 and E_T^{miss}
Angular correlations	
$\Delta\phi$((lep1,lep2),(E_T^{miss},jet1))	$\Delta\phi$ between the vector sum of leptons and the vector sum of E_T^{miss} and jet1
$\Delta\phi_{MAX}$ (lep,jet1)	Larger $\Delta\phi$ between any lepton and jet1
ΔR ((lep1,jet2)	ΔR between the lep1 and jet2
Centrality (lep2,jet1,jet2)	$(p_T(\text{lep2}) + p_T(\text{jet1}) + p_T(\text{jet2}))/(p(\text{lep2}) + p(\text{jet1}) + p(\text{jet2}))$
η (lep1,jet2)	Pseudo-rapidity of the vector sum of lep1 and jet2
m variables	
m (lep1,jet2)	m of lep1 and jet2
m (lep1,jet1)	m of lep1 and jet1
m (lep2,jet1)	m of lep2 and jet1
m (lep2,jet2)	m of lep2 and jet2
Object kinematics	
E_T^{miss}	Missing transverse momentum
E_T (jet1)	jet1 transverse energy
E (lep1)	lep1 energy
E (jet2)	jet2 energy

CMS: tW MVA

CMS: PRL 112 (2014)

1 jet (1 b-tagged)

Variable Name	Description
# of loose jets	Number of loose jets, $p_T > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.9$
# of central loose jets	Number of loose jets, $p_T > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$
# of b-tagged loose jets	Number of loose jets, $p_T > 20\,\mathrm{GeV}$, q_b-tagged, $\lvert\eta\rvert < 2.4$
p_T^{sys}	Vector sum of p_T of leptons, jet, and E_T^{miss}
H_T	Scalar sum of p_T of leptons, jet, and E_T^{miss}
$p_T(\mathrm{jet})$	p_T of the leading, tight, b-tagged jet
$p_T(\mathrm{loose\ jet})$	p_T of leading loose jet, defined as 0 for events with no loose jet present
p_T^{sys}/H_T	Ratio of p_T^{sys} to H_T for the event
m_{sys}	Invariant mass of the combination of the leptons, jet, and E_T^{miss}
$\mathrm{Centrality}(\mathrm{j}\ell\ell)$	Centrality of jet and leptons, defined as ratio of transverse to total energy
$H_T(\mathrm{leptons})/H_T$	Ratio of scalar sum of p_T of the leptons to the H_T of full system
$p_T(\mathrm{j}\ell\ell)$	Vector sum of p_T of jet and leptons
E_T^{miss}	Missing transverse energy in the event

tW: systematics

ATLAS-CONF-2013-100
CMS: PRL 112 (2014)

ATLAS

Source	$\Delta\sigma/\sigma$ [%] observed	$\Delta\sigma/\sigma$ [%] expected
Data statistics	7.1	8.6
MC statistics	2.8	3.5
Experimental uncertainties		
Lepton modeling	2.4	2.4
Jet identification	0.2	0.6
Jet energy scale	10	12
b-jet energy scale	5.0	6.3
Jet energy resolution	0.7	0.2
E_T^{miss} scale	4.1	5.0
E_T^{miss} resolution	4.5	5.3
Flavor tagging	8.4	9.4
Theory uncertainties		
$Wt/t\bar{t}$ overlap modeling	1.4	1.6
PDF	2.5	3.2
Background normalization	3.6	4.4
ISR/FSR	5.9	6.0
Wt generator and PS	11	11
$t\bar{t}$ generator and PS	7.5	9.2
Luminosity	3.7	3.9
Total (syst)	20	23
Total (syst+stat)	21	24

CMS

Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$
ME/PS matching thresholds	3.3	14%
Renormalization/factorization scale	2.9	12%
Top-quark mass	2.2	9%
Fit statistical	1.9	8%
Jet energy scale	0.9	4%
Luminosity	0.7	3%
Z+jets data/simulation scale factor	0.6	3%
tW DR/DS scheme	0.5	2%
$t\bar{t}$ cross section	0.4	2%
Lepton identification	0.4	2%
PDF	0.4	2%
Jet energy resolution	0.2	1%
b-tagging data/simulation scale factor	0.2	<1%
$t\bar{t}$ spin correlations	0.1	<1%
Pileup	0.1	<1%
Top-quark p_T reweighting	0.1	<1%
E_T^{miss} modeling	0.1	<1%
Lepton energy scale	0.1	<1%
Total	5.5	24%

CMS: s-channel MVAs

CMS PAS TOP-13-009

- electron

Variable	Description
m_T	tranverse W boson mass
$\Delta\Phi_{top,b'}$	difference in azimuthal angle between top quark and recoiled b-tagged jet
$\not{E}_T$	missing transverse energy
$M_{\ell b2}$	invariant mass of the lepton and the second-to-leading b-tagged jet
$\cos\theta^*$	cosine of the angle between the lepton and the b-tagged jet recoiling against the top quark, in the top-quark rest frame
p_T^{bb}	vector sum of p_T of the two b-tagged jets
$\Delta R_{bb}(*)$	angular separation between the two b-tagged jets
p_T^{ℓ}	transverse momentum of the lepton
$m_{\ell\nu b}$-best	invariant mass of lepton, neutrino and one of the b-tagged jets reconstructed with the best-mass top method, as described in Sec.2
$\Delta R_{b'\ell}$	angular separation between the b-tagged jet recoiling against the top quark and the lepton
H_T	scalar sum of p_T of all jets

- muon

Variable	Description
p_T^{bb}	vector sum of p_T of the two b-tagged jets
$m_{\ell\nu b}$-best	invariant mass of lepton, neutrino and one of the b-tagged jets reconstructed with the best-mass top method, as described in Sec.2
m_T	tranverse W boson mass
$M_{\ell b2}$	invariant mass of the lepton and the second-to-leading b-tagged jet
$\not{E}_T$	missing transverse energy
$\Delta\Phi_{top,b'}$	difference in azimuthal angle between top quark and the recoiled b-tagged jet
$\cos\theta_l$	cosine of the angle between the lepton and the beam axis in top-quark rest frame
ΔR_{bb}	angular separation between the two b-tagged jets
H_T	scalar sum of p_T of all jets
p_T^{ℓ}	transverse momentum of the lepton

ATLAS: s-channel systematics

ATLAS: PLB 740 (2015)

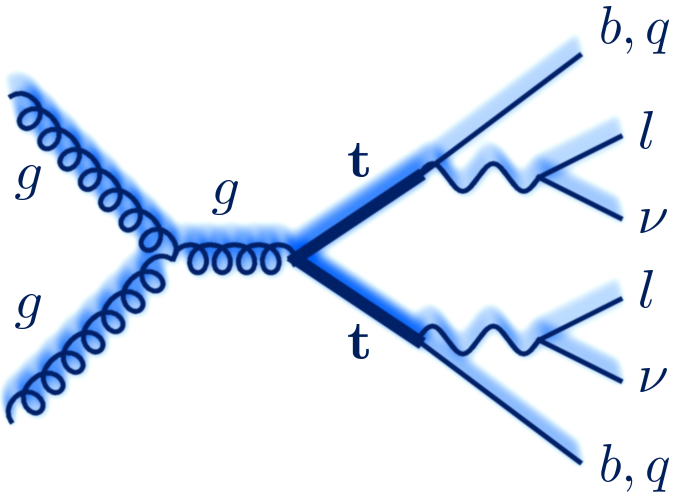
Source	$\Delta\sigma/\sigma$ [%]
Data statistics	± 35
Simulation statistics	± 29
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	± 54
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	$+0/-3$
Jet energy scale	± 39
Jet energy resolution	± 5
Jet tagging efficiencies	± 4
Jet reconstruction efficiency	< 1
Lepton energy scale/resolution	< 1
Lepton efficiencies	$+2/-1$
Signal modelling and scale	± 11
$t\bar{t}$ modelling	± 6
W+jets shape modelling	± 8
ISR/FSR	± 3
PDF	< 1
Background normalization	± 7
Multijet normalization	± 12
Integrated luminosity	± 5
Total systematic	± 80
Total	± 87

CMS: R measurement in $t\bar{t}$

PL B 736 (2014) 33

- definition: $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$
  assuming 3 quark generations & CKM unitarity: $R \equiv |V_{\mathrm{tb}}|^2$

- event selection

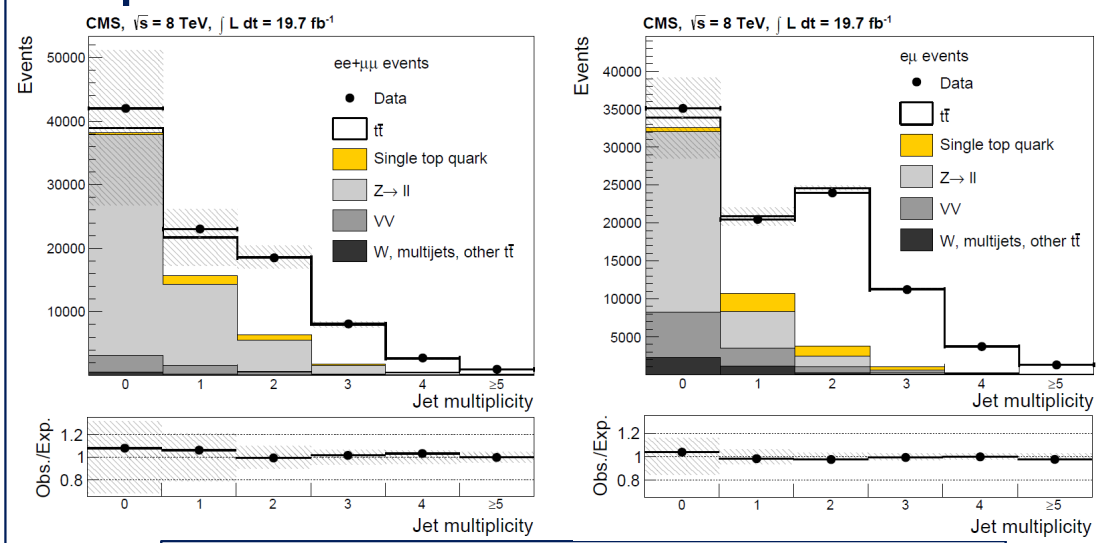


- **2 oppositely charged leptons** (e/μ)
  $p_{\mathrm{T}} > 20\ \mathrm{GeV},\ |\eta| < 2.4$
- at least **2 jets** $p_{\mathrm{T}} > 30\ \mathrm{GeV},\ \ |\eta| < 2.4$
  $\not{E}_{\mathrm{T}} > 40\ \mathrm{GeV}$ (only $ee/\mu\mu$ channels)
- main background ($Z/\gamma^{\star} \to ll$) estimated from data

- 3 steps to measure R

  - How many $t\bar{t}$ events are in data?
    $\Rightarrow \sigma(t\bar{t})$
  - How many events have also jets from top decay present?
    → gives handle on $\mathcal{B}(t \to Wq)$
  - How many of those jets are b-tagged?
    → gives handle on $\mathcal{B}(t \to Wb)$

step 1: cross section measurement

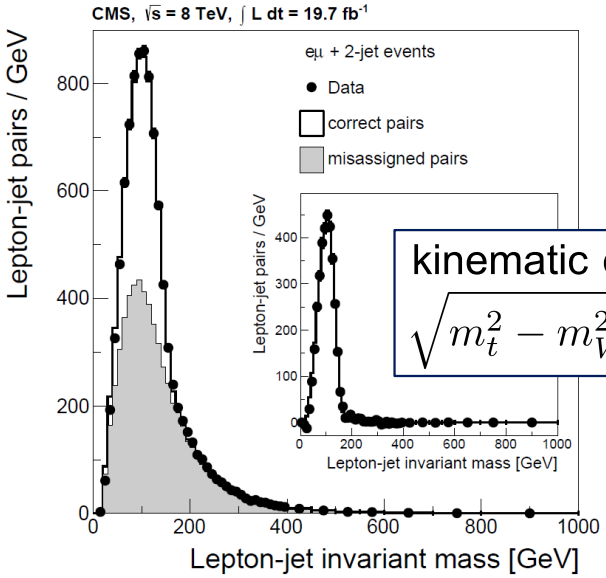


$$\sigma(t\bar{t}) = 238 \pm 1(\mathrm{stat}) \pm 15(\mathrm{syst})\ \mathrm{pb}$$

CMS: R measurement in $t\bar{t}$

PL B 736 (2014) 33

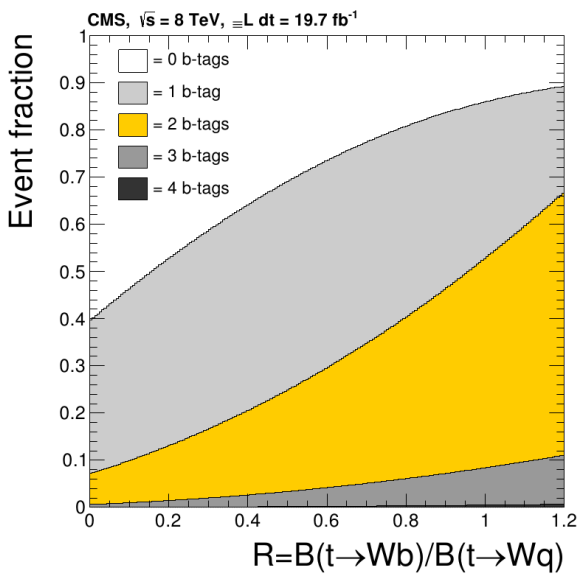
step 2: jets from top decay



kinematic endpoint:

$$\sqrt{m_t^2 - m_W^2} \approx 153 \text{ GeV}$$

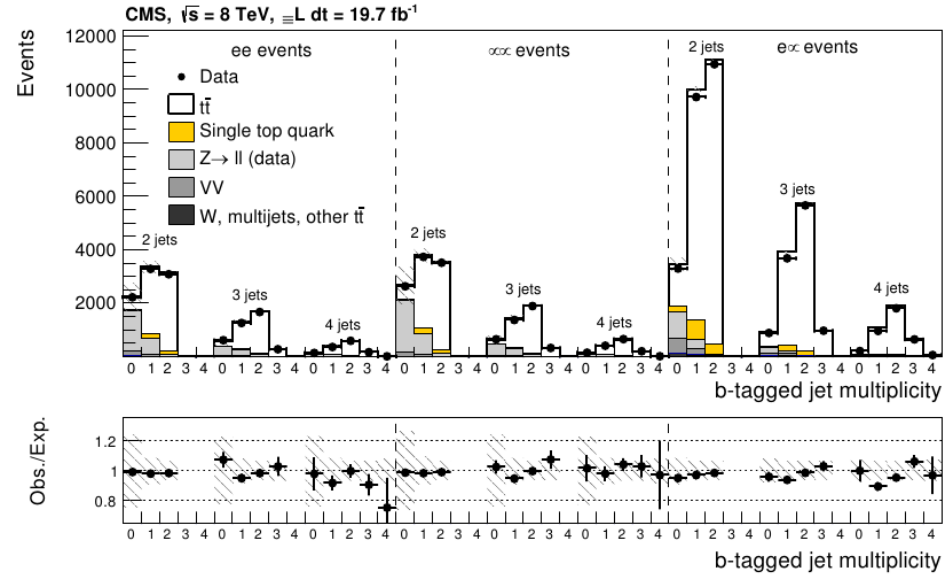
step 3: b-tagged jets from top decay

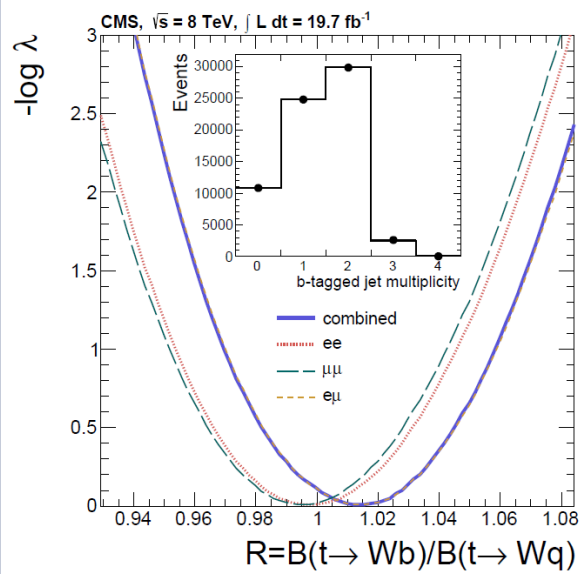


using MVA b-tagger ($\epsilon_{t\bar{t}} \approx 84\%$)

measurement

binned-likelihood fit in $3 \cdot 3 \cdot 4 = 36$ categories





$e\mu$ channel dominates combination through lower stat. uncertainty

final result

$$|V_{\text{tb}}| = 1.007 \pm 0.016$$

$$|V_{\text{tb}}| > 0.975 \text{ @95\%CL}$$

R measurement

PL B 736 (2014) 33

- purity

Parameter	Jet multiplicity	Dilepton channel ee	$\mu\mu$	eμ
$f_{t\bar{t}} \equiv \epsilon(t\bar{t})$	2	0.67 ± 0.07	0.65 ± 0.08	0.85 ± 0.06
	3	0.79 ± 0.06	0.78 ± 0.07	0.90 ± 0.07
	4	0.81 ± 0.11	0.82 ± 0.11	0.94 ± 0.10
$k_{st} \equiv \epsilon(tW)$	2	0.062 ± 0.004	0.063 ± 0.004	0.062 ± 0.003
	3	0.040 ± 0.003	0.040 ± 0.003	0.041 ± 0.002
	4	0.036 ± 0.004	0.036 ± 0.006	0.029 ± 0.003

- selection efficiency of jets from top decay

Dilepton channel	# jets	$f_{\text{correct}}^{\text{data}}$	$f_{\text{correct}}^{\text{MC}}$	data/MC
ee	2	0.28 ± 0.05	0.277 ± 0.001	1.03 ± 0.19
	3	0.22 ± 0.07	0.223 ± 0.001	0.99 ± 0.29
	4	0.19 ± 0.07	0.175 ± 0.001	1.09 ± 0.43
$\mu\mu$	2	0.28 ± 0.06	0.276 ± 0.001	1.00 ± 0.21
	3	0.24 ± 0.06	0.227 ± 0.001	1.05 ± 0.25
	4	0.20 ± 0.07	0.181 ± 0.001	1.08 ± 0.37
eμ	2	0.36 ± 0.06	0.3577 ± 0.0007	1.01 ± 0.16
	3	0.26 ± 0.05	0.2625 ± 0.0007	1.00 ± 0.18
	4	0.21 ± 0.06	0.2047 ± 0.0008	1.00 ± 0.27

R measurement: uncertainties

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Source	Uncertainty (%)
Experimental uncertainties:	
ε_b	2.4
ε_q	0.4
$f_{t\bar{t}}$	0.1
DY	0.2
misidentified lepton	0.1
JER	0.5
JES	0.5
unclustered E_T^{miss}	0.5
integrated luminosity	0.2
pileup	0.5
simulation statistics	0.5
$f_{correct}$	0.5
model calibration	0.2
selection efficiency	0.1
Theoretical uncertainties:	
top-quark mass	0.9
top-quark p_T	0.5
ME-PS	0.5
μ_R/μ_F	0.5
signal generator	0.5
underlying event	0.1
colour reconnection	0.1
hadronisation	0.5
PDF	0.1
$t \to Wq$ flavour	0.4
$\lvert V_{td}\rvert/\lvert V_{ts}\rvert$	<0.01
relative single-top-quark fraction (tW)	0.1
VV (theoretical cross section)	0.1
extra sources of heavy flavour	0.4
Total systematic	3.2