Measurements of the production cross section of top quark pairs using the ATLAS detector at the LHC

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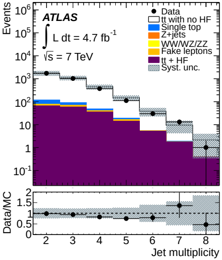
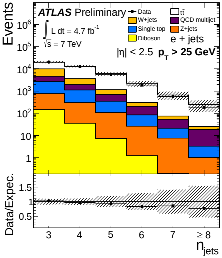
The Large Hadron Collider Physics Conference, May 13 - 18, 2013, Barcelona, Spain

Introduction

- The LHC gives us an unprecedented sample of top quarks to study
  - **Large data set** allows differential measurements, observation of difficult decay channels and associated production, requirement of 2 or more b-tags for ultra-pure sample



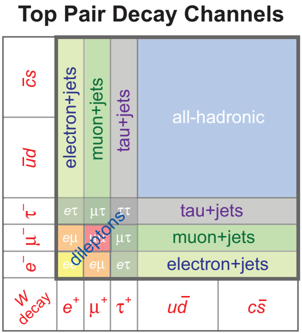


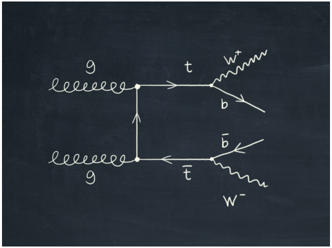
High purity dilepton $t\bar{t}$ with 2 b-tags (left), lepton+jets $t\bar{t}$ with up to 4 additional jets (right)

- These data are used for **Standard Model tests, perturbative QCD measurements, new physics searches, understanding backgrounds for Higgs and new physics searches, detector calibration**

I will show results from **seven** recent ATLAS results, showcasing **inclusive** and **differential** measurements

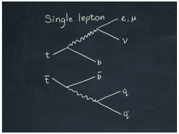
Introduction

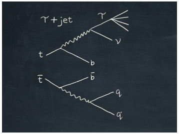


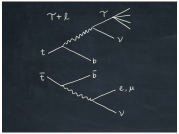


Channels defined by decay of W (and subsequent tau lepton):

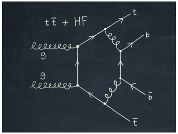
Single Lepton	(e/μ) + jets (34.3%)
Dilepton	$(ee/e\mu/\mu\mu)$ (6.4%)
All-hadronic	light jets (45.7%)
Tau+jets	hadronic tau + light jets (9.8%)
Tau+lepton	hadronic tau + (e/μ) (3.7%)

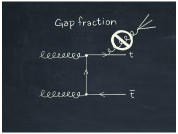
- Inclusive
  - 

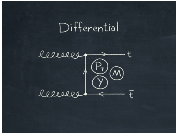
Single Lepton
  - 

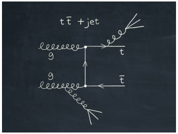
Tau+jets
  - 

Tau+lepton

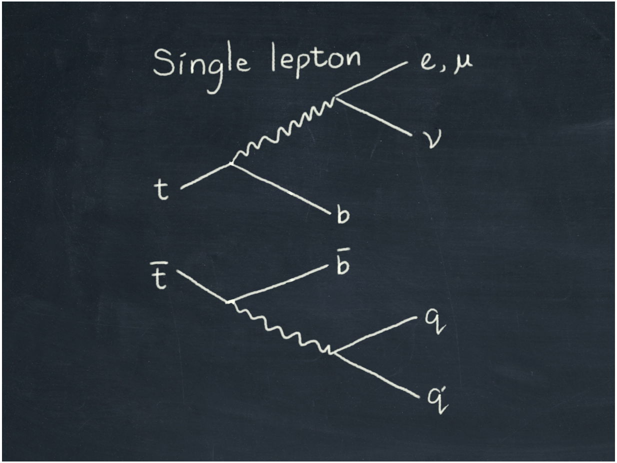
- Associated/Differential
  - 

$t\bar{t}$+heavy flavor
  - 

Gap fraction
  - 

Differential $\sigma_{t\bar{t}}$ in $m_{t\bar{t}}$, $p_{T,t\bar{t}}$, $y_{t\bar{t}}$
  - 

$t\bar{t}$+jets

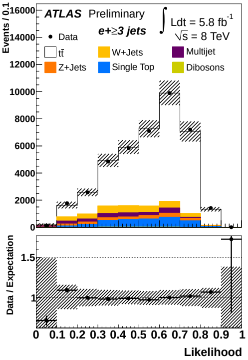


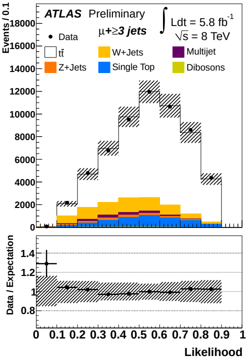
Single Lepton: $\sqrt{s} = 8$ TeV, $\mathcal{L} = 5.8\ \mathrm{fb}^{-1}$

ATLAS-CONF-2012-149

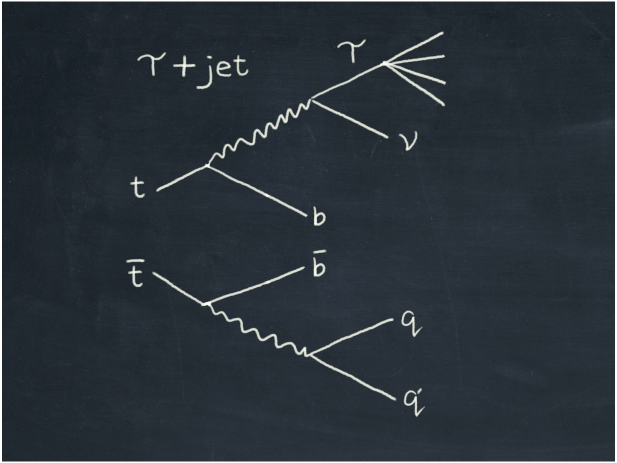
Single Lepton: $\sqrt{s} = 8$ TeV, $\mathcal{L} = 5.8\ \mathrm{fb}^{-1}$

$\sigma_{t\bar{t}} = 241 \pm 2(\mathrm{stat.}) \pm 31(\mathrm{syst.}) \pm 9(\mathrm{lumi.})\mathrm{pb}$
$\sigma_{t\bar{t}}^{\mathrm{theor.}} = 245.8^{+6.2}_{-8.4}(\mathrm{scale})\ ^{+6.2}_{-6.4}(\mathrm{pdf})\mathrm{pb}$
Czakon, Fiedler, Mitov arXiv:1303.6254





- Large $\not{E}_T$ and $m_T(W)$, 1 e/μ ($p_T(\ell) > 40$ GeV), 3 or more jets ($p_T(\mathrm{jet}) > 25$ GeV), 1 or more b-tag jet
- Employs likelihood discriminant fit for $t\bar{t}$ and W+Jets normalization
- Discriminant based on **aplanarity** and **lepton pseudorapidity**
- Dominant uncertainty (11%) is signal modeling



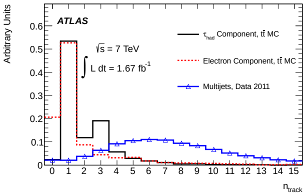
Tau+jets: $\sqrt{s} = 7$ TeV $\mathcal{L} = 1.67\ \mathrm{fb}^{-1}$

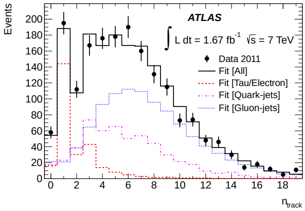
Eur. Phys. J. C, 73 3 (2013) 2328

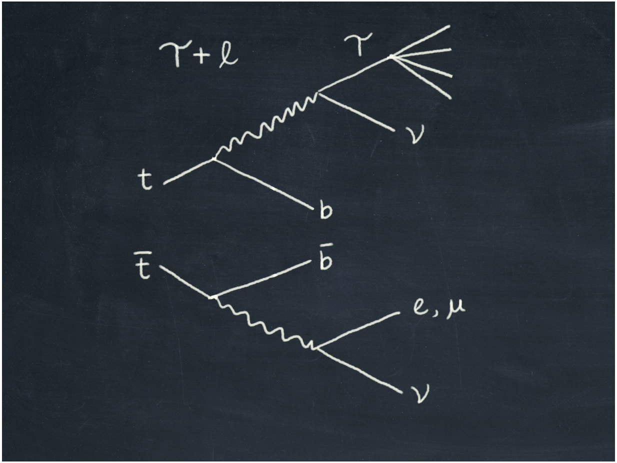
Tau+jets: $\sqrt{s} = 7$ TeV $\mathcal{L} = 1.67$ fb^{-1}

$\sigma_{t\bar{t}} = 194 \pm 18(\text{stat.}) \pm 46(\text{syst.})\text{pb}$

- Motivation: probe **flavor-dependent effects** in top quark decays, understand **new physics** backgrounds (charged Higgs)
- Require 5+ jets ($p_T(\text{jet}) > 20$ GeV), 2+ b-tagged jets, 1 tau candidate
- **Likelihood fit** to n_{track} distribution with three templates: **tau/electron**, gluon-jet (from multi-jet), quark-jet (from $t\bar{t}$ and W+jets)
- Leading uncertainties are from QCD initial/final state radiation (**ISR/FSR**) (15%) and event generator (11%)







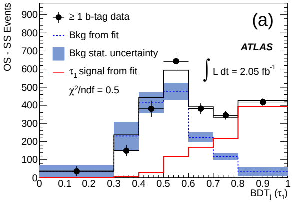
Tau+lepton: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.05\ \mathrm{fb}^{-1}$

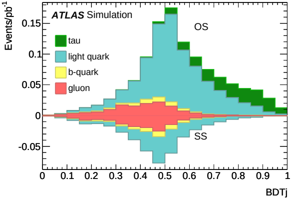
Phys. Lett. B 717 (2012) 89-108

Tau+lepton: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.05\ \mathrm{fb}^{-1}$

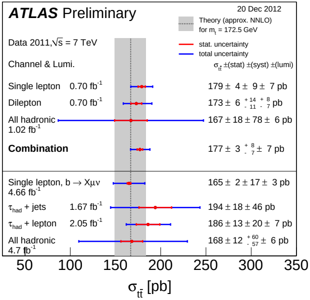
$\sigma_{t\bar{t}} = 186 \pm 13(\mathrm{stat.}) \pm 20(\mathrm{syst.}) \pm 7(\mathrm{lumi.})\mathrm{pb}$

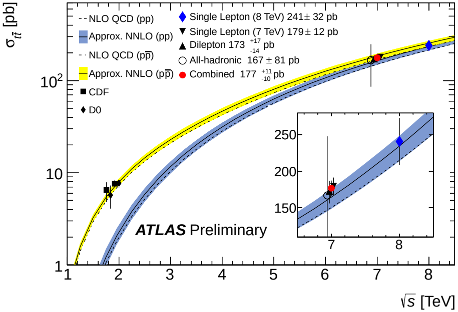
- Motivation: searches for top quark decay to b quarks+**charged Higgs**, decaying to tau + neutrino
- Require 3+ jets, 1 tau candidate, 1 lepton, $\not{E}_T > 30$ GeV
- Employs **boosted decision tree** (BDT_j) to separate hadronic taus from jets
- Further fake tau removal from subtracting **same-sign** events
- Fit to BDT_j output to extract cross section



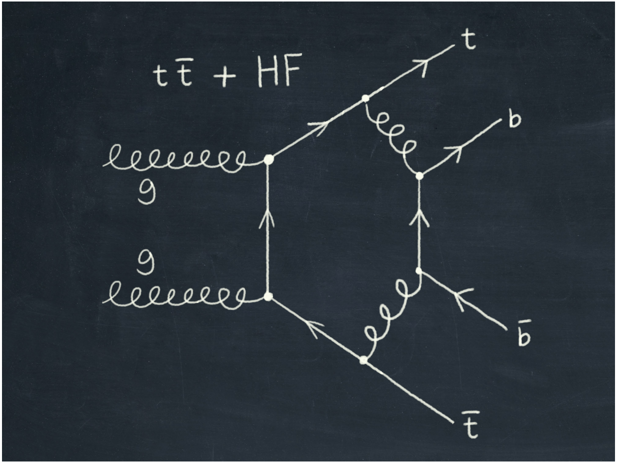


Summary of Inclusive Cross Sections





Good agreement of inclusive $t\bar{t}$ cross section with SM approx. NNLO prediction seen in all channels, $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV



$t\bar{t}$+heavy flavor: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7\ \mathrm{fb}^{-1}$

CERN-PH-EP-2013-030: submitted to PRD

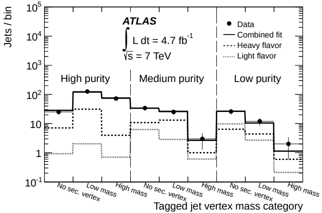
$t\bar{t}$+heavy flavor: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7\ \mathrm{fb}^{-1}$

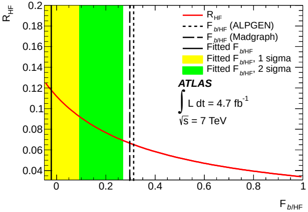
- Motivation: $t\bar{t}$+HF is an irreducible background to $\mathbf{t\bar{t} + (H \rightarrow b\bar{b})}$, can also study composite Higgs, 4-top final states
- Define **fiducial volume**: two charged leptons ($p_T(e) >$25 GeV, $p_T(\mu) >$20 GeV $|\eta| < 2.5$), and 3+ jets ($p_T >$25 GeV, $|\eta| < 2.5$)
- $\sigma_{\mathrm{fid}}(t\bar{t} + \mathrm{HF})$ measured from dilepton events with at least 3 b-tagged jets
- $\sigma_{\mathrm{fid}}(t\bar{t} + j)$ measured from dilepton events with at least 3 jets, 2 of which are b-tagged.

$$R_{\mathrm{HF}} = \frac{\sigma_{\mathrm{fid}}(t\bar{t} + \mathrm{HF})}{\sigma_{\mathrm{fid}}(t\bar{t} + j)}$$

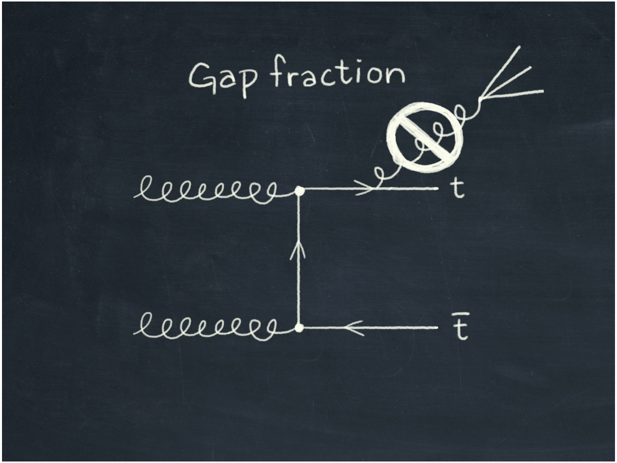
$t\bar{t}$+heavy flavor: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7\ \text{fb}^{-1}$

- **Maximum likelihood fit** to separate light/heavy flavor, 2D templates: vertex mass and jet p_T
- Fit performed in **3 mutually exclusive bins** of b-jet purity (right), boundaries defined at operating points of 60, 70, 75% efficiency
- Dominant uncertainty from **fiducial flavor composition** (fraction of $t\bar{t}$+HF events with additional b-quarks), effect is large because of different identification efficiency of b and c jets





$R_{\text{HF}} = [7.1 \pm 1.3(\text{stat})^{+5.3}_{-2.0}(\text{syst})]\%$
consistent at 1.4σ with ALPGEN and 0.6σ with POWHEG

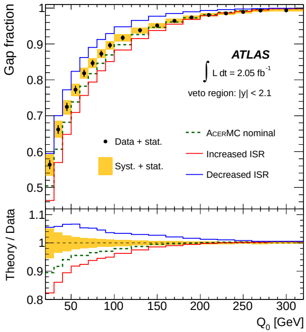


Gap fraction: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.05\ \mathrm{fb}^{-1}$

Eur.Phys.J. C72 (2012) 2043

Gap fraction: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 2.05\ \mathrm{fb}^{-1}$

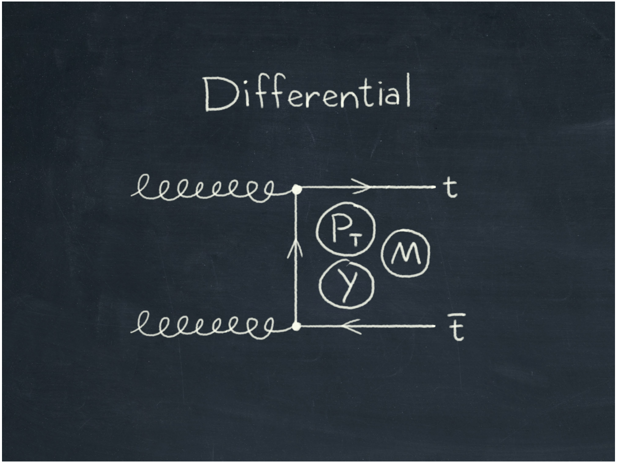
- Motivation: constrain **modeling uncertainty** and reduce impact on top quark measurements
- Compare MC@NLO, ALPGEN, SHERPA, POWHEG generators, test parameters controlling initial state radiation (**ISR**) with ACERMC
- Simulation predicts too much **forward jet activity**, MC@NLO predicts too little jet activity in very central region
- Able to constrain range of **ISR uncertainties**



Select dilepton events with 2 b-tags. Define **gap fraction**:

$$f(Q_0) = \frac{n(Q_0)}{N}$$

where **N** is the number of selected events, **$\mathbf{n(Q_0)}$** is the subset that do not contain an additional central jet with $p_T > Q_0$

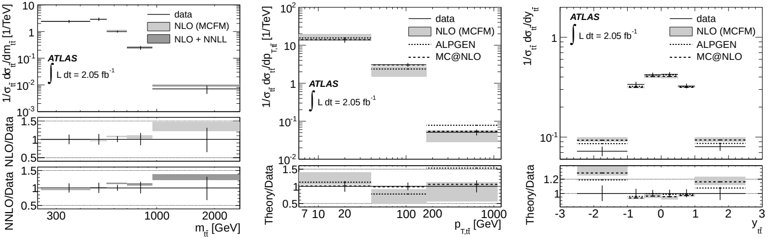


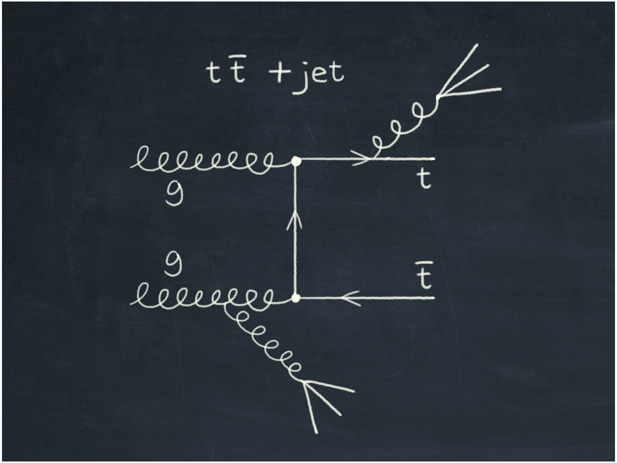
$\sigma^{-1}\ \frac{\mathrm{d}\sigma}{\mathrm{d}X}$ in $X = m_{t\bar{t}},\ p_{T,t\bar{t}},\ y_{t\bar{t}},\ \sqrt{s} = 7$ TeV, $\mathcal{L} = 2.05\ \mathrm{fb}^{-1}$

Eur. Phys. J. C (2013) 73: 2261

$\sigma^{-1} \frac{\mathrm{d}\sigma}{\mathrm{d}X}$ in $X = m_{t\bar{t}}, p_{T,t\bar{t}}, y_{t\bar{t}}, \sqrt{s} = 7$ TeV, $\mathcal{L} = 2.05\ \mathrm{fb}^{-1}$

- Motivation: precision **SM** tests, $m_{t\bar{t}}$ sensitive to new physics
- Background-subtracted **lepton+jets** events, unfolded into **parton-level** kinematic distribution
- Measurements **consistent** with SM. Full covariance matrix also published
- **Jet**-related uncertainties are generally the dominant systematics for $m_{t\bar{t}}$, **theoretical** uncertainties dominant in $y_{t\bar{t}}$, both are important in $p_{T,t\bar{t}}$ measurement



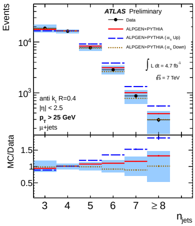


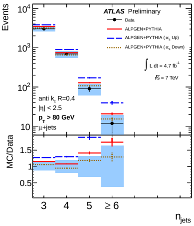
$t\bar{t}$+jets, $\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7\ \ \mathrm{fb}^{-1}$

ATLAS-CONF-2012-155

$t\bar{t}$+jets, $\sqrt{s} = 7$ TeV, $\mathcal{L} = 4.7\ \mathrm{fb}^{-1}$

- Motivation: constrain models of additional **QCD radiation** in $t\bar{t}$ events, test **perturbative QCD**
- Differential measurement in N_{jets} for jet p_T thresholds at 25, 40, 60, 80 GeV
- Background-subtracted lepton+jets events, unfolded into particle-jet multiplicity distribution
- Dominant uncertainty varies bin-to-bin, jet energy scale and background model most significant





- Measurement is systematics dominated
- MC@NLO+HERWIG model disfavored (predicting lower jet multiplicity spectrum and softer jets)

Conclusions

- Results agree well with latest SM theory predictions - ATLAS is testing the SM at high precision with cross section measurements
- Better understanding of QCD in $t\bar{t}$ final states through differential measurements paves the way for more precision in the future
- Please see:
  `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults`
  for the full list of ATLAS top quark publications - only a subset has been shown here

Thank you!

Kevin Finelli

Duke University

Special thanks to

M. Brangan for diagrams

Backup

$1/\sigma\ d\sigma/dm_{t\bar{t}}$	$m_{t\bar{t}}$ bins [GeV]				
Uncertainty [%]	250 – 450	450 – 550	550 – 700	700 – 950	950 – 2700
Total	14 / -14	15 / -15	10 / -10	18 / -16	37 / -43
Stat only	2 / -2	4 / -4	5 / -5	8 / -8	18 / -19
Syst. only	14 / -14	14 / -15	8 / -8	16 / -14	32 / -37
Luminosity	1 / -1	2 / -2	2 / -1	1 / -1	1 / -2
Jets	11 / -10	10 / -11	6 / -6	13 / -11	20 / -24
Leptons	1 / -1	1 / -1	1 / -2	2 / -2	9 / -6
$E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale	1 / -1	1 / -1	1 / -2	2 / -1	9 / -5
Fake-lepton and W backgrounds	5 / -7	10 / -7	5 / -4	5 / -6	10 / -15
Monte Carlo gen., theory, ISR/FSR, and PDF	6 /-7	7/-7	4/-4	8/-7	14/-18

$1/\sigma\ d\sigma/dp_{\mathrm{T},t\bar{t}}$	$p_{\mathrm{T},t\bar{t}}$ bins [GeV]		
Uncertainty [%]	0 – 40	40 – 170	170 – 1100
Total	14 / -16	13 / -12	23 / -22
Stat. only	4 / -4	4 / -5	12 / -11
Syst. only	13 / -16	12 / -11	20 / -19
Luminosity	1 / -1	2 / -2	2 / -5
Jets	8 / -7	6 / -7	11 / -10
Leptons	1 / -1	1 / -1	2 / -2
$E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale	4 / -4	4 / -4	3 / -1
Fake-lepton and W backgrounds	2 / -5	5 / -3	7 / -4
Monte Carlo gen., theory, ISR/FSR, and PDF	10 / -13	6 / -6	8 / -7

$1/\sigma\ d\sigma/dy_{t\bar{t}}$	$y_{t\bar{t}}$ bins					
Uncertainty [%]	-2.5 – -1	-1 – -0.5	-0.5 – 0	0 – 0.5	0.5 – 1	1 – 2.5
Total	11 / -10	7 / -7	5 / -5	5 / -5	6 / -5	9 / -9
Stat. only	5 / -5	4 / -4	3 / -3	3 / -4	4 / -4	5 / -5
Syst. only	10 / -9	5 / -5	4 / -3	4 / -4	4 / -3	7 / -7
Luminosity	1 / -2	1 / -1	1 / -1	1 / -1	1 / -1	1 / -1
Jets	4 / -4	1 / -1	1 / -1	2 / -2	1 / -1	3 / -3
Leptons	1 / -1	1 / -1	1 / -1	1 / -1	1 / -1	1 / -2
$E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale	1 / -2	1 / -2	1 / -1	1 / -1	1 / -1	1 / -1
Fake-lepton and W backgrounds	4 / -7	4 / -2	1 / -1	1/-1	1 / -1	1 / -3
Monte Carlo gen., theory, ISR/FSR, and PDF	6 / -5	3 / -4	3 / -3	2 /-2	3/-2	4/-6

Percentage uncertainties on (top) $1/\sigma\ d\sigma/dm_{t\bar{t}}$, (middle) $1/\sigma\ d\sigma/dp_{\mathrm{T},t\bar{t}}$ and (bottom) $1/\sigma\ d\sigma/dy_{t\bar{t}}$ in the combined $\ell + \mathrm{jets}$ channel.