Highlights of top-quark measurements in hadronic final states at ATLAS

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on behalf of the ATLAS collaboration

XLVII International Symposium on Multiparticle Dynamics

Tlaxcala, Mexico

September 12, 2017

Outline

- Physics motivations
- Top-quark pair production mechanisms and decays
- Recent measurements:

Top-quark inclusive cross section

- Measurements of the $t\bar{t}$ production cross-section in the τ + jets channel at $\sqrt{s} = 7$ TeV ▸ Eur.Phys.J.C(2013)73:2328
- Measurements of the $t\bar{t}$ production cross-section with hadronically decaying τ lepton at $\sqrt{s} = 8$ TeV ▸ Phys. Rev. D 95, 072003 (2017)
- Measurements of the $t\bar{t}$ production cross-section with the τ + lepton at $\sqrt{s} = 7$ TeV ▸ CERN-PH-EP-2012-102
- Measurements of the $t\bar{t}$ production cross-section in the all-hadronic channel at $\sqrt{s} = 7$ TeV ▸ ATLAS-CONF-2012-031

Top-quark differential cross-sections

- Measurements of the $t\bar{t}$ differential cross-sections in the all-hadronic channel at $\sqrt{s} = 13$ TeV ▸ ATLAS-CONF-2016-100

- Summary

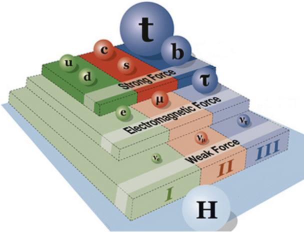
Physics motivations

Why top-quark physics?

- It is the heaviest elementary particle know;

  $m_t = 173.34 \pm 0.27(stat) \pm 0.71(syst)$ GeV

- its large mass is a foundamental parameter in the Standard Model $\Rightarrow$ highest coupling to the Higgs boson;



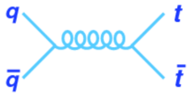
- due its very short lifetime, the top-quark decays before hadronizing $t \Rightarrow Wb \sim 10^{-24}s$ vs hadronization $\sim 10^{-23}s$ $\Rightarrow$ allows to study the properties of a bare quark;
- its cross-section is large
  - ~ 15 $t\bar{t}$ pairs/min, ~ 5 milions $t\bar{t}$ at 8 TeV with $20 fb^{-1}$
  - ~ 500 $t\bar{t}$ pairs/min,~ 30 milions $t\bar{t}$ at 13 TeV with $36 fb^{-1}$

Top-quark pair production

- Top-quark pairs production via strong interactions;
- the LO dominant process at $\sqrt{s} = 13$ TeV at LHC is the gluon-gluon fusion;

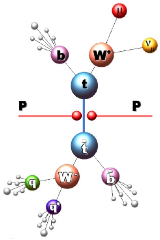
gluon-gluon fusion $\sim 87\%$

$q\bar{q}$ annihilation $\sim 13\%$



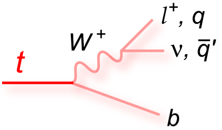
Why top pair studies?

- Stringent tests of pQCD;
- high sensitivity to gluon PDF;
- important background to Higgs and BSM processes;
- improvement in MC generators of the $t\bar{t}$ samples.

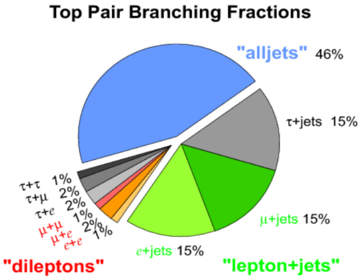


Top pair decay

- In the Standard Model, top quarks decay to Wb about 99.8% of the time;



- decay signatures are categorized according to the decay of the two W's, semi-leptonically or hadronically;

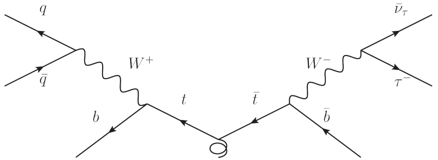


- All-hadronic: both W's decay via W $\rightarrow qq$ (46%);
- ℓ+Jets: one W deacays via W $\rightarrow \ell\nu$ (30%);
- dilepton: both W's decay via W $\rightarrow \ell\nu$ (4%).

$t\bar{t}$ cross-section in the τ + jets channel

τ + jets : $\sqrt{s} = 7\,TeV$ $\mathcal{L} = 1.67 fb^{-1}$ ▸ Eur.Phys.J.C(2013)73:2328

τ + jets : $\sqrt{s} = 8\,TeV$ $\mathcal{L} = 20.2 fb^{-1}$ ▸ arXiv:1702.08839v2



- Final state with a hadronically decaying τ lepton and jets;
- such an event topology correspond to $\sim 10\%$ of $t\bar{t}$ decays;
- this measurement is particularly important for charged Higgs boson production in top-quark decays
  - the existence of a $H^{\pm}$ would lead to an enhancement in the cross-section for the considered $t\bar{t}$ final state.

$t\bar{t}$ cross-section in the τ + jets channel at $\sqrt{s} = 7$ TeV

Eur.Phys.J.C(2013)73:2328

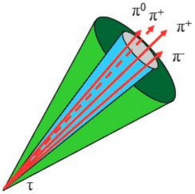
τ +jet $\sqrt{s}$ = 7 TeV: Event selection & τ decays

Event selection

- Require at least 5 jets with $p_T > 20 GeV$ and $|\eta| < 2.5$:
  - 2 jets having originated from $b - quark$;
  - 2 jets from the hadronic decay of one of the top quarks;
  - 1 τ_{had} candidate ($p_T > 40 GeV$) from the other top-quark.

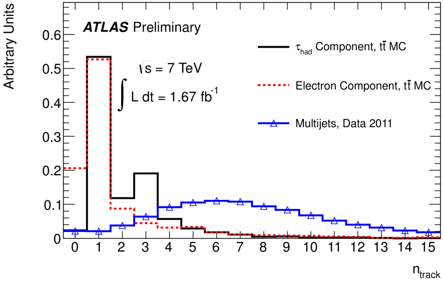
τ decays

- Hadronically decaying τ in:
  - 1 or 3 charged hadrons in the final state charged hadrons (+ other neutrals);



τ +jet $\sqrt{s}$ = 7 TeV: Data analysis

- Charged hadrons in the final state can be reconstructed as charged particle tracks in the inner-detector;
- number of tracks (n_{tracks}) associated to a τ_{had} used to separate τ_{had} contribution from misidentified jet background;
- Signal extraction from the n_{track} distribution $\Rightarrow$ data sample fitted with 3 probability density functions (templates).

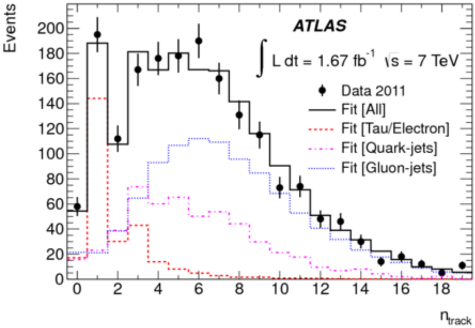


tau/electron template (simulated $t\bar{t}$ events);
gluon-jet template (Jet fakes from QCD multijet);
quark-jet template (Jet fakes from $t\bar{t}$, W+jets, single-top-quark).

τ +jet $\sqrt{s} = 7$ TeV: Fit results

- Binned-likelihood fit to n_{tracks} distribution with three templates.

$$\sigma_{t\bar{t}} = \frac{N_\tau}{\mathcal{L}\cdot\epsilon} \Rightarrow \sigma_{t\bar{t}} = 194 \pm 18\ (\text{stat.}) \pm 46\ (\text{syst.})\ \text{pb}$$



Leading uncertainties:

- QCD (ISR/FSR) (15%);
- event generator (11%).

- total systematic uncertainty on the cross-section is 24%.

$t\bar{t}$ cross-section in the τ + jets channel at $\sqrt{s} = 8$ TeV

Phys. Rev. D 95, 072003 (2017)

τ +jet $\sqrt{s} = 8$ TeV: Reconstructed object selection

Event selection

- Require 4 jets:
  - ≥ 2 jets with $E_T > 25 GeV$ and $|\eta| < 2.5$;
  - 2 jets having originated from $b - quark$, b-tagging efficiency 70%;
- 1 τ_{had} candidate ($E_T > 20 GeV$ and $|\eta| < 2.5$) $\Rightarrow$ decays into 1 or 3 charged particles:
  - single prong ($\tau_{1-prong}$) $\Rightarrow$ decays to a single charged particle;
  - three prong ($\tau_{3-prong}$) $\Rightarrow$ decays to a 3 charged particle.

Backround estimation

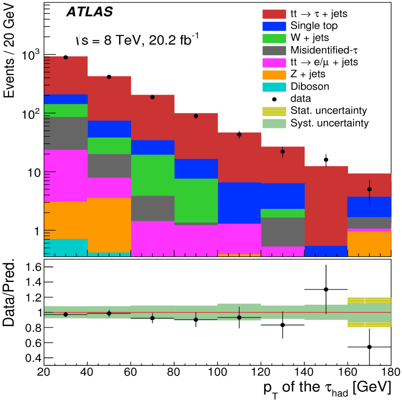
- Events where the τ_{had} in the final state is real;
- includes single top, W/Z+jets, diboson.

- Events where the τ lepton in the final state is fake (misidentified);
- dominated by multi-jet processes.

τ +jet $\sqrt{s} = 8$ TeV: Results

- Cross-section extraction for each τ_{had} and then combined:

$$\sigma_{t\bar{t}} = 239 \pm 4(stat.) \pm 28(syst) \pm 5(lumi)pb$$

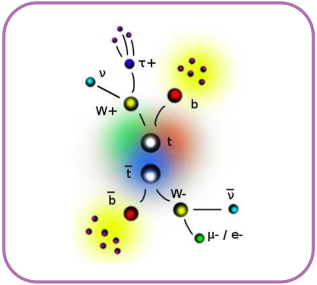


- Data prediction agreement in the signal region;
- total uncertainty 12%, agreement with the SM prediction.

$t\bar{t}$ cross-section in the τ + lepton channel at $\sqrt{s} = 7$ TeV

Phys.Lett. B717 (2012) 89-108

$t\bar{t}$ cross-section in the τ + lepton channel with $\sqrt{s}$ = 7 TeV



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

Phys.Lett. B717 (2012) 89-108

- Final states with an electron or a muon and a hadronically decaying τ lepton;
- searches for top-quark decays to b-quarks + charged Higgs, decaying to τ + neutrino.

Event Selection

- A primary vertex with $\geq$ 5 tracks (each with $p_T > 4\,GeV$);
- ≥ 1 τ candidate;
- one isolated high-p_T μ or e;
- ≥ 2 jets with $p_T > 25$ GeV and $|\eta|$<2.5;
- $E_T^{miss} > 30\,GeV$ to reduce the multi-jet background.

Signal extraction

- discriminants employed which outputs are used to separate hadronic tau from jets;
  - use **boosted decision tree** (BDT) discriminants.
- Same sign (SS) and opposite sign (OS) BDT_j distributions.

Background methods

- Fit BDT shape with background and signal template (template fitting).
- Matrix method to extract background after a cut on BDT > 0.7.

		Background template		MC	
		0 b-tag	$W+1$ jet	Signal	$t\bar{t}$
$\mu+\tau$	τ_1	490 ± 40	456 ± 32	432	388
	τ_3	135 ± 33	130 ± 50	126	116
$e+\tau$	τ_1	440 ± 50	430 ± 50	388	338
	τ_3	116 ± 32	120 ± 28	114	101
Combined	τ_1	930 ± 70	860 ± 50	820	726
	τ_3	260 ± 60	260 ± 40	239	217

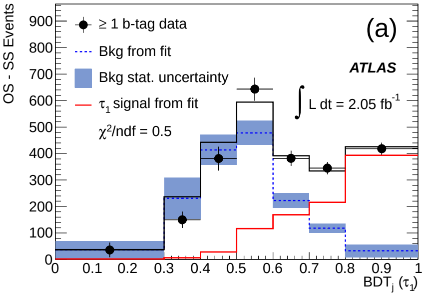
		Background template	
		0 b-tag	$W+1$ jet
$\mu+\tau$	τ_1	460 ± 50	440 ± 50
	τ_3	130 ± 40	105 ± 35
$e+\tau$	τ_1	420 ± 60	350 ± 50
	τ_3	140 ± 40	160 ± 40
Combined	τ_1	880 ± 70	800 ± 70
	τ_3	270 ± 60	260 ± 60

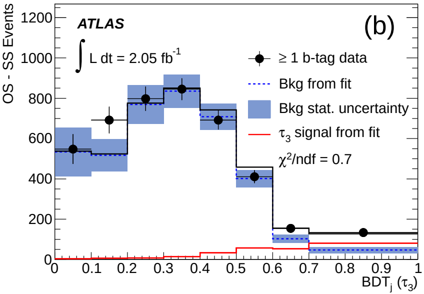
good agreement with the numbers obtained by the two methods.

Measuring the $t\bar{t}$ cross-section

- The cross-section is derived from the number of observed OS–SS signal events in the ≥ 1 b-tag data sample;
- the results are given separately for τ_1 (one track candidate) and τ_3 (> one tracks candidate) and then combined.

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





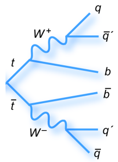
$t\bar{t}$ cross-section in the all-hadronic channel at $\sqrt{s} = 7$ TeV

ATLAS-CONF-2012-031

$t\bar{t}$ cross-section in the all-hadronic channel with $\sqrt{s} = 7\,TeV$

all-hadronic channel : $\sqrt{s} = 7\,TeV$ $\mathcal{L} = 4.7 fb^{-1}$

ATLAS-CONF-2012-031



- Final state with both W's decaying hadronically, , six jets topology;
- such an event topology correspond to $\sim 46\%$ of $t\bar{t}$ decays, large BR but large multi-jet background;
- important test of pQCD, major background to many new physics scenarios.

Event Selection

Event selection

- ≥ 1 reconstructed primary vertex with 5 or more associated tracks;
- all jets reconstructed with $|JVF| < 0.75$;
  - ≥ 5 jets with $p_T > 55 GeV$ and $|\eta| < 2.5$;
  - ≥ 1 additional jet with $p_T > 30 GeV$ and $|\eta| < 2.5$;
  - ≥ 2 of the jets should be b-tagged and have $p_T > 55 GeV$ and $|\eta| < 2.5$.

Systematic uncertainties

Source of uncertainty	Contribution (%)
Jet energy scale (JES)	$+20/-11$
b-tagging	$\pm$ 17
ISR, FSR	$\pm$ 17
Parton shower and Hadronisation	$\pm$ 13
Multi-jet trigger	$\pm$ 10
Generator	$\pm$ 7
PDF	$+7/-4$
Pile-up	$+5/-7$
Background model	$\pm$ 4
Luminosity	$\pm$ 4
Jet energy resolution	$\pm$ 3
Jet reconstruction efficiency	< 1
Total	$+36/-34$

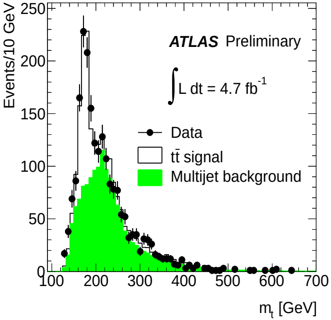
Dominant systematics

JES, b-tagging, ISR, FSR

Kinematic fit and cross-section extraction

- Kinematic fit performed to compute the top-quark mass ($m_{t\bar{t}}$) reconstruction of $t\bar{t}$ events;
- kinematic fit based on a likelihood approach to find the correct association of jets with the final-state partons of the all-hadronic channel;
- m_t used to perform an unbinned likelihood fit and extract the cross-section;
- measured cross-section compatible with the SM prediction.

$$\sigma_{t\bar{t}} = 168 \pm 12(stat.)^{60}_{-57}(syst.) \pm 7(lumi)pb$$

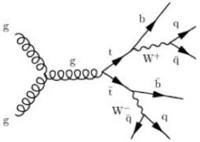


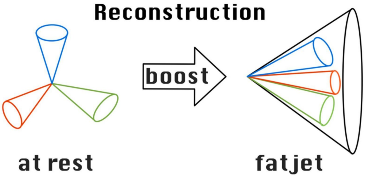
$t\bar{t}$ differential cross-section in the all-hadronic channel at $\sqrt{s} = 13$ TeV

ATLAS-CONF-2016-100

$t\bar{t}$ differential cross-section in the all-hadronic channel with $\sqrt{s} = 13\,TeV$

all-hadronic channel : $\sqrt{s} = 13\,TeV$ $\mathcal{L} = 14.7 fb^{-1}$ ▸ ATLAS-CONF-2016-100



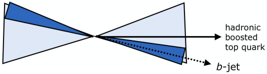


- Boosted all-hadronic $t\bar{t}$ decay mode $\Rightarrow$ only top-quark candidates with high p_T selected;
- detailed studies of high-p_T SM processes;
- searches of anomalies that could be signals for new physics.

Event selection

Event selection

- primary vertex with five or more charged tracks;
- no reconstructed e/μ with $p_T > 25$ GeV;
- at least 2 large-R jets with $p_T > 350$ GeV and $|\eta| < 2.0 \Rightarrow$ leading jet $p_T > 500$ GeV;



- $\geq$ 2 small-R jets with $p_T > 25$ GeV and $|\eta| < 2.5$;
- $\geq$ 2 small-R b-tagged jets $\Rightarrow$ each associated with just one of the top-tagged large-R jets;

$t\bar{t}$ (all-hadronic)	1190	±	240
$t\bar{t}$ (non all-hadronic)	60	±	15
Single top quark	9	±	5
Multijet events	300	±	20
Prediction	1570	±	260
Data (14.7 fb^{-1})	1512		

Large background $\Rightarrow$ multi-jet events $S_{bg} = \frac{1}{2}(\frac{G}{A} + \frac{H}{B}) \times C$

S: signal region;

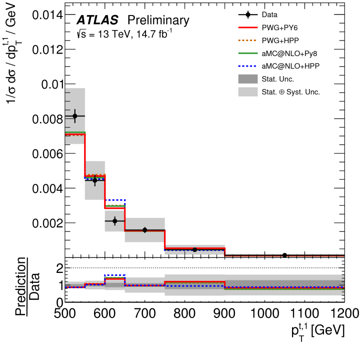
G,A,H,B: regions multi-jet dominated;

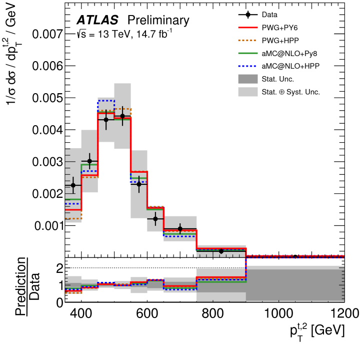
	0 t	1 t	2 t
0 b	A	D	G
1 b	B	E	H
2 b	C	F	S

Fiducial phase-space differential cross-section

Variables: $p_T^{l,1}, p_T^{l,2}, |y^{l,1}|, |y^{l,2}|, p_T^{t\bar{t}}, m^{t\bar{t}}, |y^{t\bar{t}}|, |\cos\theta*|, H_T^{t\bar{t}}, y_B^{t\bar{t}}, \Delta_\phi(t_1,t_2), \chi^{t\bar{t}}, |p_{out}^{t\bar{t}}|$

Hadronic top-quark variables

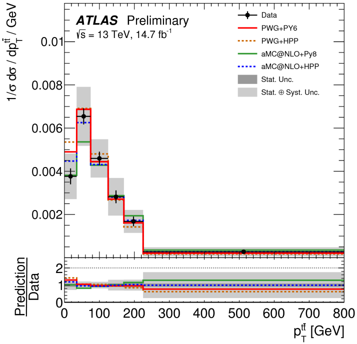


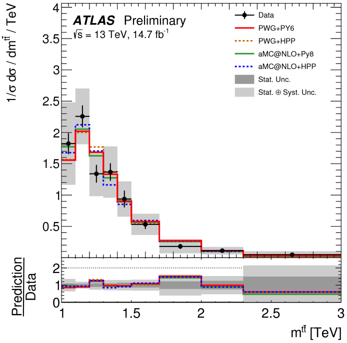


Dominant uncertainties: Large R-jets, signal modelling, b-tagging

Fiducial phase-space differential cross-section

$t\bar{t}$ system variables





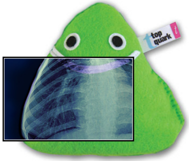
Dominant uncertainties

- Large R-jets
- signal modelling
- b-tagging

$$\sigma_{fid} = 374 \pm 13\ (\text{stat.})^{+111}_{-92}\ (\text{syst.})\ \text{fb}$$

Conclusions

- Results agree well with latest SM theory predictions;
- ATLAS is testing the SM at high precision with cross section measurements;
- shown a small set of the Top-quark ATLAS results;
- full set of top-quark measurements available at: `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults`.



All the measurements will benifit with the incoming data allowing to do more precision measurements.

Thank you for the attention!

BACKUP

tau + jets $\sqrt{s} = 7$ TeV: systematics uncertainties

Source of uncertainty	Relative uncertainty
ISR/FSR	15%
Event generator	11%
Hadronisation model	6%
PDFs	2%
Pile-up	1%
b-jet tagging efficiency	9%
Jet energy scale	5%
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance mismodelling	5%
b-jet trigger efficiency	3%
Jet energy resolution	2%
Fit systematic uncertainties	4%
Luminosity	4%
Total uncertainty	24%

tau + jets $\sqrt{s} = 8$ TeV: number of events yield

Event counts	$\tau_{\text{1-prong}}$	$\tau_{\text{3-prong}}$	τ_{had}
$t\bar{t} \to e/\mu + \text{jets}$	21.8 ± 4.7	6.8 ± 2.5	28.3 ± 5.3
Single top	107 ± 10	33.9 ± 5.8	141 ± 12
$W + \text{jets}$	71.7 ± 8.5	27.1 ± 5.2	99 ± 10
$Z + \text{jets}$	7.2 ± 2.7	1.6 ± 1.3	8.7 ± 3.0
Diboson	1.0 ± 1.0	0.4 ± 0.6	1.5 ± 1.2
Misidentified-τ_{had}	46.6 ± 6.8	24.9 ± 5.0	74.9 ± 8.7
Expected $t\bar{t} \to \tau + \text{jets}$	1084 ± 33	312 ± 18	1398 ± 37
Total Expected	1339 ± 37	407 ± 20	1751 ± 42
Data	1278	395	1678

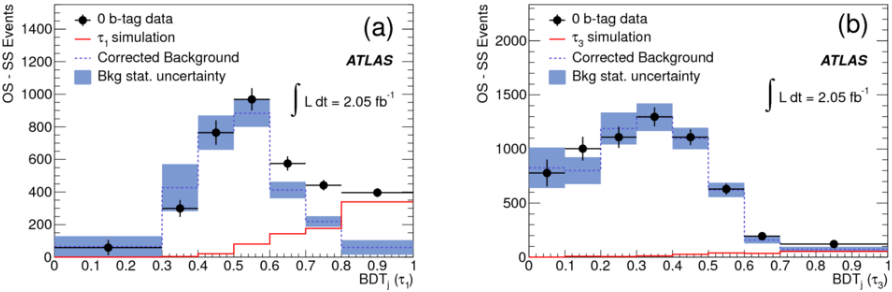
$tau + \textbf{jets}\ \sqrt{s} = 8$ TeV: systematic uncertainties

Uncertainty	$\tau_{\text{1-prong}}$	$\tau_{\text{3-prong}}$	τ_{had}
Total Systematic	- 11 /+ 11	- 16 /+ 14	- 12 /+ 12
Jet energy scale	- 4.0 /+ 4.2	- 8.4 /+ 5.7	- 5.0 /+ 4.5
b-tag efficiency	- 4.7 /+ 5.0	- 4.8 /+ 5.0	- 4.7 /+ 5.0
c-mistag efficiency	- 1.6 /+ 1.6	- 1.5 /+ 1.5	- 1.6 /+ 1.6
Light-jet mistag efficiency	- 0.3 /+ 0.3	- 0.5 /+ 0.5	- 0.4 /+ 0.4
$E_{\text{T}}^{\text{miss}}$	- 0.3 /+ 0.5	- 1.7 /+ 0.5	- 0.6 /+ 0.4
τ_{had} identification	- 3.5 /+ 3.4	- 6.0 /+ 5.6	- 4.1 /+ 3.9
τ_{had} energy scale	- 2.1 /+ 2.0	- 1.2 /+ 1.4	- 1.9 /+ 1.9
Jet vertex fraction	- 0.1 /+ 0.3	- 0.3 /+ 0.3	- 0.2 /+ 0.3
Jet energy resolution	- 1.4 /+ 1.4	- 0.2 /+ 0.2	- 1.1 /+ 1.1
Generator	- 1.5 /+ 1.5	- 2.5 /+ 2.5	- 2.1 /+ 2.1
Parton Shower	- 2.0 /+ 2.0	- 2.6 /+ 2.6	- 2.1 /+ 2.1
ISR/FSR	- 6.2 /+ 6.2	- 8.5 /+ 8.5	- 6.7 /+ 6.7
Misidentified-τ_{had} background	- 1.3 /+ 1.4	- 2.0 /+ 2.2	- 1.6 /+ 1.6
W + jets background	- 2.9 /+ 2.9	- 3.6 /+ 3.6	- 3.0 /+ 3.0
Statistics	- 2.2 /+ 2.2	- 5.6 /+ 5.6	- 1.7 /+ 1.7
Luminosity	- 2.3 /+ 2.3	- 2.3 /+ 2.3	- 2.3 /+ 2.3

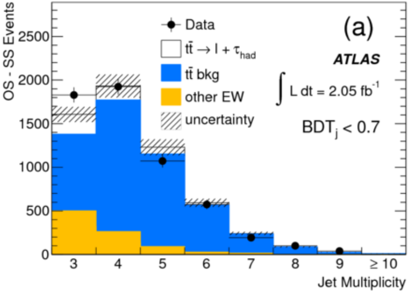
τ + lepton $\sqrt{s} = 7$ TeV: systematic uncertainties

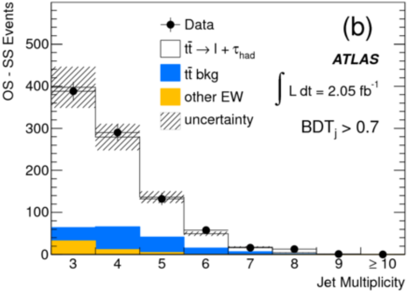
Source	$\mu + \tau$	$e + \tau$
μ (ID/Trigger)	−1.1 /+1.5	–
e (ID/Trigger)	–	±2.9
JES	−2.0/+2.2	−1.9 /+2.8
JER	±1.0	±1.2
ISR/FSR	±4.8	±3.5
Generator	±0.7	±0.7
PDF	±2.0	±2.1
b-tag	−7.7/+9.0	−7.5/+8.9
τ_1 ID	−3.0/+3.2	−2.7/+3.0
τ_3 ID	−3.1/+3.4	−2.9/+3.2

τ + lepton $\sqrt{s} = 7$ TeV: BDT fit



τ + lepton $\sqrt{s} = 7$ TeV: matrix method





$t\bar{t}$ differential cross-section $\sqrt{s} = 13$ TeV: fiducial phase-space distributions