Measurements of the top quark branching ratios into channels with leptons and quarks with the ATLAS detector

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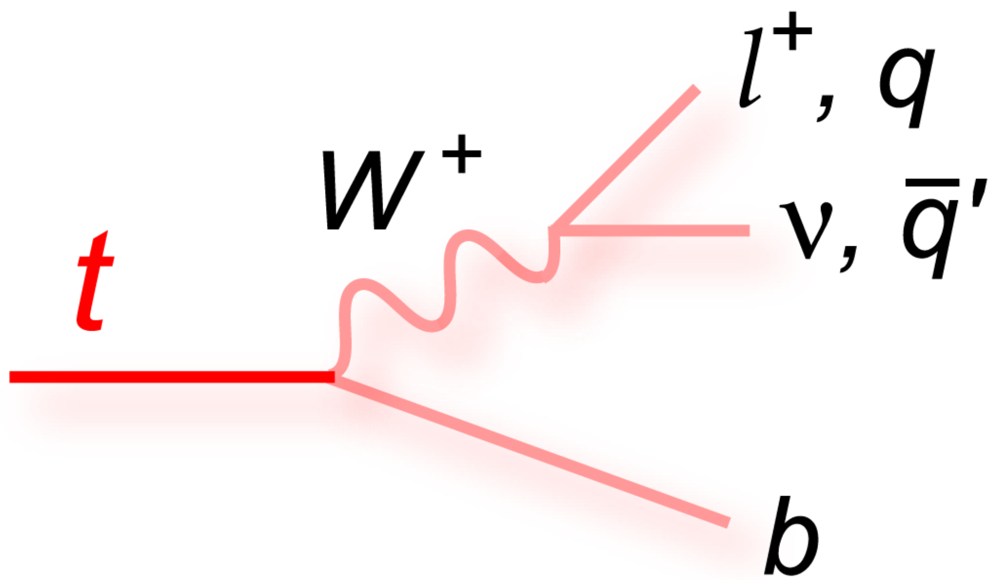
Introduction

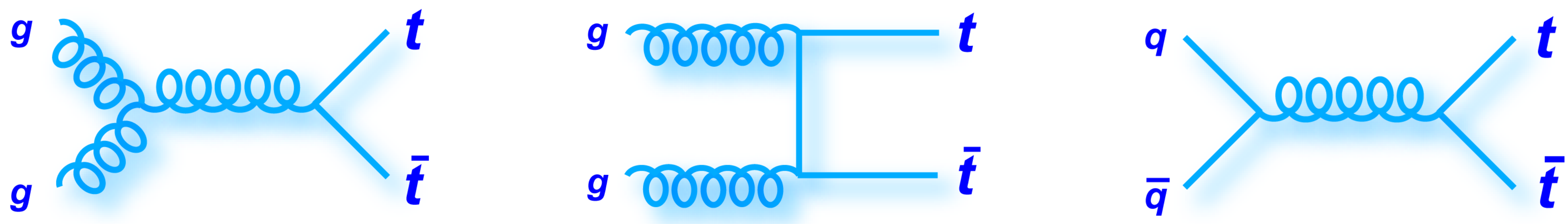
Top (t) quark → W-boson + beauty (b) quark with > 95% probability. In the Standard Model (SM), the branching ratio (BR) of the t-quark is thus given by that of the W-boson, which are very well measured with 0.3% precision (assuming lepton universality) by the LEP experiments, and predicted with an uncertainty of the order of 0.1%.



In the SM, BR of the t-quark into leptons are same.
But, in new physics models, the BR to τ-leptons could be different, eg. via contributions from the charged Higgs ($t \to H^+ b$), or decays containing supersymmetric stop quarks ($t \to \tilde{t} + X$).

Introduction

At the LHC, top anti-top pair production happens via gluon-gluon (>84%) and quark-quark processes.



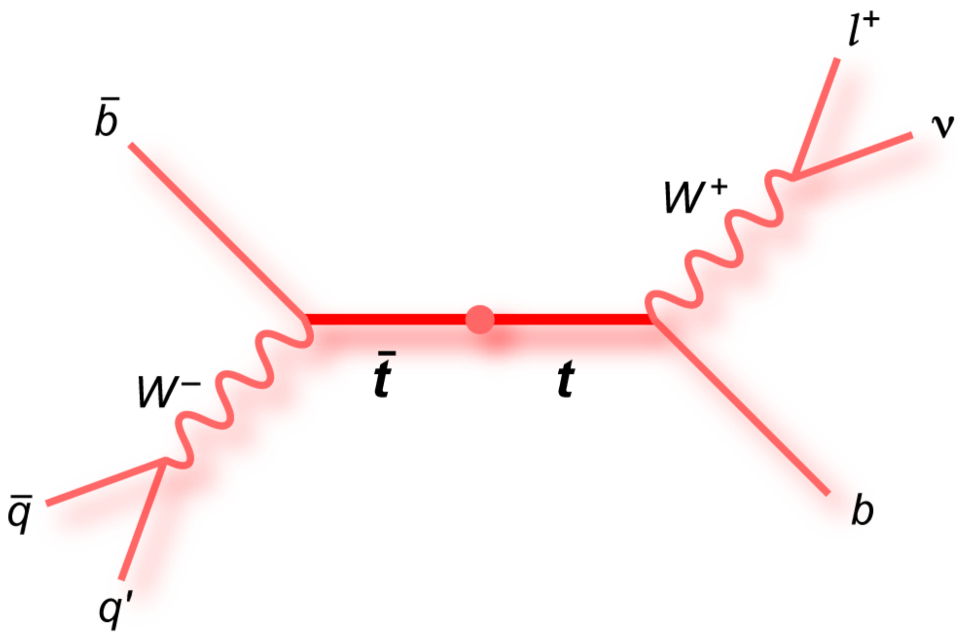
Almost similar diagrams could also lead to pair production of $\tilde{t}$, decaying via $\tilde{t} \rightarrow b\, \nu_\tau\, \tilde{\tau}$ channel followed by $\tilde{\tau} \rightarrow \tau$ + gravitino decays which could change the measured BR to τ-leptons.

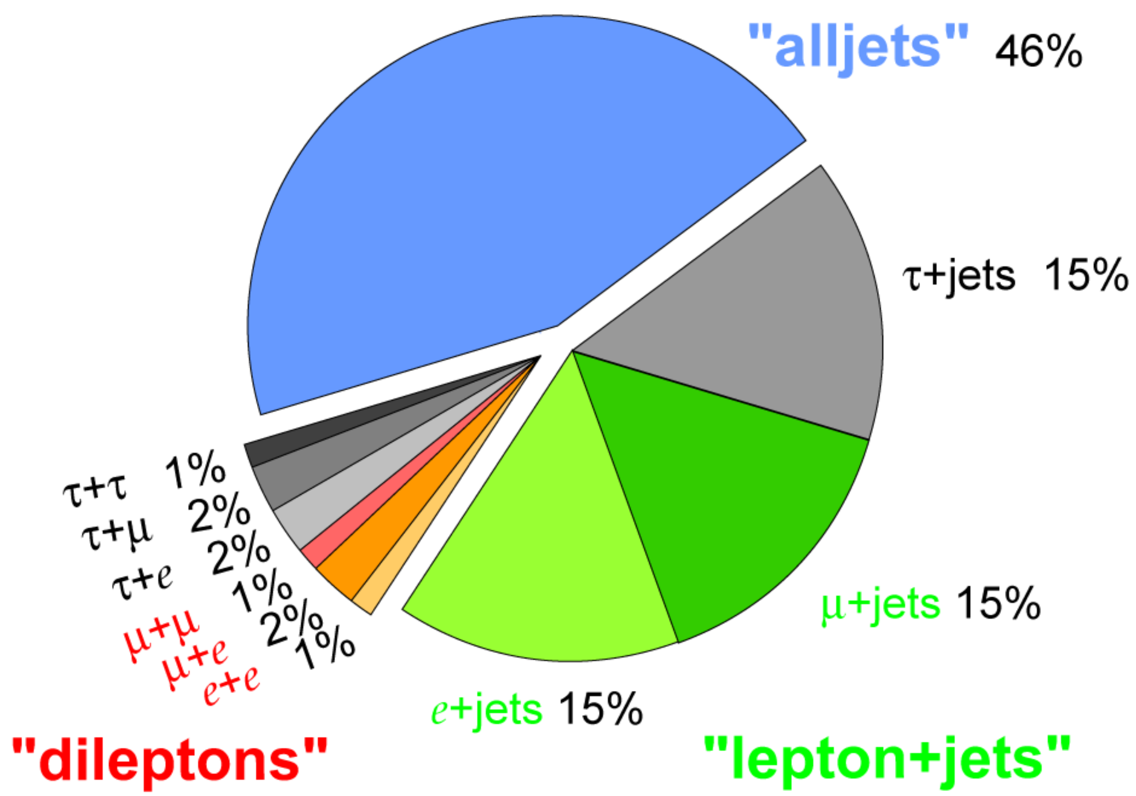
Predicted cross-section for pair production of $\tilde{t}$-quark is same as that of pair production of t-quark for $m_{\tilde{t}} = 120$ GeV and 12% of the value for $m_{\tilde{t}} = 180$ GeV.

ICHEP2016 limits on $m_{\tilde{t}}$ from LHC are > 800 GeV.

Event Topology

Top-pair events are classified by leptonic or hadronic decays of the 2 W-bosons and presence of b-jet(s).





This analysis requires presence of ≥ 1 lepton (ℓ=e/μ) in the event, produced directly from $W \rightarrow \ell\nu$ or indirectly via $W \rightarrow \tau\nu$ decays, contributions from which are not distinguished, but summed.

Events are classified based of the decays of the other W-boson: $W \rightarrow$ jets for **ℓ+jets**, $W \rightarrow \ell\nu$ for **ℓℓ'+jets**, $W \rightarrow \tau_h\nu$ for **$\ell\tau_h$+jets**, where τ_h refers to the hadronic decays of the τ-leptons.

Analysis overview

$\geq$ 1 b-jets events are classified into 7 mutually exclusive final states:

- **e+jets, μ+jets:**

In ℓ+jets channels, 3 invariant masses from 2- and 3-jet systems, and a transverse mass distributions are fitted.

- **ee+jets, μμ+jets, eμ+jets:**

In ℓℓ'+jets channels, the di-lepton effective mass distributions from 2 different missing transverse energy ($\not{E}_T$) regions are fitted.

Backgrounds are smallest in the eμ+jets channel.

- **eτ_h+jets, μτ_h+jets:**

In ℓτ_h+jets channels, a multivariate discriminant from a boosted decision tree (BDT) output that separates jets from τ_h is fitted.

Signal significance for ℓτ_h+jets channel is used for optimization, since it has largest background and smallest number of signal events.

Data and Monte Carlo sets

Results presented here were recorded at center-of-mass energy of $\sqrt{s}$ = 7 TeV, the full 2011 data sample corresponding to an integrated luminosity of $\int L = 4.6\ fb^{-1}$.
Reference: ATLAS Collaboration, Phys. Rev. D 92, 072005 (2015)

In 2011, ATLAS employed a 3 level trigger system: hardware based level-1 trigger, followed by software based level-2 and event filter to bring the recorded event rate to 75 KHz and 300 Hz for analysis, respectively.

This analysis uses events recorded with single lepton triggers:

- single-muon trigger with p_T > 18 GeV, or
- single-electron trigger with E_T > 20 GeV, rising to 22 GeV, during periods of high instantaneous luminosity from 2.4 to $3.7\times10^{33}\ cm^{-2}\ s^{-1}$.

Process	Monte Carlo generators
$t\bar{t}$	POWHEG + PYTHIA (Systematics: MCNLO/ALPGEN + HERWIG)
single-top	MCNLO + HERWIG
W/Z + jets	ALPGEN + HERWIG + JIMMY
WW/WZ/ZZ	HERWIG + JIMMY

Event Selection

Use common selection criteria as much as possible for uniformity:

- 1 muon with $p_T > 20$ GeV and/or 1 electron with $E_T > 25$ GeV

- $E_T > 20$ GeV for τ_h
  - Consider τ_h seeded with 1 charged track (selects 77% of τ_h)
  - τ_h overlapping with e/μ/jet objects not double-counted as τ_h

- At least 2 jets with $E_T > 25$ GeV (including b-jet requirement)
- $\geq$ 1 b-jet with 70% efficiency, 0.8% mis-tag rate for all channels
  - In ℓ+jets channels, anti-isolated e/μ are multi-jet backgrounds

- $\not{E}_T > 30$ GeV

Event Selection

Use common selection criteria as much as possible for uniformity:

- 1 muon with $p_T > 20$ GeV and/or 1 electron with $E_T > 25$ GeV
  - In ℓ+jets channels, $p_T > 25$ GeV for muon & 1 isolated-lepton
  - In ℓℓ'+jets channels, require oppositely charged isolated e/μ
- $E_T > 20$ GeV for τ_h
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  - Consider τ_h seeded with 1 charged track (selects 77% of τ_h)
  - τ_h overlapping with e/μ/jet objects not double-counted as τ_h
  - In ℓ+jets, ℓℓ'+jets channels remove events with identified τ_h
  - In $\ell\tau_h$+jets channel, lepton & τ_h must have opposite charge
- At least 2 jets with $E_T > 25$ GeV (including b-jet requirement)
- ≥ 1 b-jet with 70% efficiency, 0.8% mis-tag rate for all channels
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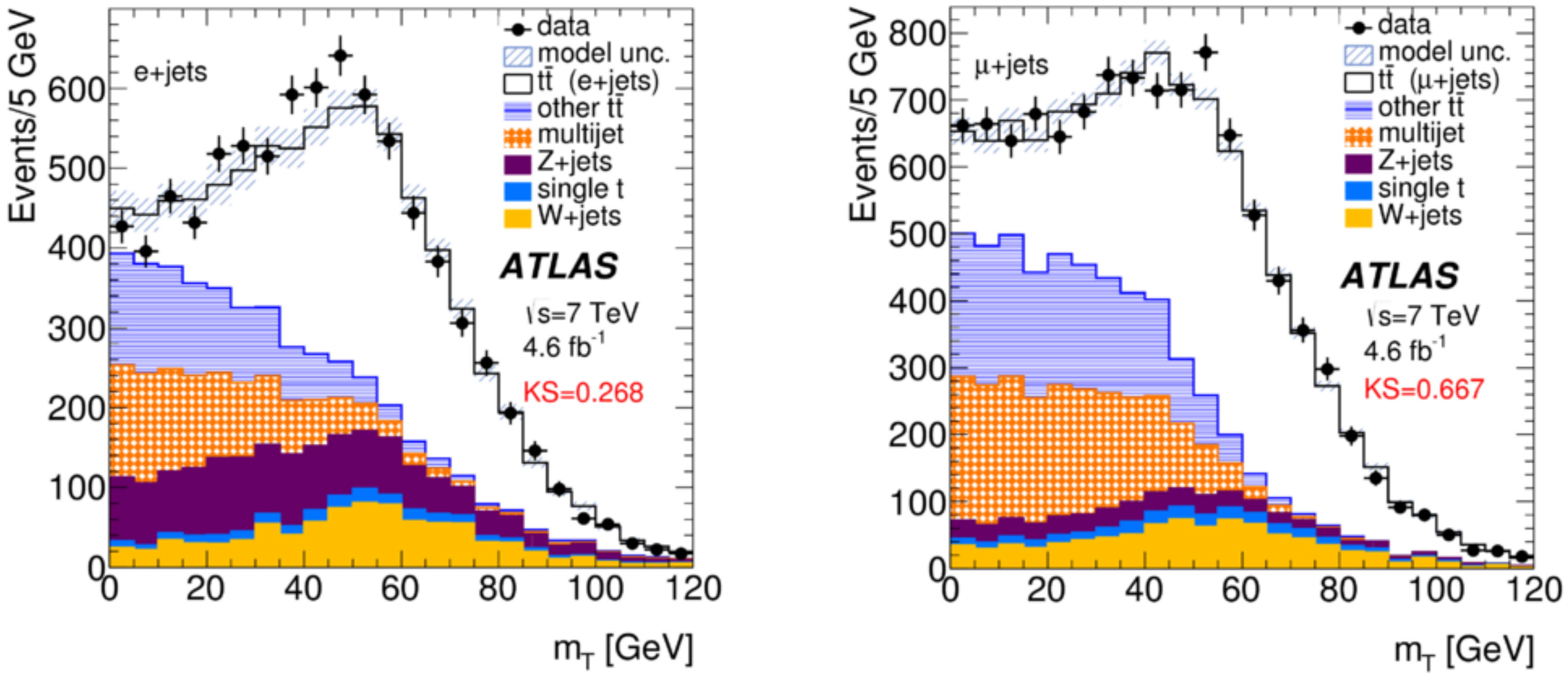
  - In $\ell\tau_h$+jets channel, lepton & τ_h must have opposite charge
- At least 2 jets with $E_T > 25$ GeV (including b-jet requirement)
- ≥ 1 b-jet with 70% efficiency, 0.8% mis-tag rate for all channels
  - In ℓ+jets channels, anti-isolated e/μ are multi-jet backgrounds
  - In ℓ+jets channels, number of jets ≥ 4 (including b-jet)
- $\not{E}_T > 30$ GeV, except in ℓ+jets channels where $\not{E}_T > 20$ GeV

ℓ+jets channels

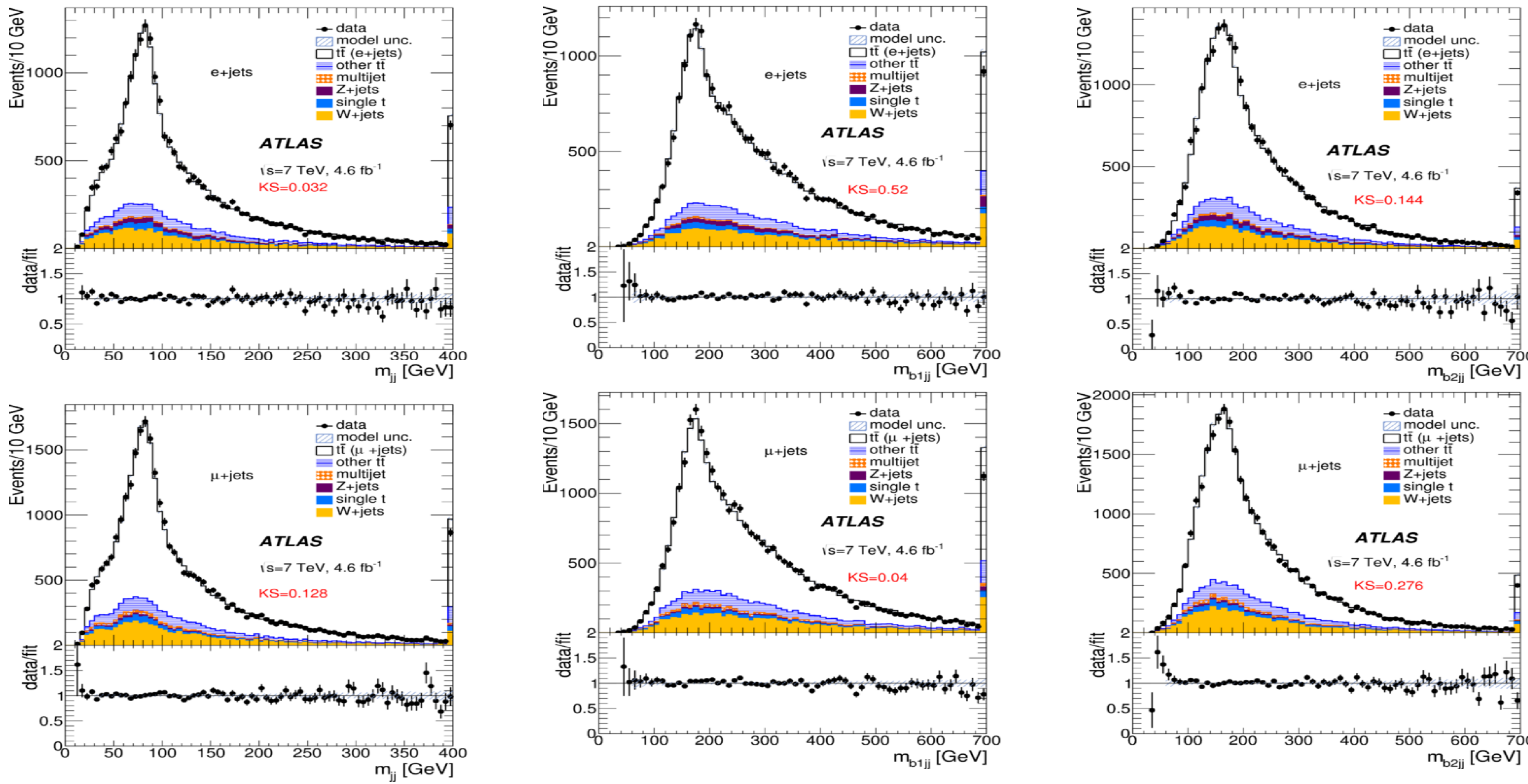
Important Backgrounds:

- W(→ℓν) + jets modeled from MC
- Z(→ℓℓ) + jets [1 mis-identified ℓ] cross-checked with data
- Multi-jet [1 jet mis-identified as ℓ] modeled from data



For events with fake $\not{E}_T$ (< 30 GeV): transverse mass (m_T) between ℓ & $\not{E}_T$ is fitted after fixing single-top & Z+jets contributions from MC.

ℓ+jets channels



For events with $\not{E}_T$ >30 GeV: a 3D fit is performed using di-jet mass (M_{jj}) between 2 highest E_T jets not b-tagged & 2 3-jet masses (M_{b1jj}, M_{b2jj}) between 1st and 2nd highest E_T b-jet and the ones used for m_{jj}.

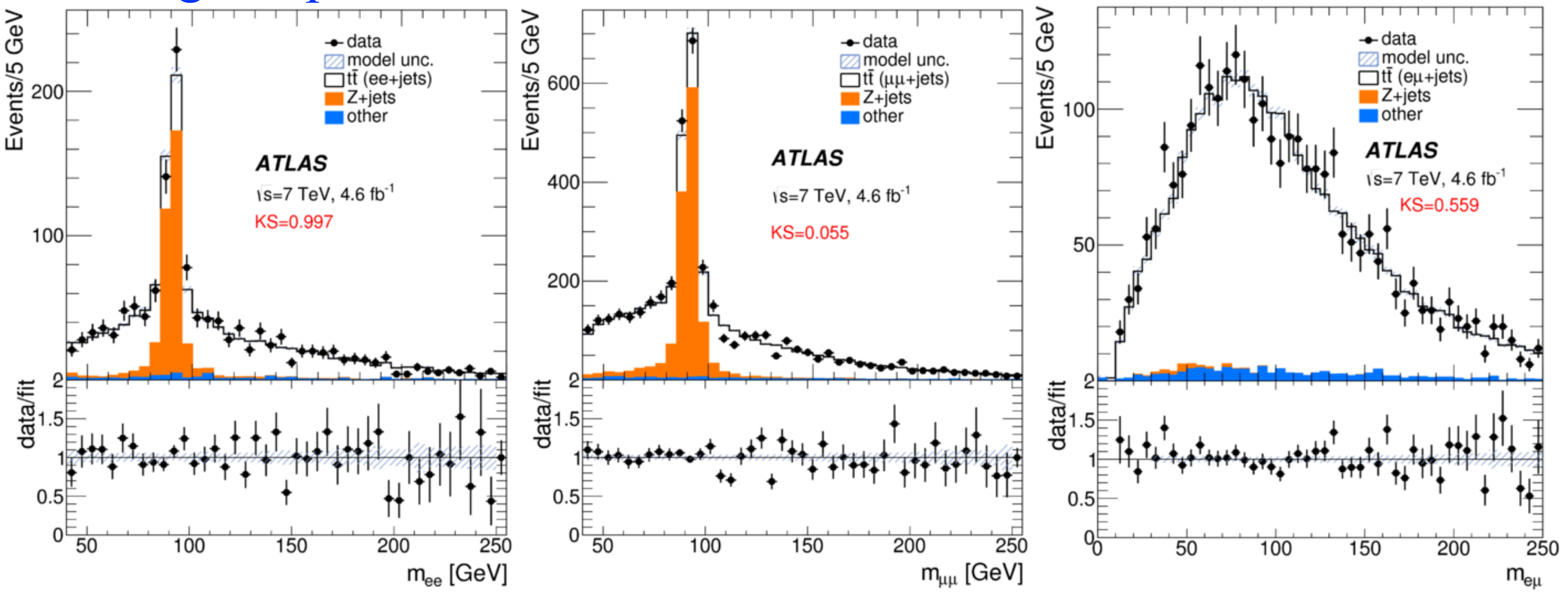
ℓ+jets channels

Channel	e+jets	μ+jets
$t\bar{t} \to \ell$+jets (MC)	19710±280 (18966± 31)	25090±310 (24233± 34)
$t\bar{t}$ (other) (MC)	2674± 30 (2577± 11)	3393± 30 (3277± 16)
W+jets (MC)	4800±500 (4140± 70)	5600±500 (5850± 90)
Z+jets (MC)	1900±500	790±200
Single top (MC)	910± 70	1170± 80
Diboson (MC)	5.0± 0.2	6.1± 0.2
Multijet	1000±120	2800±140
Total Background	11333±700	13700±600
Signal+Background	31000±800	38800±700
Data	30733	40414
χ^2/ndf	188/207	218/207
S/B	1.7	1.8

ℓℓ'+jets channels

<u>Important Backgrounds:</u>

- Z(→ℓℓ') + jets modeled from MC templates, but very small in eμ
- Multi-jet [jets mis-identified as ℓ] modeled from same sign data
- Single-top, Di-boson modeled from MC



Fit di-lepton mass in 2 separate bins (30 < $\not{E}_T$ < 60 GeV, $\not{E}_T$ > 60 GeV) to account for varying amounts of Z + jets in different $\not{E}_T$ regions.

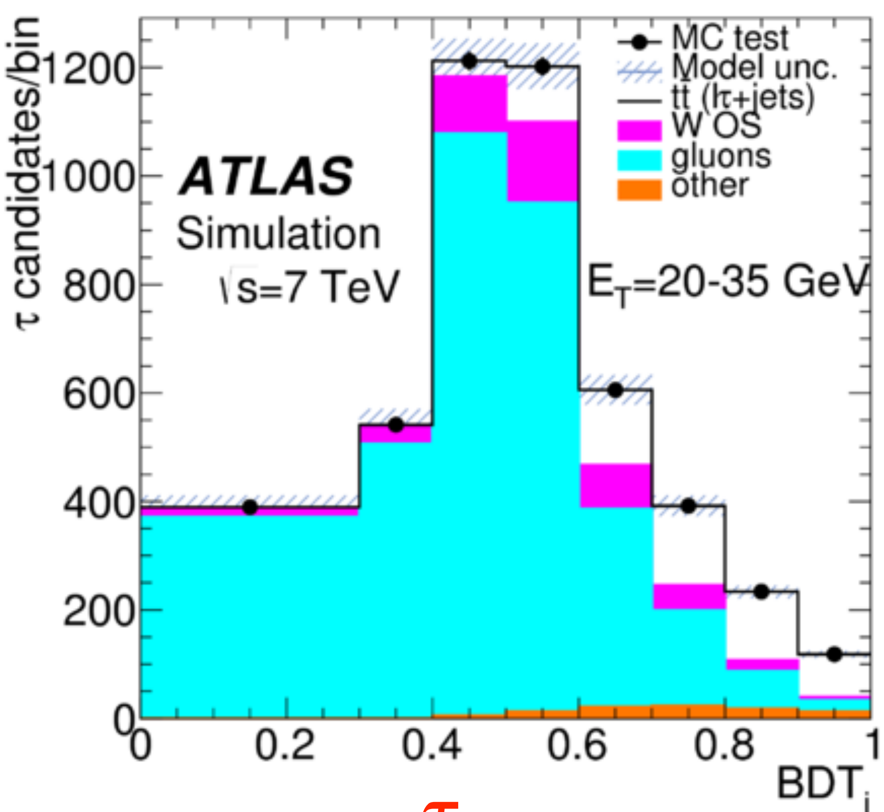
$\ell\ell$'+jets channels

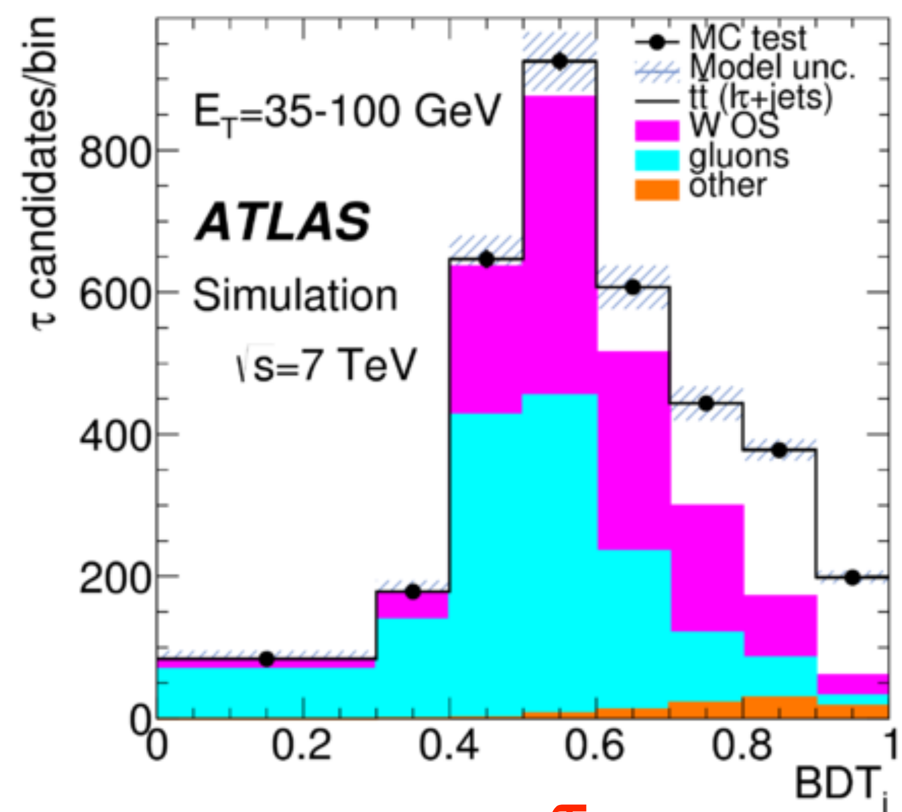
Channel	$\mu\mu$+jets	ee+jets	$e\mu$+jets
$t\bar{t}$	2890± 80	1000±40	2640±50
(MC)	(2536± 11)	(903± 6)	(2420±11)
Z+jets	1380± 50	379±11	13± 4
(MC)	(1267± 8)	(385±11)	(13± 4)
Single top (MC)	86± 8	36± 7	98± 9
Diboson (MC)	22± 1	8.1±0.5	3.3±0.3
Fake leptons	17± 10	17± 8	19±10
Total Background	1430± 50	442±15	136±12
Signal+Background	4400±100	1440±40	2770±80
Data	4102	1447	2848
χ^2/ndf	35/34	31/34	58/49
S/B	2.1	2.3	19.4

$\ell\tau_h$+jets channels

Important Backgrounds:

- $t\bar{t} \rightarrow \ell +$ jets (jets mis-identified as τ_h)
- Z / $t\bar{t} \rightarrow \ell\ell +$ jets (ℓ mis-identified as τ_h)
- W+jets, multi-jets (one jet mis-identified as ℓ and another jet as τ_h)



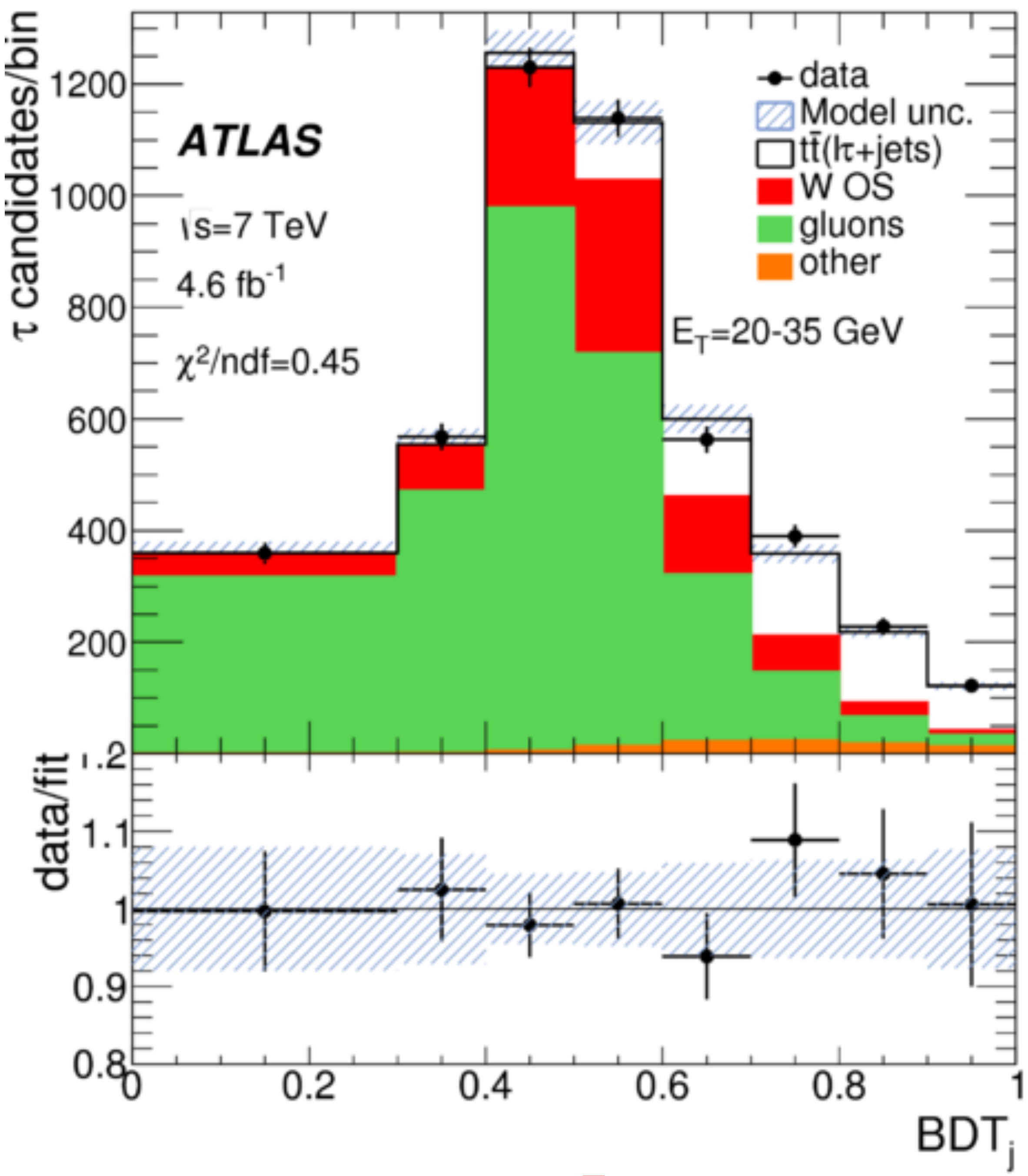


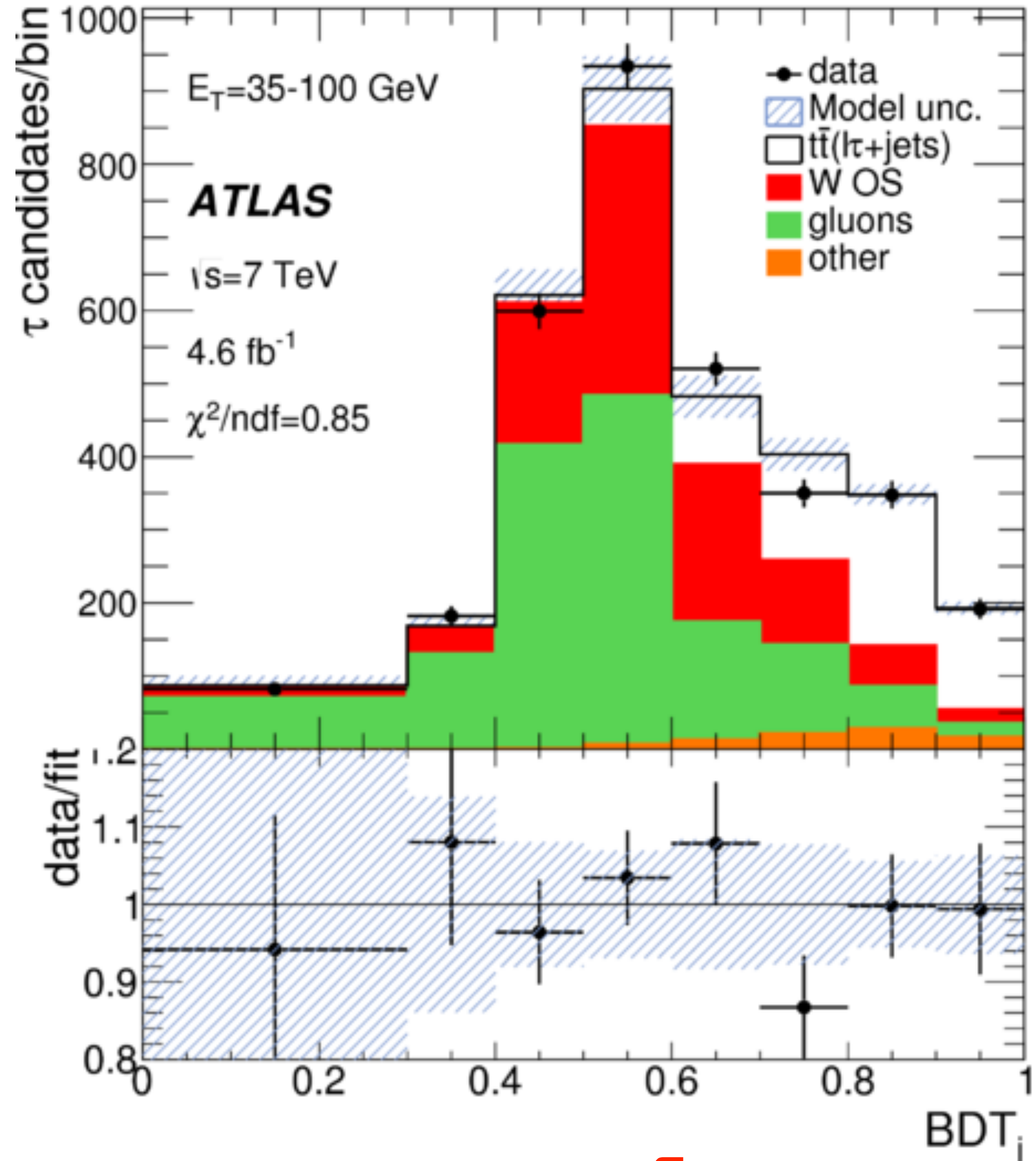
Region 1 ($20 \leq E_T^\tau \leq 35$ GeV) Region 2 ($35 \leq E_T^\tau \leq 100$ GeV)

Separate templates for τ_h (MC), gluon/quark-jets (Data) are validated by a fit to BDT output that separates jets from τ_h using MC ensemble.

$\ell\tau_h$+jets channels

Fit data to obtain signal τ_h contribution





Region 1 ($20 \leq E_T^\tau \leq 35$ GeV) Region 2 ($35 \leq E_T^\tau \leq 100$ GeV)

$\ell\tau_h$+jets channels

Signal τ_h composition

Channel	Region 1	Region 2
$t\bar{t} \to \ell\tau_{\text{had}}$+jets	611.5 ± 5.4	621.4 ± 5.4
$t\bar{t} \to \ell\ell$+jets	13.0 ± 0.7	13.0 ± 0.7
Z + jets	54.5 ± 3.3	45.3 ± 3.0
Single Top	23.6 ± 2.3	27.1 ± 2.4
Dibosons	1.5 ± 0.2	2.2 ± 0.3
Total	705.2 ± 6.8	709.5 ± 6.8

N_S^{fitted} : # of signal events

$B_{\text{non-}t\bar{t}}$: τ_h from other sources

$B_{\ell\text{epton}}$: ℓ mis-identified as τ_h

$N_{t\bar{t}}^{\text{fitted}} = N_S^{\text{fitted}} - B_{\text{non-}t\bar{t}} - B_{\ell\text{epton}}$ is in good agreement with $N_{t\bar{t}}^{\text{MC}}$

	$N_{t\bar{t}}^{\text{MC}}$	$\text{B}_{\text{non }t\bar{t}\ \tau}$	B_{lepton}	N_S^{Fitted}	$N_{t\bar{t}}^{\text{Fitted}}$
$20 < E_{\text{T}}^{\tau} < 35$ GeV	611 ± 5	76.2 ± 3.5	17.1 ± 1.1	N/A	N/A
$35 < E_{\text{T}}^{\tau} < 100$ GeV	621 ± 5	69.5 ± 3.3	17.6 ± 1.1	N/A	N/A
Combined E_{T}^{τ} bins	1232 ± 8	146 ± 5	34.8 ± 1.5	1460 ± 60 (χ^2/ndf =0.69)	1280 ± 60

Measuring cross-section & BR

Definitions

$\mathcal{A}\cdot\epsilon$: acceptance $\times$ efficiency

- $N_{\mu j}$=(observed number of $t\bar{t} \to \mu$+jets)/ $\mathcal{A}\cdot\epsilon_{\mu j}$
- N_{ej}=(observed number of $t\bar{t} \to e$+jets)/$\mathcal{A}\cdot\epsilon_{ej}$
- $N_{\mu\mu}$=(observed number of $t\bar{t} \to \mu\mu$+jets) /$\mathcal{A}\cdot\epsilon_{\mu\mu}$
- N_{ee}=(observed number of $t\bar{t} \to e+e$+jets) /$\mathcal{A}\cdot\epsilon_{ee}$
- $N_{e\mu}$=(observed number of $t\bar{t} \to e+\mu$+jets) /$\mathcal{A}\cdot\epsilon_{e\mu}$
- N_{τ}=(observed number of $t\bar{t} \to \ell+\tau_h$+jets) /$\mathcal{A}\cdot\epsilon_{\ell\tau}$
- $N_j=N_{\mu j}+N_{ej}$
- $N_\ell=N_{\mu\mu}+N_{ee}+N_{e\mu}$
- B_μ: top quark branching ratio to $\mu\nu_\mu(\nu_\tau)+X$
- B_e: top quark branching ratio to $e\nu_e(\nu_\tau)+X$
- B_τ: top quark branching ratio to $\tau_h\nu_\tau+X$
- B_j: top quark branching ratio to jets
- B_ℓ: $B_\mu+B_e$

	e+jets	μ+jets	ee+jets	$\mu\mu$+jets	$e\mu$+jets	$\ell\tau$+jets
$\mathcal{A}_{ch}\cdot\epsilon_{ch}(\%)$	14.02±0.02	17.88±0.02	7.09±0.04	19.74±0.08	9.50±0.04	4.36±0.02

Calculate B.R. and cross section

Note that B_μ and B_e include events coming from τ leptons decaying leptonically. With these definitions the following relations hold:

$$N_j = 2\sigma_{t\bar{t}} \cdot B_\ell \cdot B_j \cdot \mathcal{L} \quad (1)$$

$$N_\ell = \sigma_{t\bar{t}} \cdot B_\ell^2 \cdot \mathcal{L} \quad (2)$$

$$N_\tau = 2\sigma_{t\bar{t}} \cdot B_\ell \cdot B_\tau \cdot \mathcal{L} \quad (3)$$

$$B_j + B_\ell + B_\tau = 1 \quad (4)$$

where $\mathcal{L}$ is the integrated luminosity. Solving four equations with four unknowns:

$$B_j = N_j/(N_j + 2N_\ell + N_\tau) \quad (5)$$

$$B_\ell = 2N_\ell/(N_j + 2N_\ell + N_\tau) \quad (6)$$

$$B_\tau = N_\tau/(N_j + 2N_\ell + N_\tau) \quad (7)$$

$$\sigma_{t\bar{t}} \cdot \mathcal{L} = (N_j + 2N_\ell + N_\tau)^2/4N_\ell \quad (8)$$

Systematic Uncertainties

Relative uncertainties (%)

	$\sigma_{t\bar{t}}$	B_j	B_ℓ	B_τ
μ uncertainty	1.3	0.15	0.6	0.5
e uncertainty	1.1	0.15	0.5	0.5
Jet energy scale	$-6.9/+4.9$	$-1.6/+1.4$	$-1.9/+2.7$	$-3.8/+4.3$
Jet energy resolution	1.2	0.3	0.8	0.7
ISR/FSR	2.0	0.3	1.3	4.0
MC generator	3.6	0.6	0.8	1.9
PDF	2.9	0.3	0.1	0.3
b-tag	$-1.3/+5.0$	0.3	1.0	1.5
τ identification	0.5	0.15	1.1	3.5
τ background correction	0.2	<0.1	<0.1	2.5
W+jets HF content	$-4.1/+2.7$	$-1.0/+0.7$	$-1.1/+2.3$	$-1.3/+2.1$
Total	$-9.7/+9.2$	$-2.1/+1.8$	$-3.4/+4.2$	$-7.1/+7.6$
Luminosity	1.8	<0.1	<0.1	<0.1

Results

	N_{ej}	$N_{\mu j}$	N_{ee}	$N_{\mu\mu}$	$N_{e\mu}$	$N_{\ell\tau}$
	$N_{\ell j}$			$N_{\ell\ell}$		
Measured	30.62±0.26	30.57±0.29	3.06±0.12	3.19±0.10	6.06±0.12	6.39±0.30
	61.19±0.40			12.31±0.20		
SM	30.40±1.2	30.40±1.2	2.86±0.11	2.86±0.11	5.72±0.20	6.39±0.25
NNLO+NNLL	60.64±2.4			10.95±0.44		

The $N_{\ell x}$ are in units of events/pb^{-1} .

	Measured (top quark)	SM	LEP (W)
$\sigma_{t\bar{t}}$	178 ± 3 (stat.) ± 16 (syst.) ± 3 (lumi.) pb	$177.3 \pm 9.0^{+4.6}_{-6.0}$ pb	
B_j	66.5 ± 0.4 (stat.) ± 1.3 (syst.)	67.51±0.07	67.48±0.28
B_e	13.3 ± 0.4 (stat.) ± 0.5 (syst.)	12.72±0.01	12.70±0.20
B_μ	13.4 ± 0.3 (stat.) ± 0.5 (syst.)	12.72±0.01	12.60±0.18
B_τ	7.0 ± 0.3 (stat.) ± 0.5 (syst.)	7.05±0.01	7.20±0.13

Summary

- A single parameter fit to ℓ + jets, $\ell\ell'$ + jets and $\ell\tau_h$ + jets yields a cross-section of $\sigma_{t\bar{t}} = 178 \pm 17$ pb, in good agreement with SM prediction of $\sigma_{t\bar{t}} = 177.3 \pm 9.0\,^{+4.6}_{-6.0}$ pb using NNLO + NNLL.

- This analysis is the first measurement of top quark hadronic and semi leptonic branching ratios. Branching ratio measurements have smaller systematic uncertainties than cross-section measurements because of cancellation in ratios. The precision ranges from 2.3% for $t \rightarrow$ jets to 7.6% for $t \rightarrow \tau_h + X$.

- The measured branching ratio $\mathcal{B}_\tau$ will vary by more than the observed uncertainty if the $\mathcal{B}(\tilde{t} \rightarrow b\,\nu_\tau\,\tilde{\tau})$ times the production cross-section of the $\tilde{t}$-quark is > 3% of that of pair production of t-quark.