Top quark pair production at ATLAS

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On behalf of the ATLAS Collaboration

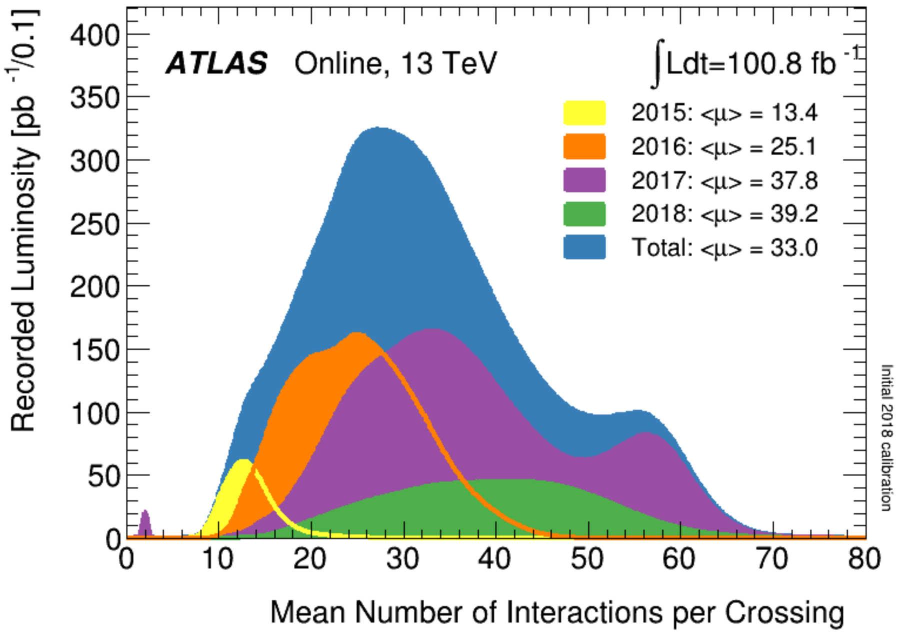
LHCP June 4-9, 2018

Outline

All results [here]

- Introduction
- Recent results for $t\bar{t}$ production cross-sections:
  - ❑ Inclusive and fiducial x-section in single lepton final state @8 TeV
  - ❑ Differential x-section with N jets in single lepton final state @13 TeV
  - ❑ Differential x-section in all-hadronic boosted final state @13 TeV
- Conclusions

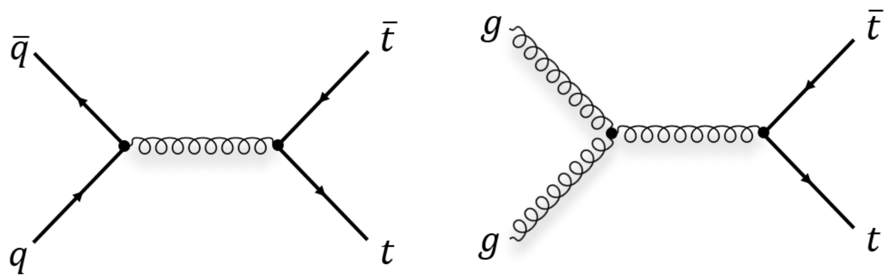
Data taking efficiency > 90%



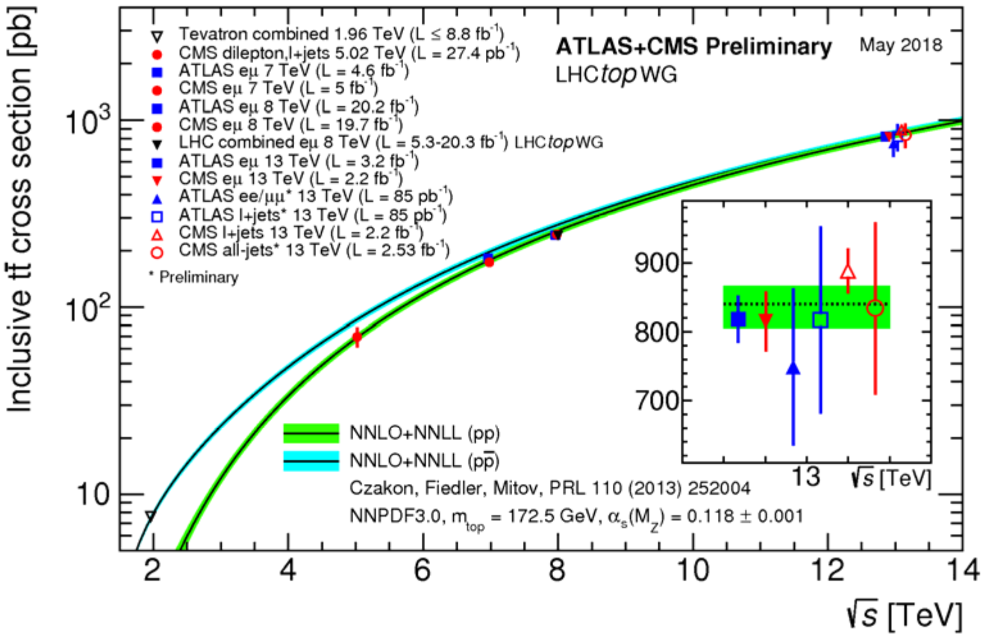
Motivation

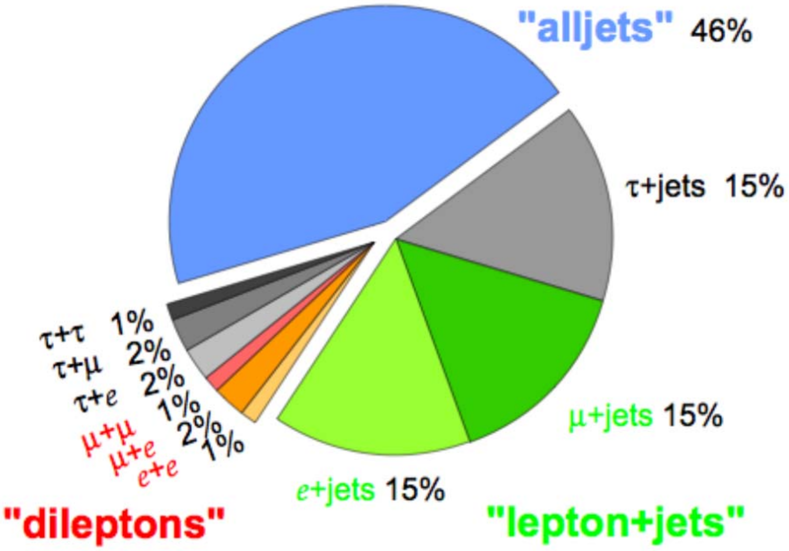
- Top quark is a unique particle:
  - ☐ Large mass (~ 172.5 GeV) ➡ Coupling to the Higgs boson, $\mathcal{O}(1)$, may play a special role in EWSB
  - ☐ Only known quark to decay before hadronizing – access properties of bare quark
- LHC is a “top factory” – produce Pair of top quarks or Single top
  - $\sigma(t\bar{t})$ at 13 TeV: 832^{+40}_{-46} pb (NNLO + NNLL theory for m_{top} = 172.5 GeV)
- Measurements of production cross-sections:
  - ☐ Test of pQCD, constrain Parton Distribution Functions
  - ☐ Differential x-sections can be more sensitive to BSM effects, e.g., p_T^{top} spectrum
- Heavy BSM particles could decay to $t\bar{t}$

Top quark pair production



~10% at the LHC ~90%





Top Pair Branching Fractions

All hadronic final state: large BR and backgrounds

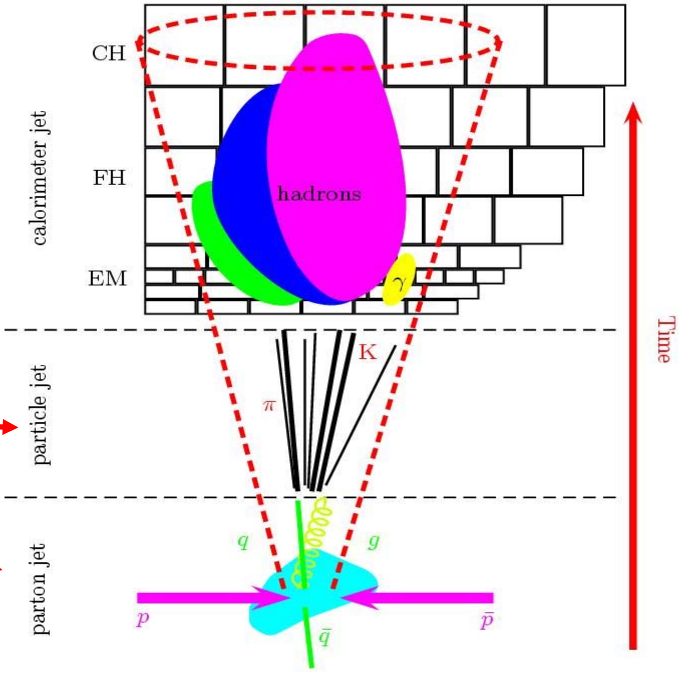
Can be used to probe highly boosted top quarks

Lepton+jets: large BR, high pT isolated lepton

Dilepton: Small BR, very clean, two high pT leptons

Cross-section measurements

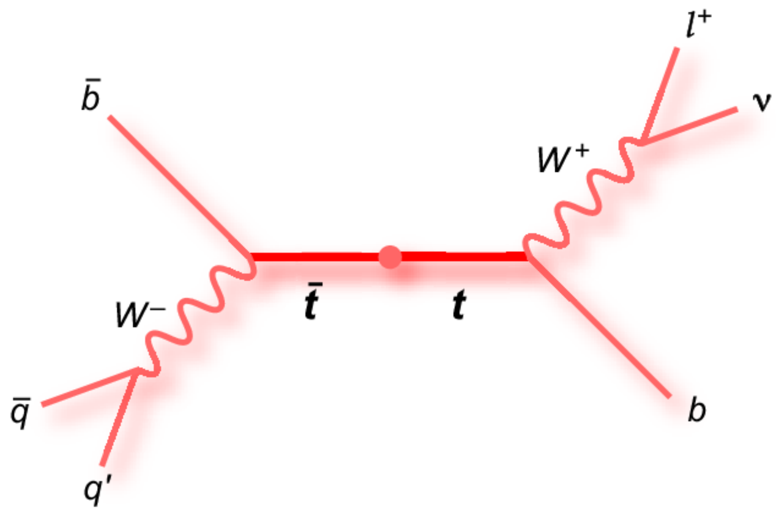
- **Can be inclusive or differential – in fiducial or total phase space, absolute or normalized**
  - ❑ Extract # of observed events, after subtracting background – Correction due to selection efficiency
- **Unfolding** - Differential cross sections are obtained from the reconstruction-level distributions by correcting for detector and reconstruction effects
  - ❑ Unfolding can be to parton or (stable) particle level



Typically quarks in MC history (t, b) after QCD radiation but before Wb decay

- **Fiducial cross-section:**
  - ❑ Pros: Less model dependence
- **Total cross-section:**
  - ❑ Correct fiducial cross-section by fiducial acceptance and branching fractions
  - ❑ Pros: Easy interpretation

Event topologies



Single lepton final state has ≥ 4 jets

All-hadronic final state has ≥ 6 jets

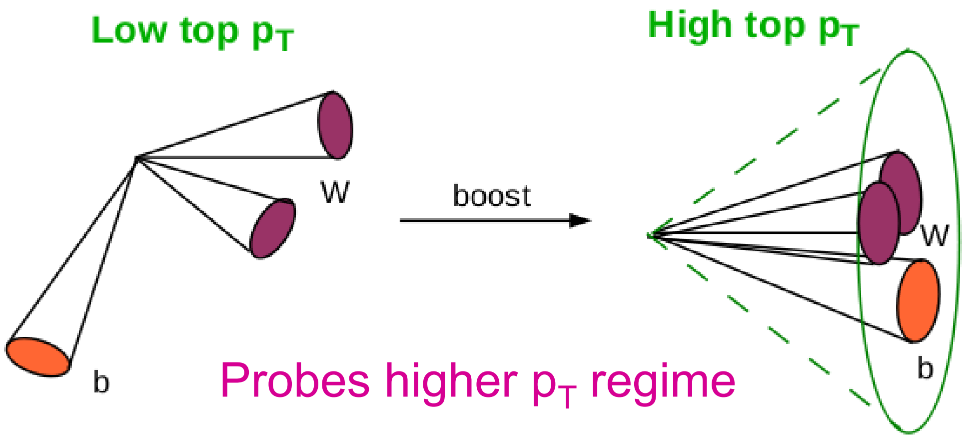
Extra jets can arise due to Initial or Final state radiation

b-jets tagged with MVA techniques

$W \longrightarrow c\bar{s}$ can be source of fake b-jets

Objects used in analyses:

Muons, Electrons, (b-) jets, MET



Probes higher p_T regime

Inclusive & fiducial $t\bar{t}$ cross-sections in ℓ+jets

Submitted to EPJC (arXiv 1712.06857)

- Dataset: $\mathcal{L} \sim 20.2\ \text{fb}^{-1}$ @ 8 TeV
- Lepton (e or μ) can come from leptonic tau decay

- To reduce JES & b-tagging systematics - three disjoint signal regions:
  - SR1: ≥ 4 jets, 1 b-tag – largest sample and backgrounds (W+jets is dominant)
  - SR2: 4 jets, 2 b-tags – background is expected to be small, unambiguous matching of reco objects to top decay, hadronic W mass is sensitive to JES
  - SR3: ≥ 4 jets, ≥ 2 b-tags – (excluding events from SR2). Contains $t\bar{t}$ events with extra gluon radiation, sensitive to mis-ID of c-jet (from $W \longrightarrow c\bar{s}$) as b-jet
  - Each SR has a discriminating variable defined for the x-section result

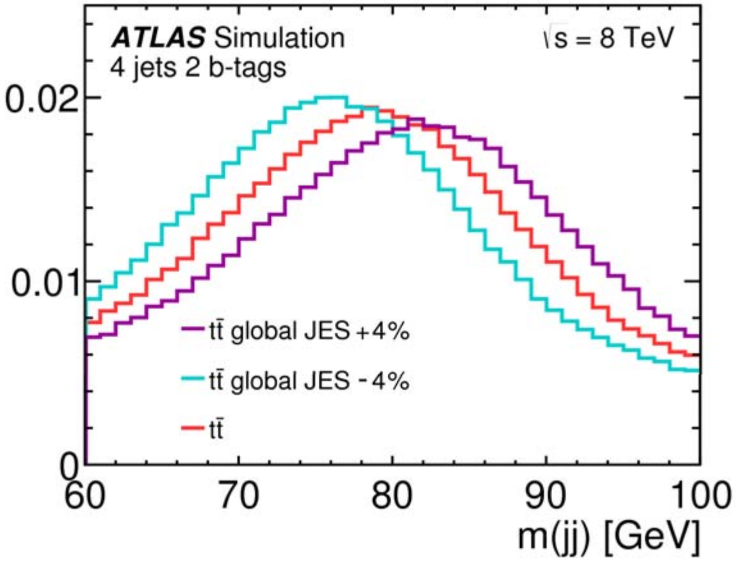
70% b-tagging WP

Discriminating variables for the three signal regions -

1) SR1 and SR3 – use a NN, that discriminates S from W+jet background (estimated using Z+jets data)

2) SR2 – has unambiguous matching - use m(jj), where j is untagged jet

Ratio of single to double b-tag events: SR1/(SR2+SR3) is sensitive to b-tag efficiency



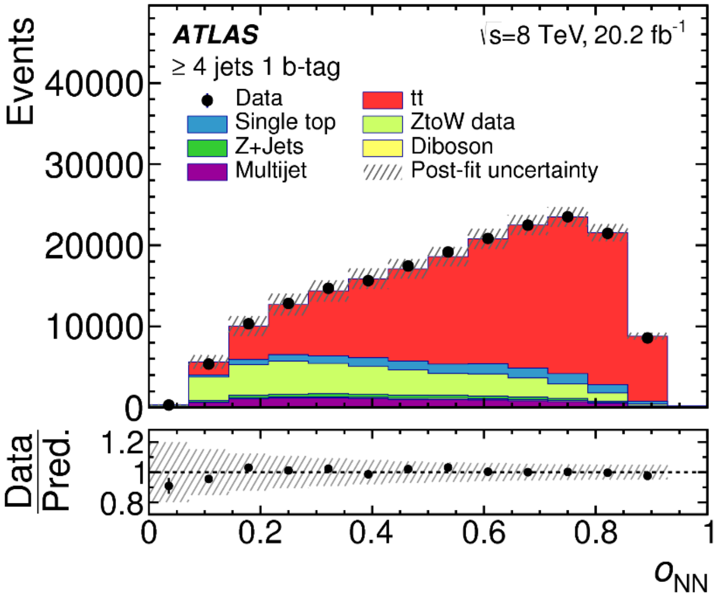
Simultaneous fit to the three signal regions:

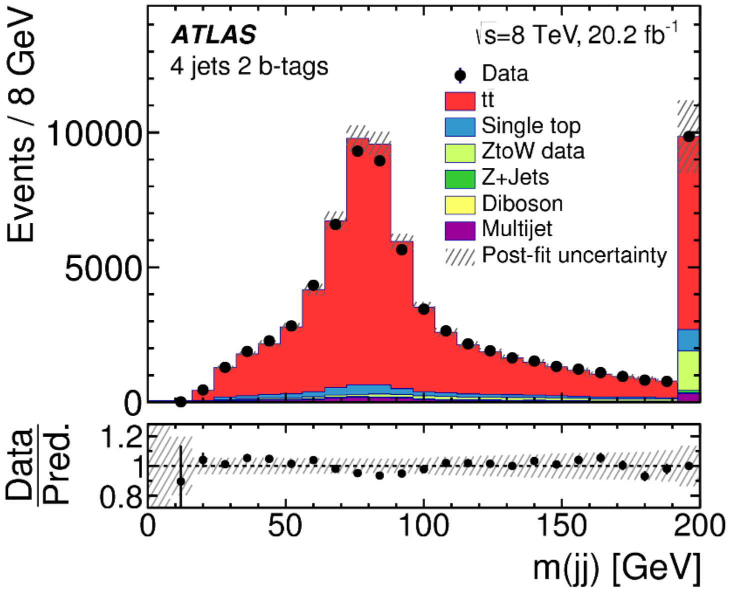
Scale Factors for $t\bar{t}$ and W+jet components,

and NP for JES & b-tagging systematics

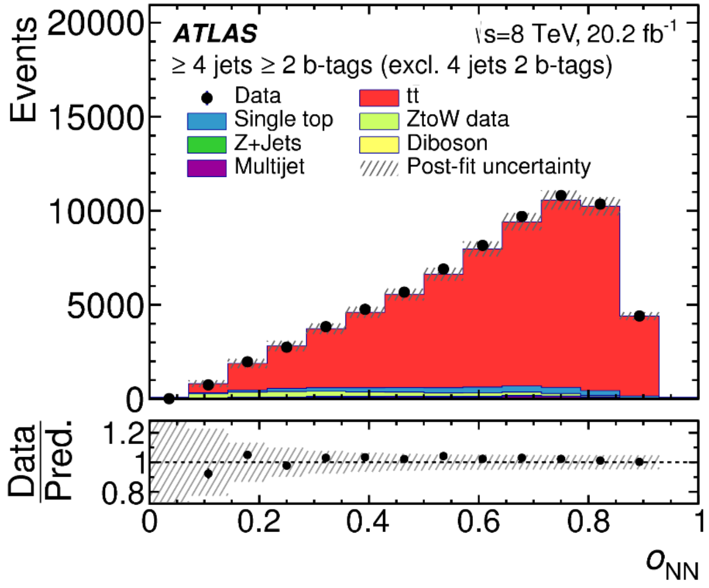
Other systematic uncertainties come from:

Physics object modelling, Signal MC variations, PDF variations ,Background modelling, Luminosity





Post-fit



Results for σ($t\bar{t}$): *(for m_t = 172.5 GeV)*

(Lumi)

Inclusive cross-section: 248.3±0.7±12.8±4.7 pb

Theory prediction: 253^{+13}_{-15} pb (NNLO + NNLL)

Scale factors: for $t\bar{t}$	0.982	± 0.005
W+jets 1 btag	1.08	± 0.02
≥ 2 btag	1.41	± 0.08

Fiducial cross-section: 48.8±0.1±2.0±0.9 pb

(Fid. Volume: 1 electron or muon, and ≥ 3 particle-level jets)

Differential $t\bar{t}$ cross sections in association with jets - ℓ+jets – Submitted to JHEP (arXiv: 1802.06572)

- Dataset: $\mathcal{L} \sim 3.2\ \text{fb}^{-1}$ @ 13 TeV
- Analysis uses 3 configurations:
  - ❑ 4-jet exclusive (i.e., 0 additional jet)
  - ❑ 5-jet exclusive (i.e., 1 additional jet)
  - ❑ 6-jet inclusive (i.e., ≥ 2 additional jets)
    - useful for $t\bar{t}$H and searches with high jet multiplicity

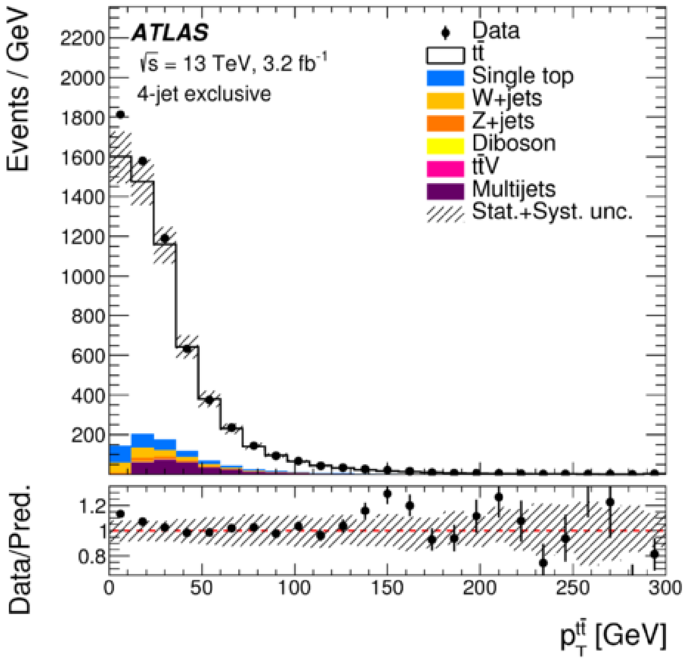
A previous analysis inclusive in # jets – JHEP 11 (2017) (arXiv: 1708.00727)

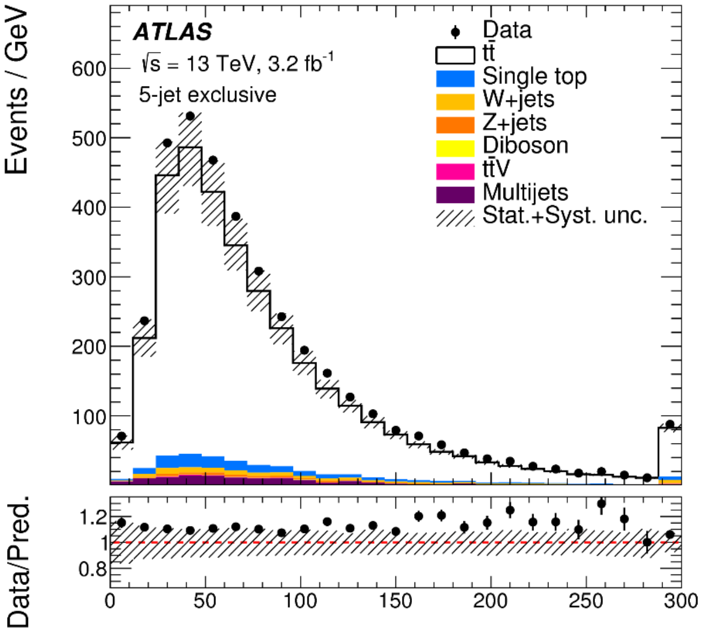
Additional jets from ISR or FSR

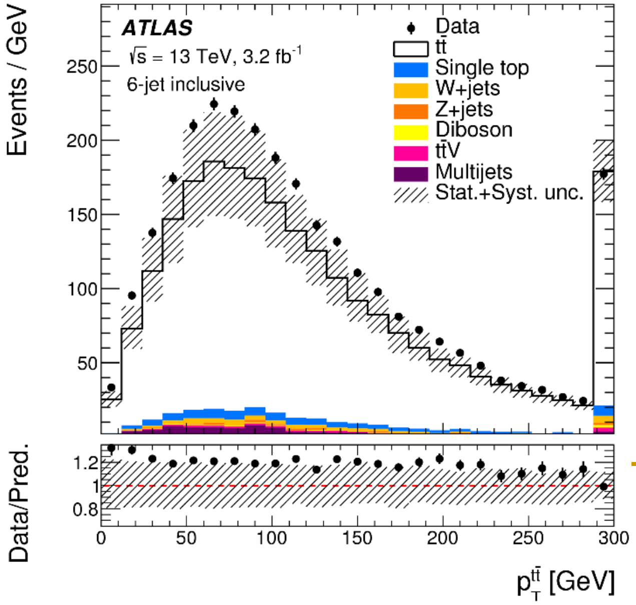
- Analysis focusses on effect of gluon radiation on $t\bar{t}$ kinematics
- Differential cross-sections as functions of kinematic variables:
  - ❑ p_T^t (had), $p_T(t\bar{t})$, $\left|p_{\text{out}}^{t\bar{t}}\right| = \left|\vec{p}^{\,t,\text{had}} \cdot \frac{\vec{p}^{\,t,\text{lep}} \times \hat{z}}{|\vec{p}^{\,t,\text{lep}} \times \hat{z}|}\right| \longrightarrow$

Out-of-plane p_T expected to be more sensitive to direction of gluon radiation

$< p_T(t\bar{t}) >$ α Number of jets – in 5-jet and 6-jet, $t\bar{t}$ recoils against additional jets







Analysis details

- Particle level description:
  - Lepton (e or μ) can come from leptonic tau decay, but not from the decay of a hadron
  - Dileptons where only one lepton satisfies fiducial selection are included in fiducial measurement
- At least two btagged jets – at the 77% efficiency working point

- Pseudo-top algorithm used to reconstruct the leptonic top decay (for both particle- and detector-level)
  - Neutrino p_x, p_y from MET, and p_z determined from W-mass constraint
  - The two b-tagged jets with the highest p_T are selected as coming from the top pair
  - W is combined with b-jet closest to charged lepton to make leptonic top
- Hadronic W is made with all remaining jets – choose jj pair closest to W mass
- During unfolding, electron and muon channels are combined

4-jet exclusive	
Sample	Yield
$t\bar{t}$	61400^{+3300}_{-3400}
W+jets	2200^{+1400}_{-1600}
Z+jets	840^{+630}_{-620}
Diboson	140^{+100}_{-100}
Single top	3600^{+360}_{-360}
Multijet	3300^{+1700}_{-1800}
$t\bar{t}\ V$	103^{+17}_{-17}
Total prediction	71600^{+4800}_{-5000}
Data	75768
Data/prediction	1.06 ± 0.07

5-jet exclusive	
Sample	Yield
$t\bar{t}$	36900^{+3700}_{-3700}
W+jets	890^{+600}_{-680}
Z+jets	340^{+330}_{-330}
Diboson	100^{+100}_{-100}
Single top	1730^{+240}_{-240}
Multijet	1460^{+770}_{-780}
$t\bar{t}\ V$	132^{+21}_{-21}
Total prediction	41600^{+4000}_{-4300}
Data	46243
Data/prediction	1.11 ± 0.11

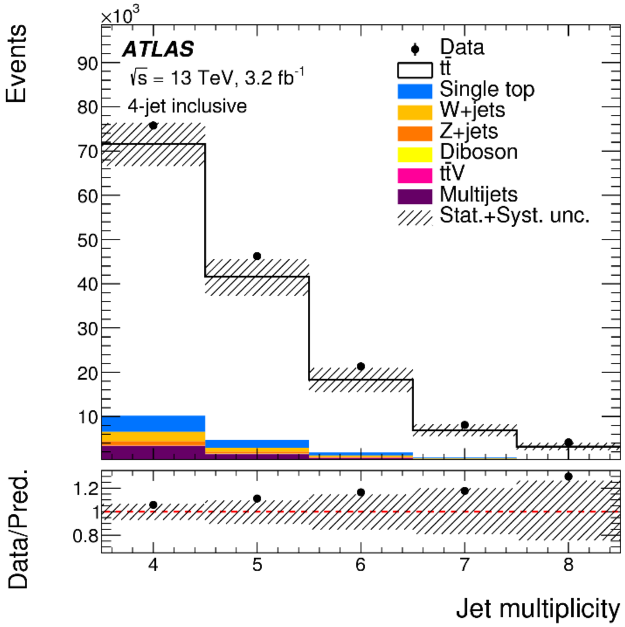
6-jet inclusive	
Sample	Yield
$t\bar{t}$	25400^{+4700}_{-4400}
W+jets	540^{+400}_{-450}
Z+jets	160^{+100}_{-100}
Diboson	110^{+57}_{-57}
Single top	980^{+210}_{-200}
Multijet	920^{+500}_{-500}
$t\bar{t}\ V$	224^{+40}_{-40}
Total prediction	28400^{+4900}_{-4900}
Data	33582
Data/prediction	1.2 ± 0.2

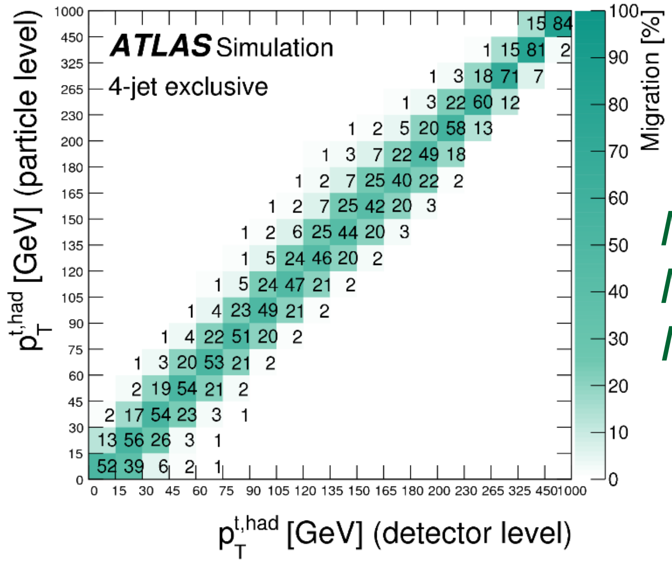
1) Single top: modelled using MC, and x-section normalized to NNLO+NNLL predictions

2) Multi-jet: from data using matrix method

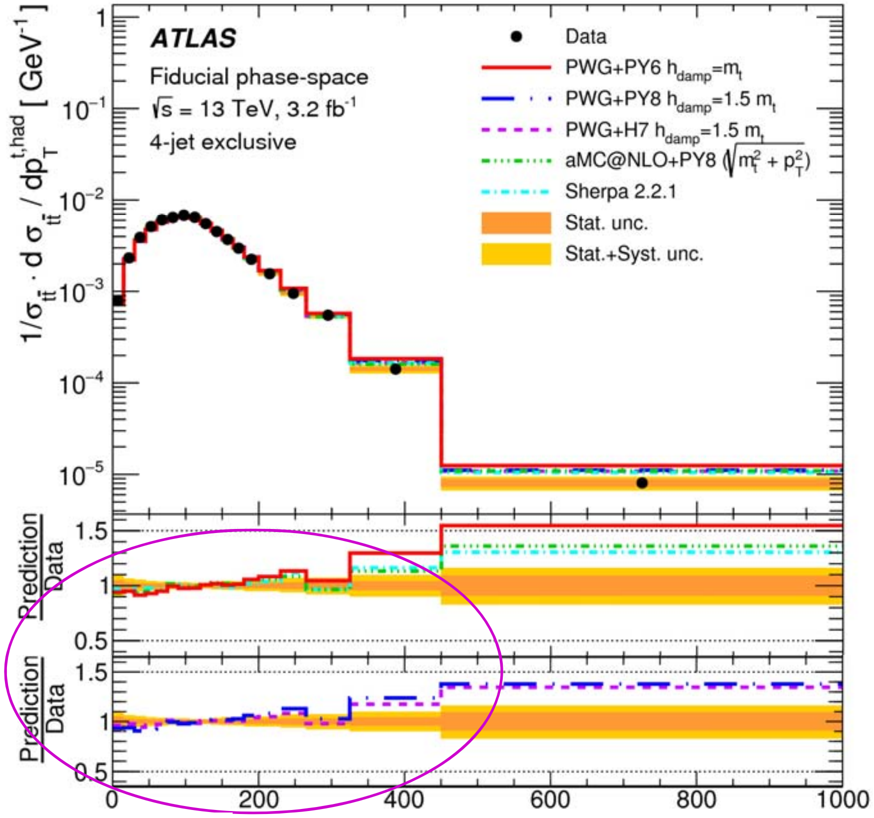
3) W+jets: by using simulations & data-driven techniques

4) Z+jets, Diboson, $t\bar{t}$V: from MC and normalized to theory

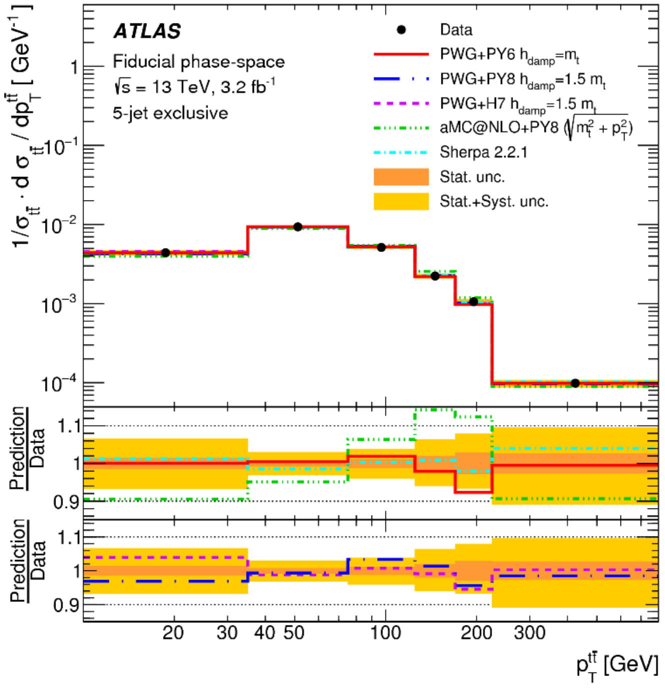


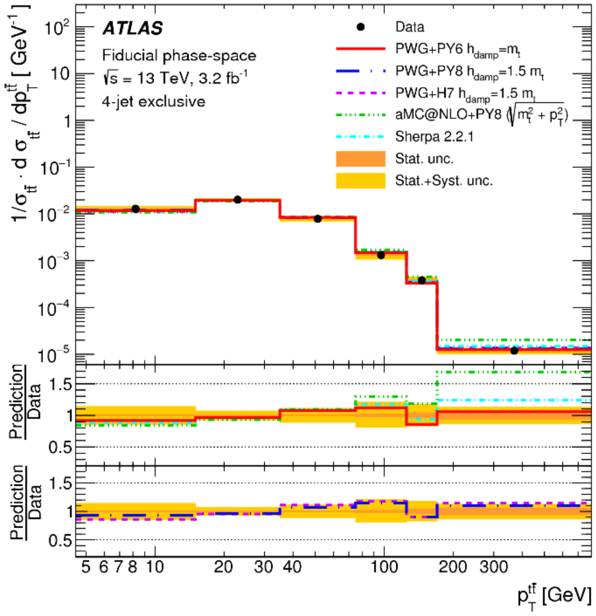


Migration Matrix used In Unfolding



Normalized Differential distributions



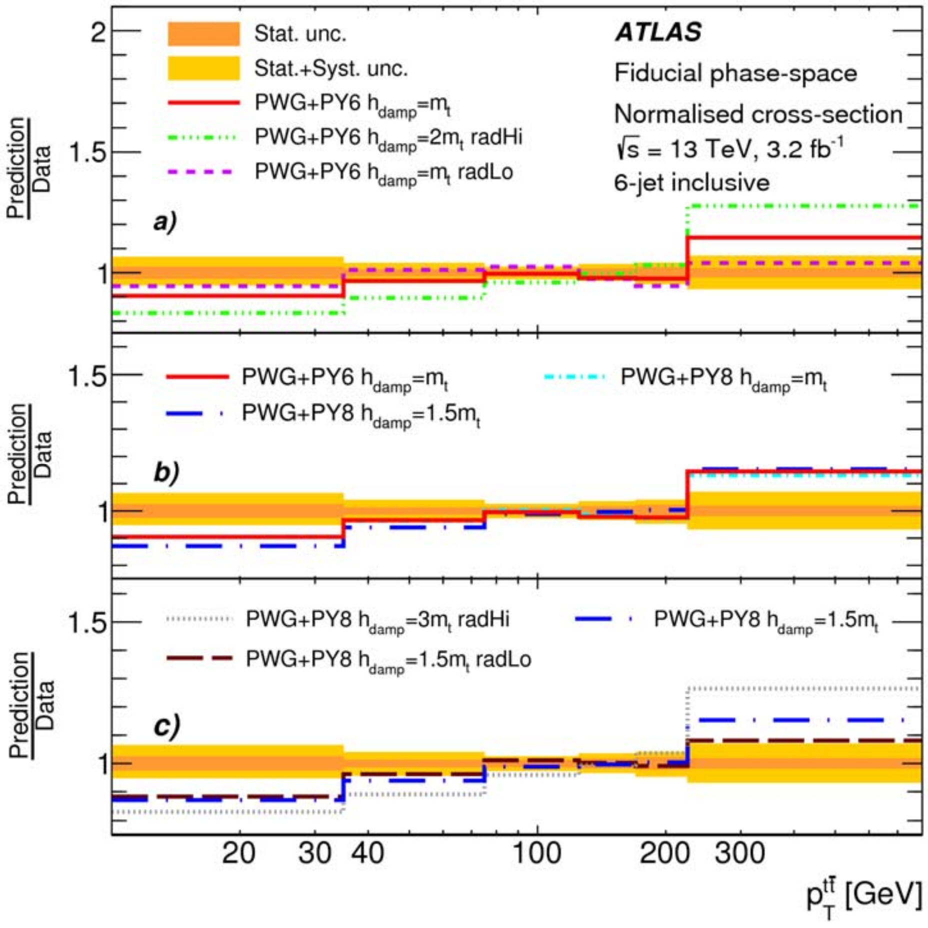


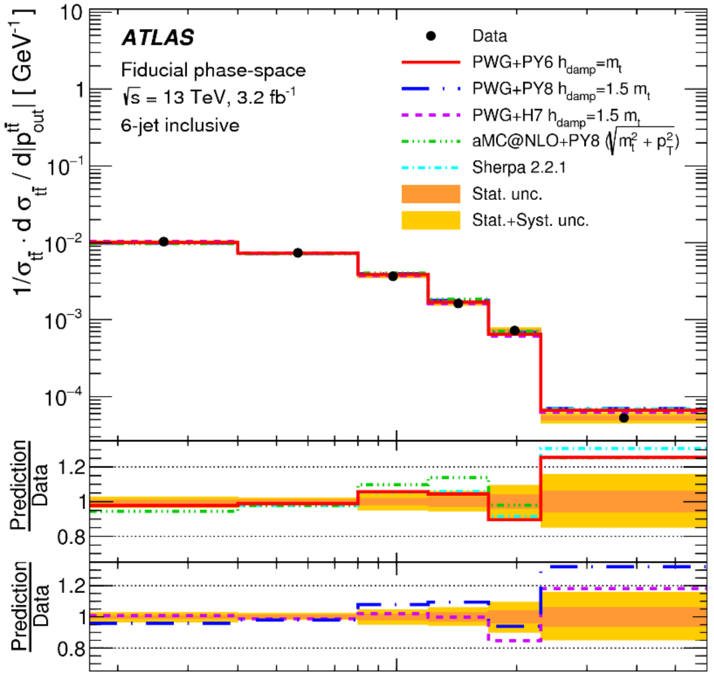
Spectra are flatter in 5-, 6-jet regions

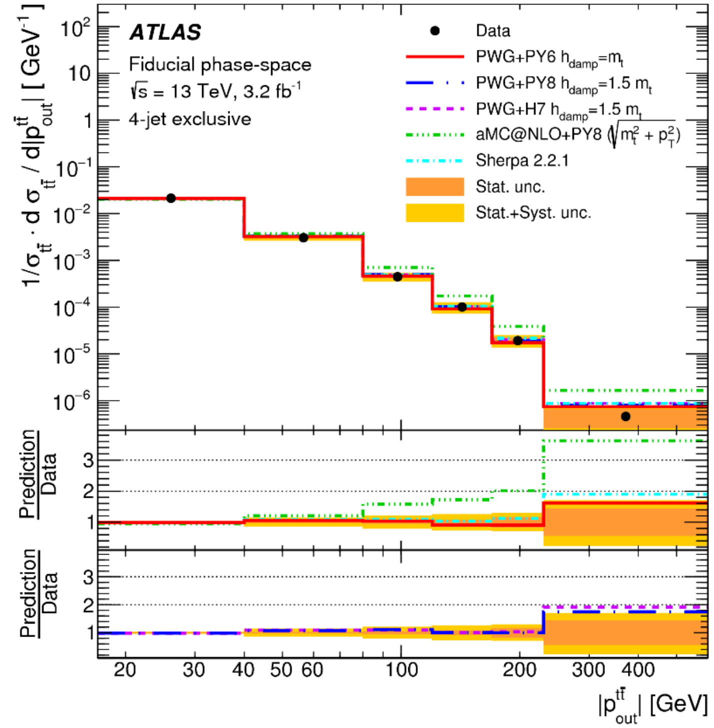
Systematic uncertainties:

JES, b-tagging, lepton & MET

S & B modelling, Luminosity



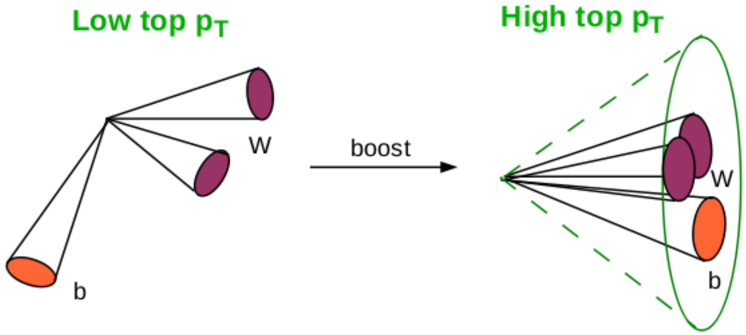




Differential cross-section measurements allow for detailed testing of various generators, highlighting issues that may not be apparent in inclusive measurements

Differential $t\bar{t}$ cross-sections of boosted top quarks in all-hadronic final states - Submitted to PRD (arXiv: 1801.02052)

- Dataset: $\mathcal{L} \sim 36.1\ \text{fb}^{-1}$ @ 13 TeV
- Events contain two large-R jets, with pT > 500 and 350 GeV
  - ❑ Boosted regime $\longrightarrow$ $t\bar{t}$ production at TeV scale



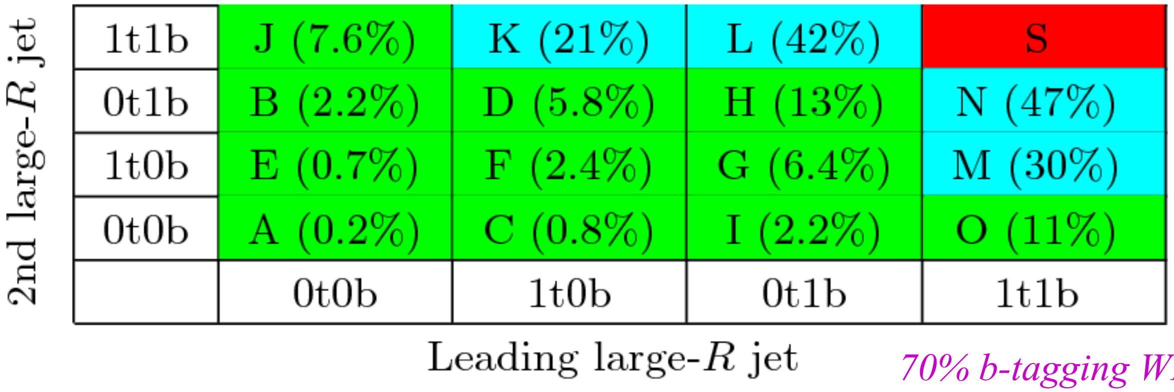
- Use rapidity of top quarks (in lab & CM frame) to study production
- Other variables include mass, p_T, H_T, rapidity, $\Delta\varphi$, p_{out} of the $t\bar{t}$ system, and cosθ* (in the Collins-Soper frame)

$t\bar{t}$ (all-hadronic)	3250 ± 470
$t\bar{t}$ (non-all-hadronic)	200 ± 40
Single-top-quark	24 ± 12
$t\bar{t}+W/Z/H$	33 ± 10
Multijet events	810 ± 50
Prediction	4320 ± 530
Data ($36.1\ \mathrm{fb}^{-1}$)	3541

Uncertainties include stat. and syst., but not modelling nor inclusive $t\bar{t}$ x-section contributions

Single top does not include the t-channel process – selection criteria disfavor this process

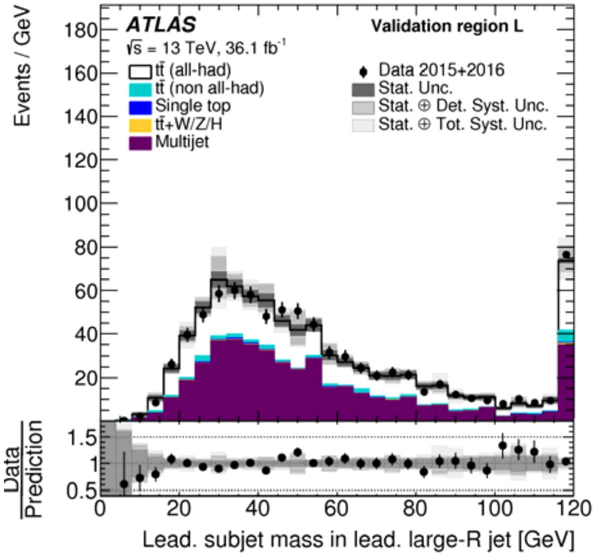
Multijet is estimated from data using a set of control & validation regions



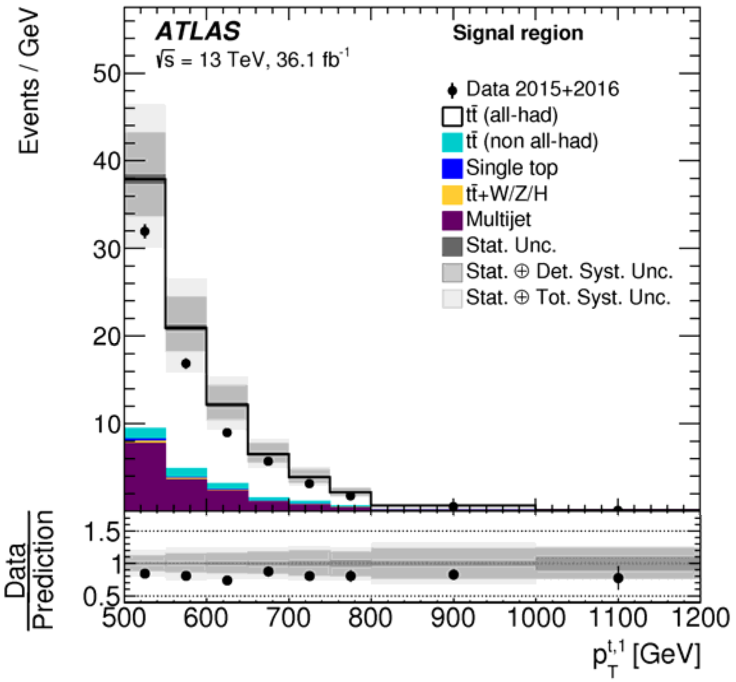
2nd large-R jet				
1t1b	J (7.6%)	K (21%)	L (42%)	S
0t1b	B (2.2%)	D (5.8%)	H (13%)	N (47%)
1t0b	E (0.7%)	F (2.4%)	G (6.4%)	M (30%)
0t0b	A (0.2%)	C (0.8%)	I (2.2%)	O (11%)
	0t0b	1t0b	0t1b	1t1b

Leading large-R jet

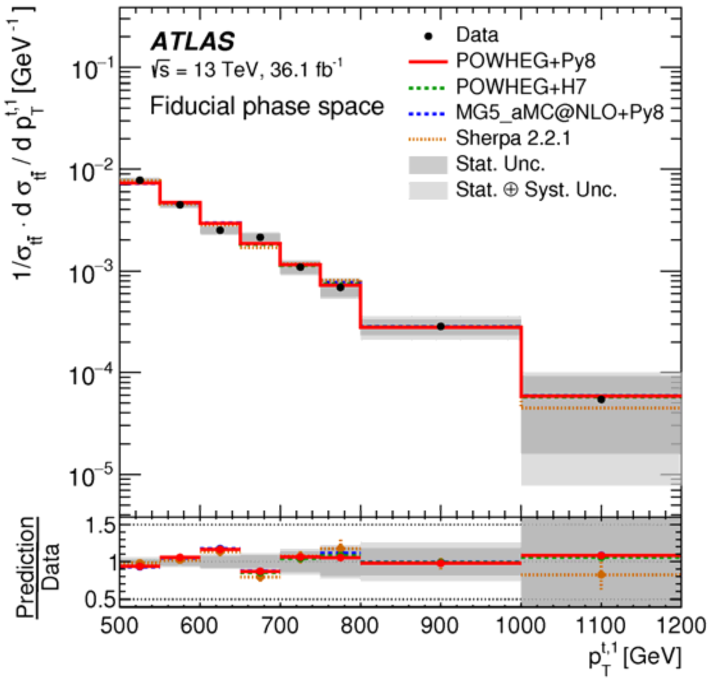
70% b-tagging WP

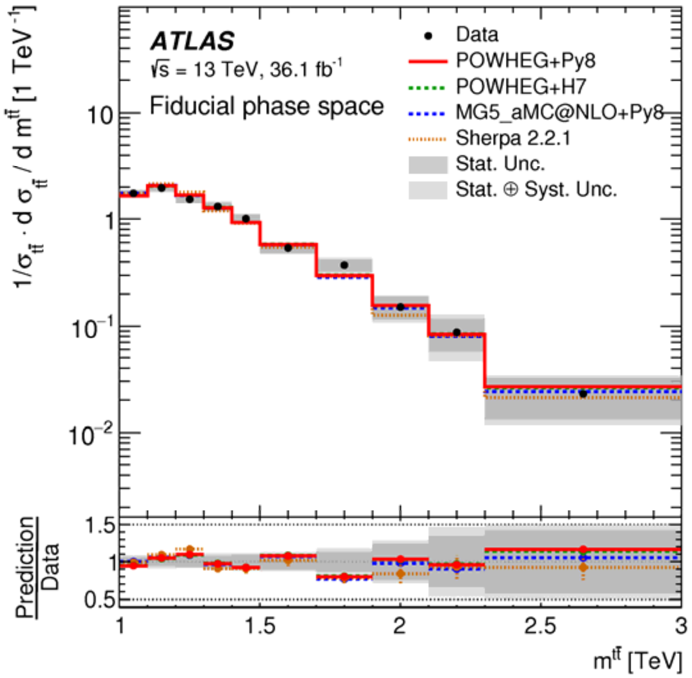


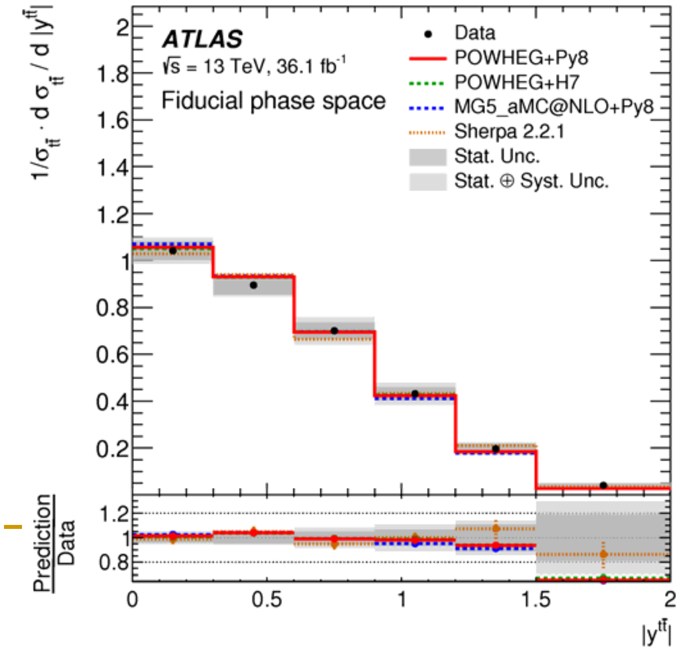
"1tNb" means that the large-R jet is top-tagged and has N b-jets – based on pT-dependent requirements on two variables: jet mass, measured from clusters in the calorimeter, and the N-subjettiness ratio τ_{32} (= τ_3/ τ_2) - Use 50% top-tagging WP



Unfolded →







Inclusive fiducial x-section:

σ_{fid} = 292 ± 7 ± 76 fb

Theory prediction:

384 ± 36 fb

Unfolding also done at parton level in fiducial phase space

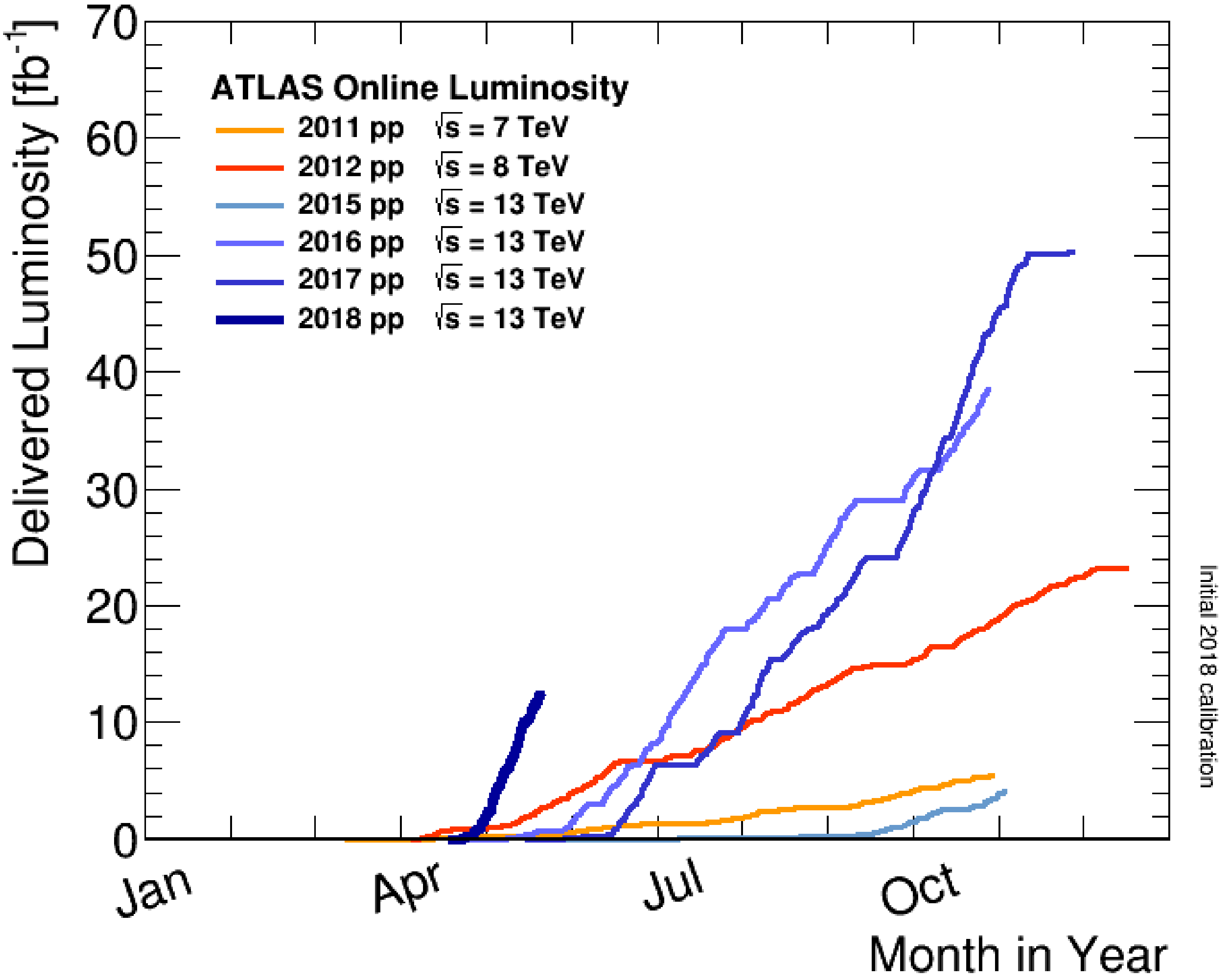
Conclusions

- LHC Run-1and Run-2 provide high statistics studies of top quark production characteristics
  - ❑ Probe high pT region via boosted topologies

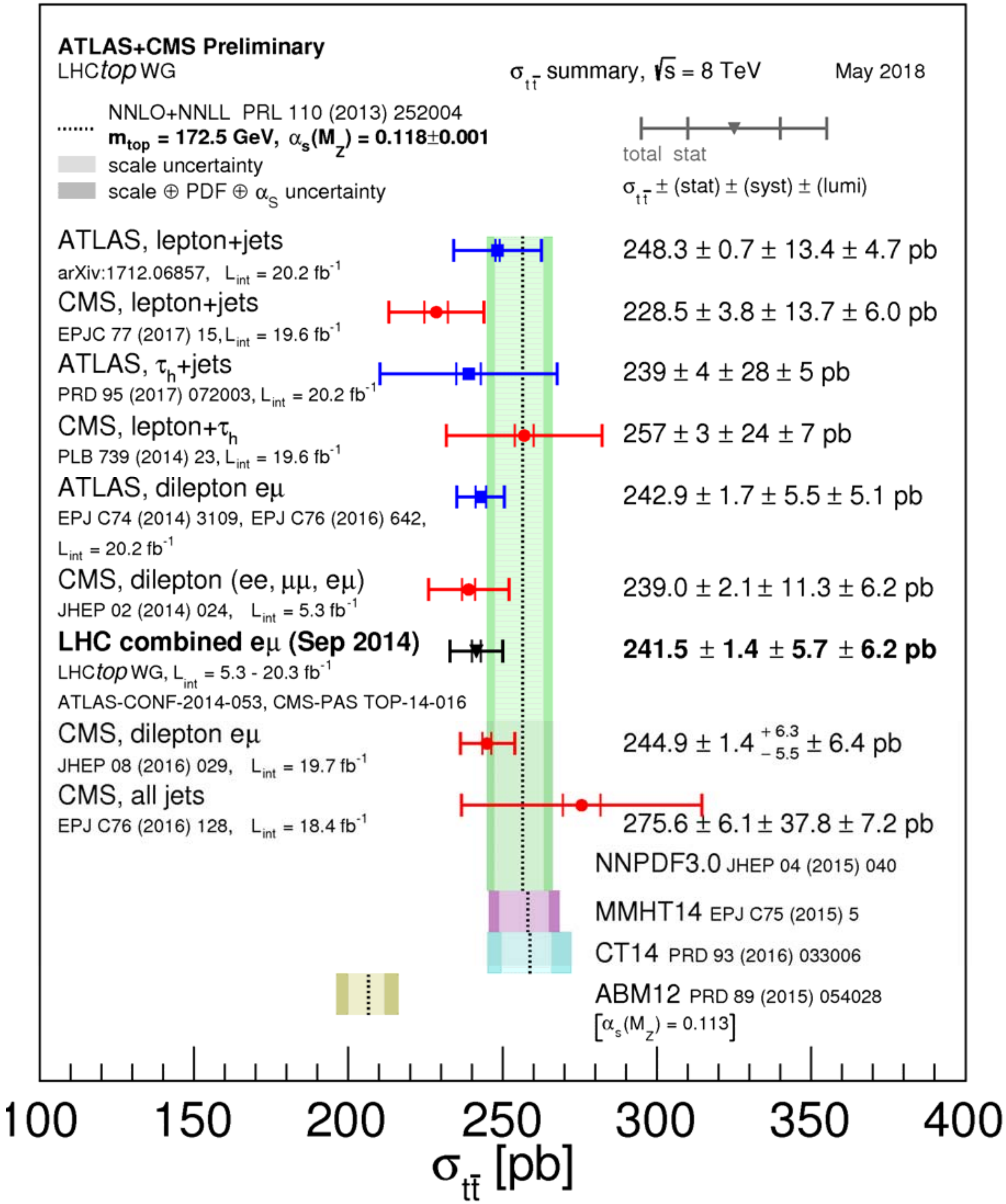
- Inclusive cross-sections in good agreement with theory, although some discrepancies in differential cross-sections

- Future promises to yield more interesting results
  - ❑ Data from 2017 and 2018 are being analyzed

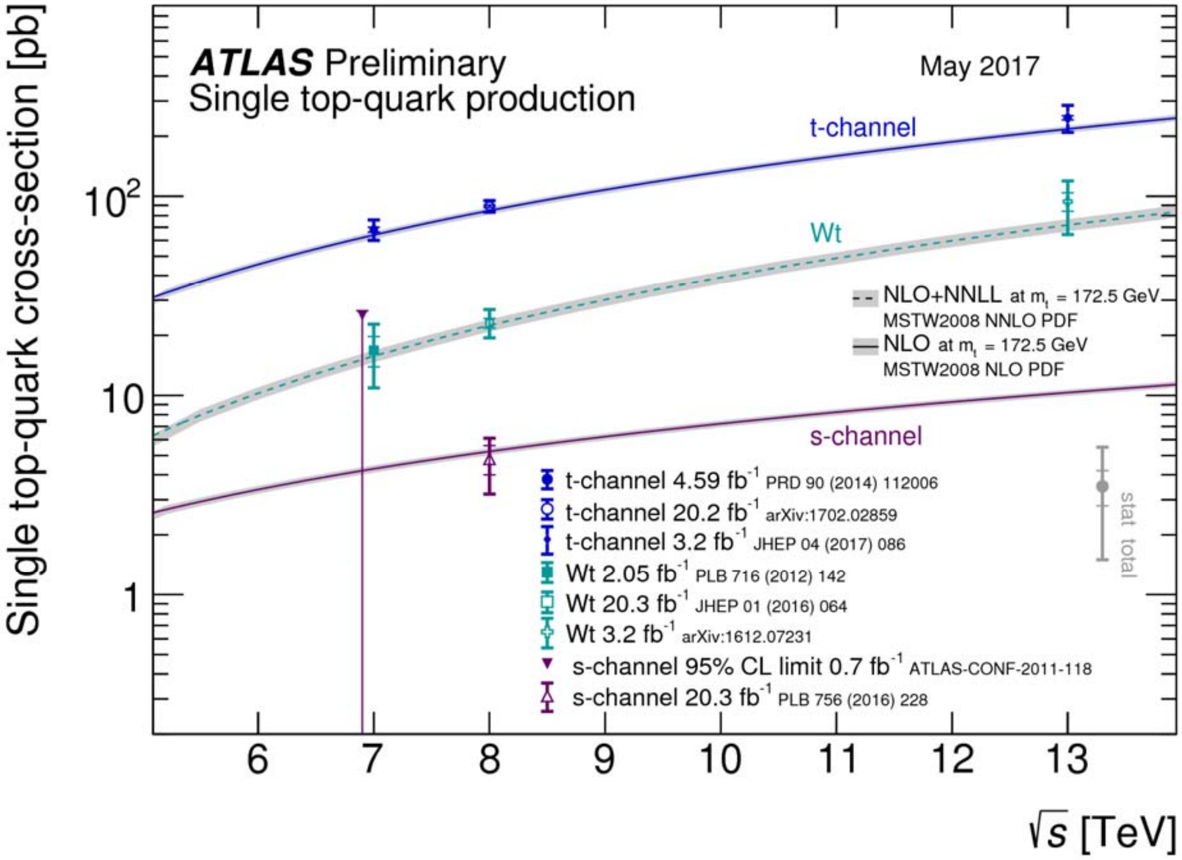
Extra slides

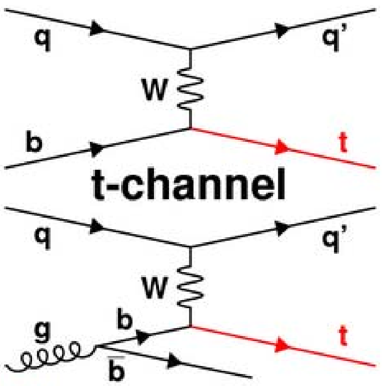


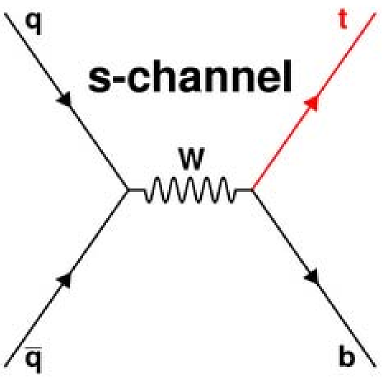
ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
Delivered Luminosity [fb^{-1}]
70
60
50
40
30
20
10
0
Jan
Apr
Jul
Oct
Month in Year
Initial 2018 calibration

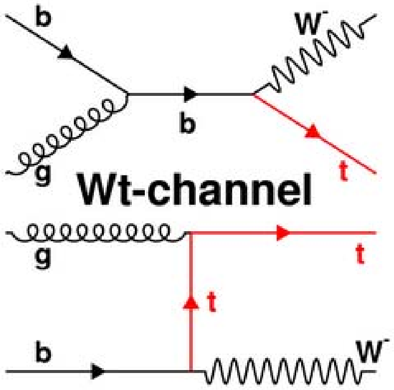

ATLAS+CMS Preliminary
LHCtopWG
σ_tt̄ summary, √s = 8 TeV
May 2018
NNLO+NNLL PRL 110 (2013) 252004
m_top = 172.5 GeV, α_s(M_Z) = 0.118±0.001
scale uncertainty
scale ⊕ PDF ⊕ α_S uncertainty
total stat
σ_tt̄ ± (stat) ± (syst) ± (lumi)
ATLAS, lepton+jets
arXiv:1712.06857, L_int = 20.2 fb^-1
248.3 ± 0.7 ± 13.4 ± 4.7 pb
CMS, lepton+jets
EPJC 77 (2017) 15, L_int = 19.6 fb^-1
228.5 ± 3.8 ± 13.7 ± 6.0 pb
ATLAS, τ_h+jets
PRD 95 (2017) 072003, L_int = 20.2 fb^-1
239 ± 4 ± 28 ± 5 pb
CMS, lepton+τ_h
PLB 739 (2014) 23, L_int = 19.6 fb^-1
257 ± 3 ± 24 ± 7 pb
ATLAS, dilepton eμ
EPJ C74 (2014) 3109, EPJ C76 (2016) 642,
L_int = 20.2 fb^-1
242.9 ± 1.7 ± 5.5 ± 5.1 pb
CMS, dilepton (ee, μμ, eμ)
JHEP 02 (2014) 024, L_int = 5.3 fb^-1
239.0 ± 2.1 ± 11.3 ± 6.2 pb
LHC combined eμ (Sep 2014)
LHCtopWG, L_int = 5.3 - 20.3 fb^-1
ATLAS-CONF-2014-053, CMS-PAS TOP-14-016
241.5 ± 1.4 ± 5.7 ± 6.2 pb
CMS, dilepton eμ
JHEP 08 (2016) 029, L_int = 19.7 fb^-1
244.9 ± 1.4 +6.3 −5.5 ± 6.4 pb
CMS, all jets
EPJ C76 (2016) 128, L_int = 18.4 fb^-1
275.6 ± 6.1 ± 37.8 ± 7.2 pb
NNPDF3.0 JHEP 04 (2015) 040
MMHT14 EPJ C75 (2015) 5
CT14 PRD 93 (2016) 033006
ABM12 PRD 89 (2015) 054028
[α_s(M_Z) = 0.113]
100
150
200
250
300
350
400
σ_tt̄ [pb]

Single top


ATLAS Preliminary
Single top-quark production
May 2017
t-channel
Wt
s-channel
NLO+NNLL at m_t = 172.5 GeV
MSTW2008 NNLO PDF
NLO at m_t = 172.5 GeV
MSTW2008 NLO PDF
t-channel 4.59 fb^{-1} PRD 90 (2014) 112006
t-channel 20.2 fb^{-1} arXiv:1702.02859
t-channel 3.2 fb^{-1} JHEP 04 (2017) 086
Wt 2.05 fb^{-1} PLB 716 (2012) 142
Wt 20.3 fb^{-1} JHEP 01 (2016) 064
Wt 3.2 fb^{-1} arXiv:1612.07231
s-channel 95% CL limit 0.7 fb^{-1} ATLAS-CONF-2011-118
s-channel 20.3 fb^{-1} PLB 756 (2016) 228
stat
total
Single top-quark cross-section [pb]
10^2
10
1
6
7
8
9
10
11
12
13
$\sqrt{s}$ [TeV]


q
q'
W
b
t
t-channel
q
q'
W
g
b
t
$\bar{b}$


q
t
s-channel
W
$\bar{q}$
b


b
W^-
b
g
t
Wt-channel
g
t
t
b
W^-

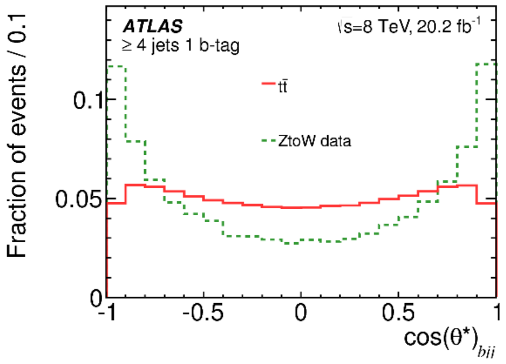
Cross-section measurements

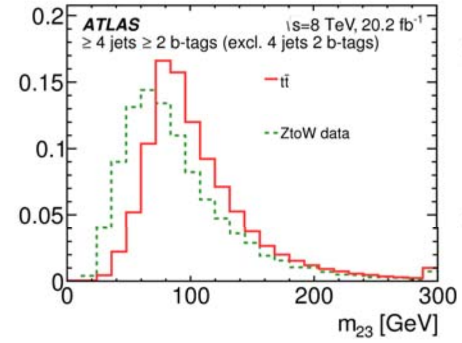
- Detector level - Select events satisfying event and object selection criteria
- Particle level - Jets constructed from stable particles, dressed leptons, etc.
- Parton level - Typically quarks in MC history (t, b) after QCD radiation but before Wb decay
- Unfolding - measured differential cross sections are obtained from the reconstruction-level distributions by correcting for detector and reconstruction effects.
  - ☐ Unfolding can be to particle or parton level
- Fiducial cross-section:
  - ☐ Extract # of observed events, after subtracting background - Correction due to selection efficiency
  - ☐ Pros: Less model dependence - Cons: Harder to compare to fixed order calculations
- Total cross-section:
  - ☐ Correct fiducial cross-section by fiducial acceptance and branching fractions
  - ☐ Pros: Easy interpretation – Cons: Significant model dependence
- Differential cross-sections can be either fiducial or total, absolute or normalized

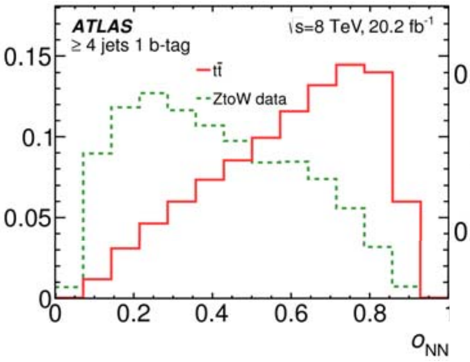
Inclusive & fiducial $t\bar{t}$ cross-sections in ℓ+jets Submitted to EPJC (arXiv 1712.06857)

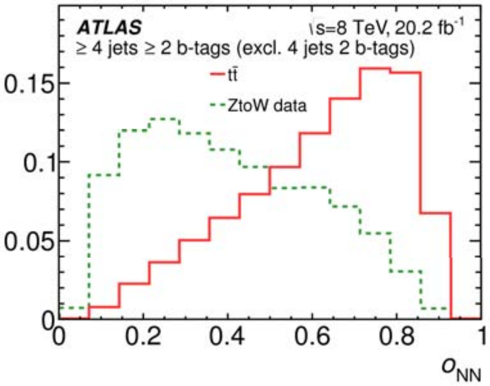
Variable	Definition
m_{12}	The smallest invariant mass between jet pairs.
$\cos(\theta^*)_{bjj}$	Cosine of the angle between the hadronic top-quark momentum and the beam direction in the $t\bar{t}$ rest frame.
$m(\ell\nu b)$	Mass of the reconstructed semileptonically decaying top quark.
A	Aplanarity.
$m(bjj)$	Mass of the reconstructed hadronically decaying top quark.
$m_{\ell 1}$	The smallest invariant mass between the charged lepton and a jet.
m_{23}	The second smallest invariant mass between jet pairs.

Inputs to NN

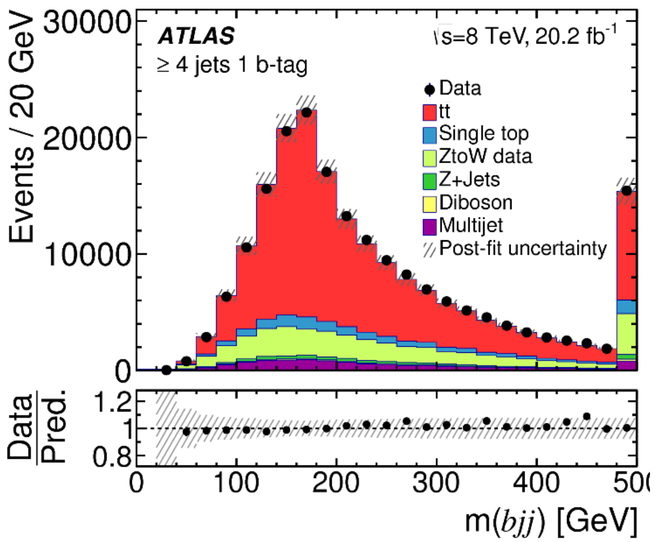




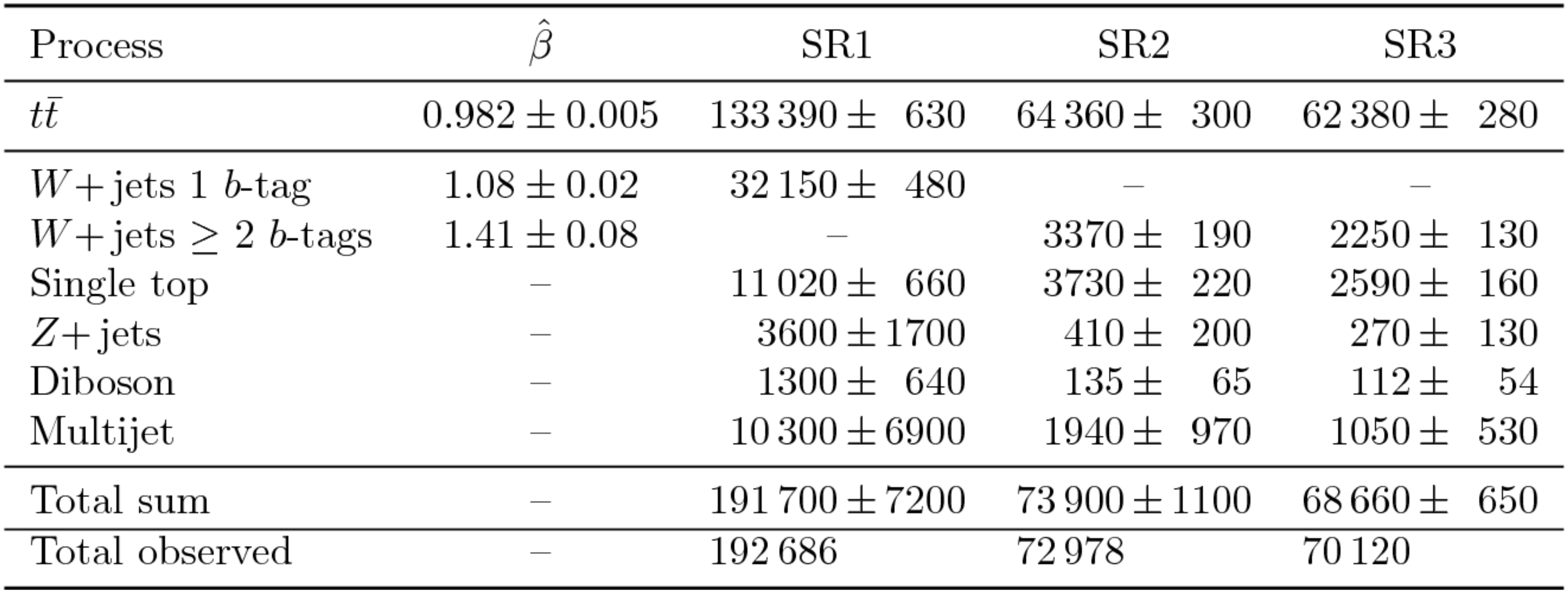




Source	$\frac{\Delta\sigma_{\rm inc}}{\sigma_{\rm inc}}$ [%]	$\frac{\Delta\sigma_{\rm fid}}{\sigma_{\rm fid}}$ [%]
Statistical uncertainty	0.3	0.3
Physics object modelling		
Jet energy scale	1.1	1.1
Jet energy resolution	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
$E_{\rm T}^{\rm miss}$ scale	0.1	0.1
$E_{\rm T}^{\rm miss}$ resolution	<0.1	<0.1
Muon momentum scale	<0.1	<0.1
Muon momentum resolution	<0.1	<0.1
Electron energy scale	0.1	0.1
Electron energy resolution	<0.1	<0.1
Lepton identification	1.4	1.4
Lepton reconstruction	0.3	0.3
Lepton trigger	1.3	1.3
b-tagging efficiency	0.3	0.3
c-tagging efficiency	0.5	0.5
Mistag rate	0.3	0.3
Signal Monte Carlo modelling and parton distribution functions		
NLO matching	1.1	0.9
Scale variations	2.2	1.0
Parton shower	1.3	0.9
PDF	3.0	0.1
Background normalisation for non-fitted backgrounds		
Single top	0.3	0.3
Z+jets	0.2	0.2
Diboson	0.1	0.1
Background modelling		
$Z$to$W$ modelling	1.1	1.1
Multijet	0.6	0.6
Luminosity	1.9	1.9
Total (syst.)	5.7	4.5
Total (syst.+stat.)	5.7	4.5



Fiducial acceptance ~ 20%



Process	$\hat{\beta}$	SR1	SR2	SR3
$t\bar{t}$	0.982 ± 0.005	$133\,390 \pm 630$	$64\,360 \pm 300$	$62\,380 \pm 280$
W+jets 1 b-tag	1.08 ± 0.02	$32\,150 \pm 480$	–	–
W+jets $\geq$ 2 b-tags	1.41 ± 0.08	–	3370 ± 190	2250 ± 130
Single top	–	$11\,020 \pm 660$	3730 ± 220	2590 ± 160
Z+jets	–	3600 ± 1700	410 ± 200	270 ± 130
Diboson	–	1300 ± 640	135 ± 65	112 ± 54
Multijet	–	$10\,300 \pm 6900$	1940 ± 970	1050 ± 530
Total sum	–	$191\,700 \pm 7200$	$73\,900 \pm 1100$	$68\,660 \pm 650$
Total observed	–	192 686	72 978	70 120

After performing a binned maximum-likelihood fit to the NN discriminant distributions and the $m(jj)$ distribution, and estimating the total uncertainty, the inclusive $t\bar{t}$ cross-section is measured to be:

$$\sigma_{\mathrm{inc}}(t\bar{t}) = 248.3 \pm 0.7\,(\mathrm{stat.}) \pm 13.4\,(\mathrm{syst.}) \pm 4.7\,(\mathrm{lumi.})\ \mathrm{pb}$$

assuming a top-quark mass of $m_{\mathrm{top}} = 172.5\ \mathrm{GeV}$.

The fiducial cross-section measured in the fiducial volume defined in Sect. 4.2 with acceptance $A_{\mathrm{fid}} = 19.6\%$ is:

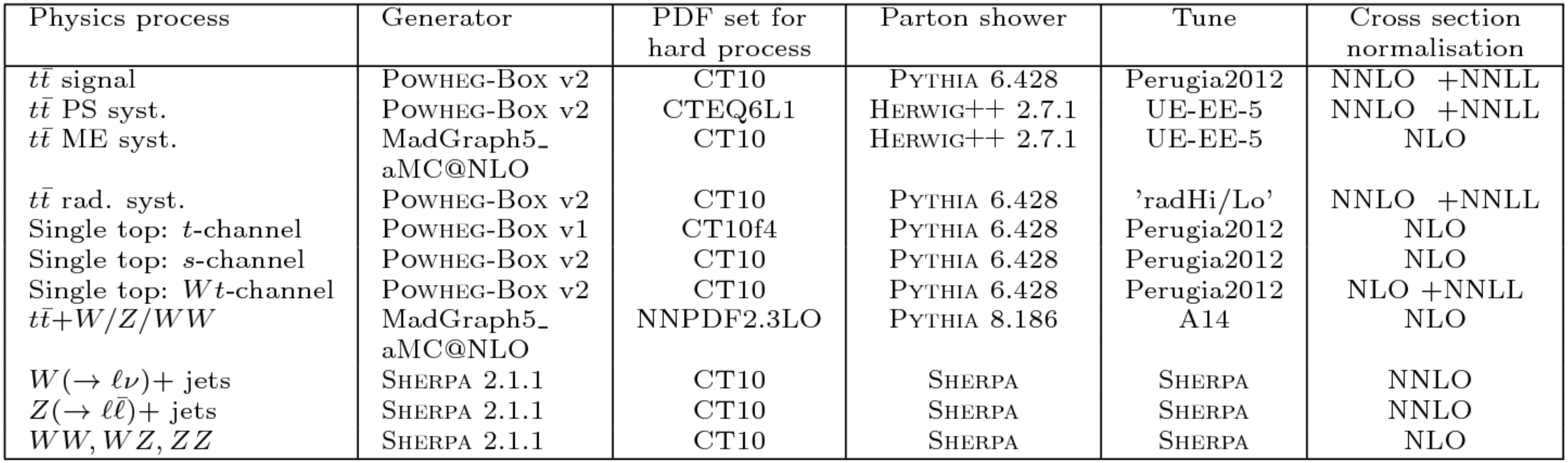
$$\sigma_{\mathrm{fid}}(t\bar{t}) = 48.8 \pm 0.1\,(\mathrm{stat.}) \pm 2.0\,(\mathrm{syst.}) \pm 0.9\,(\mathrm{lumi.})\ \mathrm{pb}.$$

The dependence of the inclusive $t\bar{t}$ cross-section measurement on the assumed value of m_{top} is mainly due to acceptance effects and can be expressed by the function:

$$\sigma_{t\bar{t}}(m_{\mathrm{top}}) = \sigma_{t\bar{t}}(172.5\ \mathrm{GeV}) + p_1 \cdot \Delta m_{\mathrm{top}} + p_2 \cdot \Delta m_{\mathrm{top}}^2\,,$$

with $\Delta m_{\mathrm{top}} = m_{\mathrm{top}} - 172.5\ \mathrm{GeV}$. The parameters $p_1 = -2.07 \pm 0.07\ \mathrm{pb/GeV}$ and $p_2 = 0.07 \pm 0.02\ \mathrm{pb/GeV}^2$ are determined using dedicated signal samples with different m_{top} values, where signal template distributions are obtained from the alternative samples and the fit to data is repeated.

Differential $t\bar{t}$ cross sections in association with jets - ℓ+jets – Submitted to JHEP (arXiv: 1802.06572)



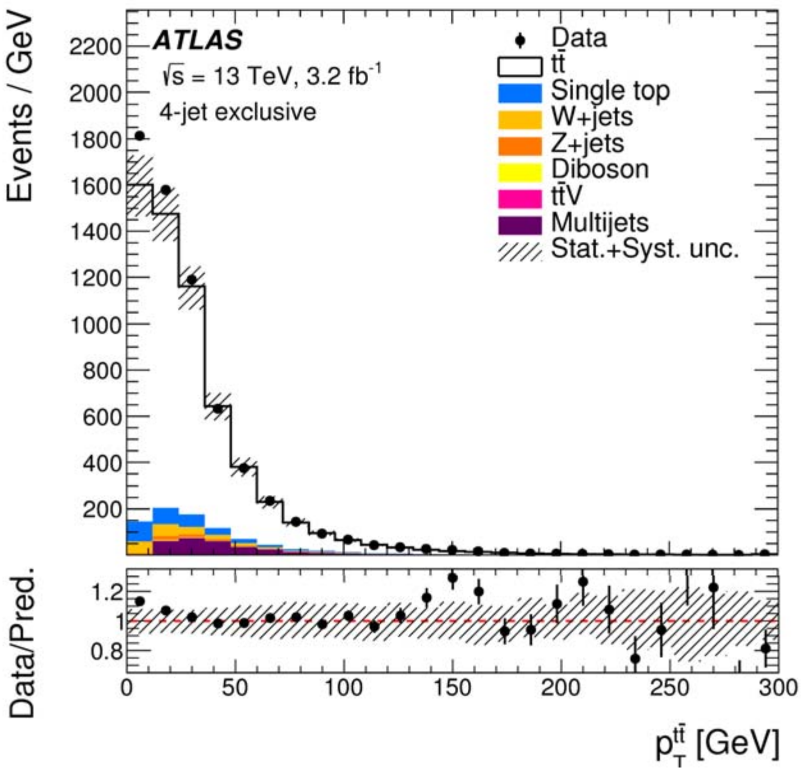
Physics process	Generator	PDF set for hard process	Parton shower	Tune	Cross section normalisation
$t\bar{t}$ signal	Powheg-Box v2	CT10	Pythia 6.428	Perugia2012	NNLO +NNLL
$t\bar{t}$ PS syst.	Powheg-Box v2	CTEQ6L1	Herwig++ 2.7.1	UE-EE-5	NNLO +NNLL
$t\bar{t}$ ME syst.	MadGraph5_aMC@NLO	CT10	Herwig++ 2.7.1	UE-EE-5	NLO
$t\bar{t}$ rad. syst.	Powheg-Box v2	CT10	Pythia 6.428	'radHi/Lo'	NNLO +NNLL
Single top: t-channel	Powheg-Box v1	CT10f4	Pythia 6.428	Perugia2012	NLO
Single top: s-channel	Powheg-Box v2	CT10	Pythia 6.428	Perugia2012	NLO
Single top: Wt-channel	Powheg-Box v2	CT10	Pythia 6.428	Perugia2012	NLO +NNLL
$t\bar{t}+W/Z/WW$	MadGraph5_aMC@NLO	NNPDF2.3LO	Pythia 8.186	A14	NLO
$W(\rightarrow \ell\nu)+$ jets	Sherpa 2.1.1	CT10	Sherpa	Sherpa	NNLO
$Z(\rightarrow \ell\bar{\ell})+$ jets	Sherpa 2.1.1	CT10	Sherpa	Sherpa	NNLO
WW, WZ, ZZ	Sherpa 2.1.1	CT10	Sherpa	Sherpa	NLO

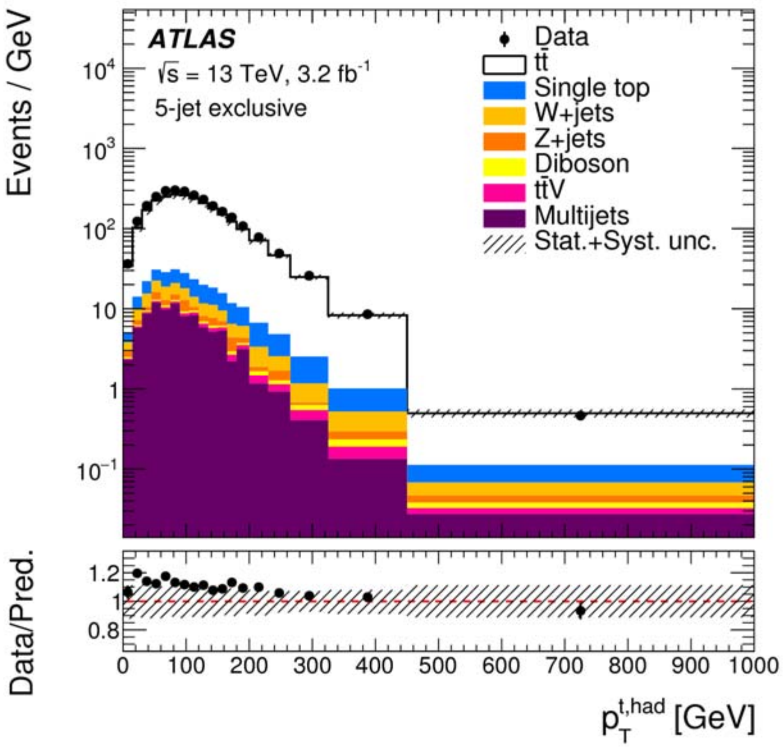
Unfolding procedure

The unfolding step uses a migration matrix ($\mathcal{M}$) derived from simulated $t\bar{t}$ events which maps the binned particle-level events to the binned reconstruction-level events. The probability for particle-level events to be reconstructed in the same bin is therefore represented by the elements on the diagonal, and the off-diagonal elements describe the fraction of particle-level events that migrate into other bins. Therefore, the elements of each row add up to unity (within rounding). The number of bins is optimised for maximum information extraction under stable unfolding conditions. This is achieved by requiring that closure and stress tests are satisfied without introducing any bias. The unfolding is performed using four iterations to balance the unfolding stability with respect to the previous iteration (below 0.1%) and the growth of the statistical uncertainty. The effect of varying the number of iterations by one was found to be negligible. Finally, the efficiency ϵ is defined as the ratio of the number of matched events to the number of events passing the particle-level selection. This factor corrects for the inefficiency of the reconstruction.

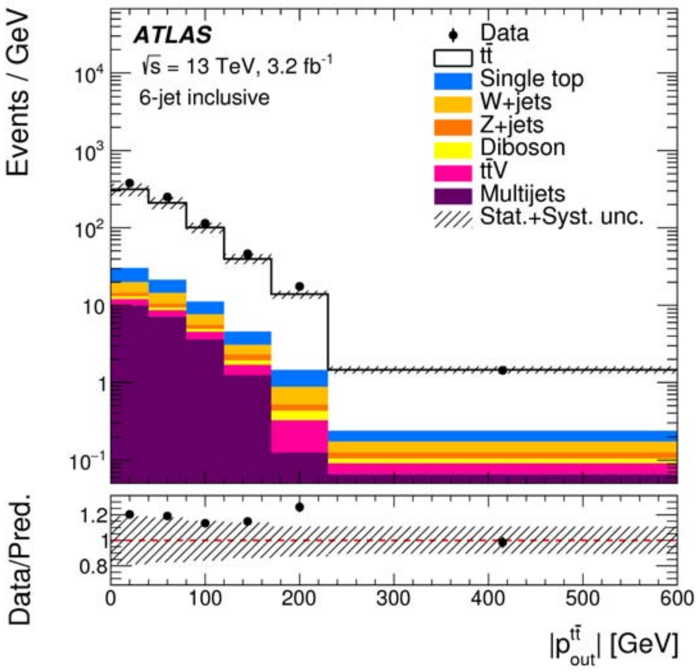
The unfolding procedure for an observable X at particle level is summarised by the following expression for the absolute differential cross section:

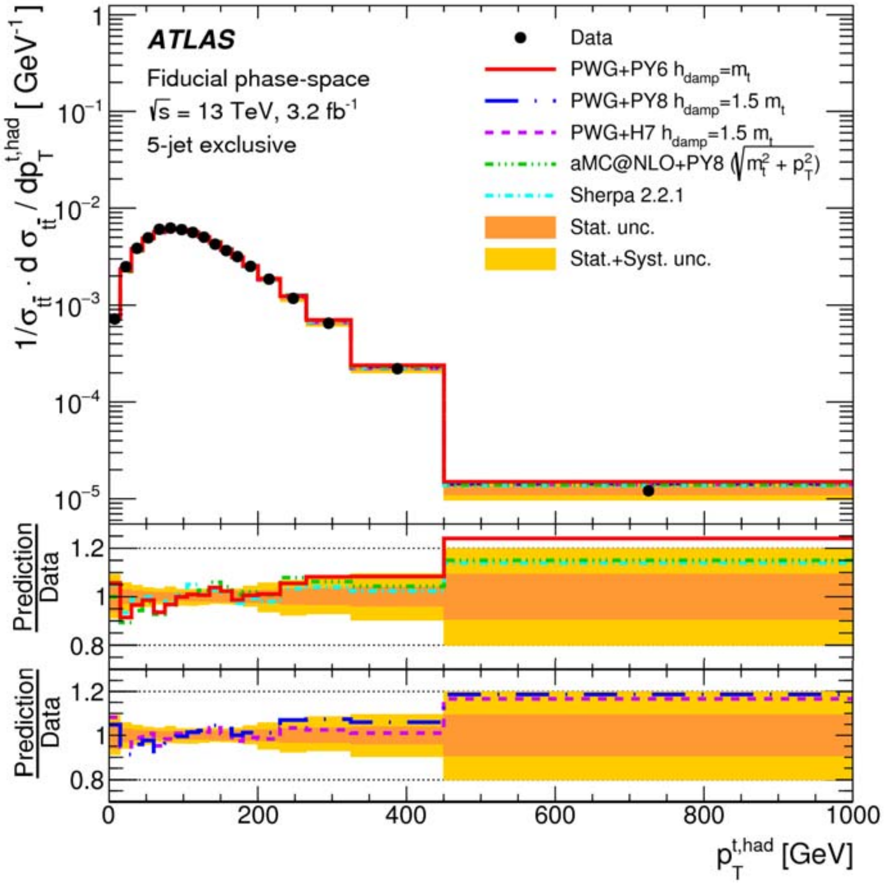
$$\frac{\mathrm{d}\sigma^{\mathrm{fid}}}{\mathrm{d}X^i} \equiv \frac{1}{\mathcal{L}\cdot\Delta X^i}\cdot\frac{1}{\epsilon^i}\cdot\sum_j \mathcal{M}_{ij}^{-1}\cdot f_{\mathrm{match}}^j\cdot f_{\mathrm{acc}}^j\cdot\left(N_{\mathrm{reco}}^j - N_{\mathrm{bg}}^j\right),$$

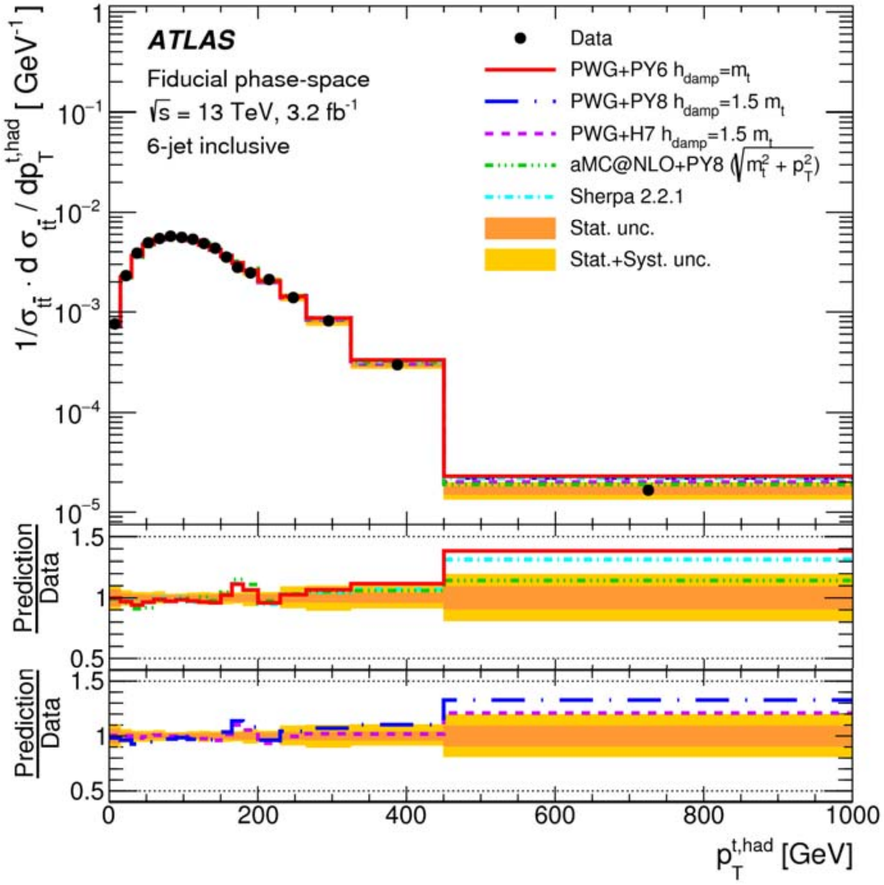




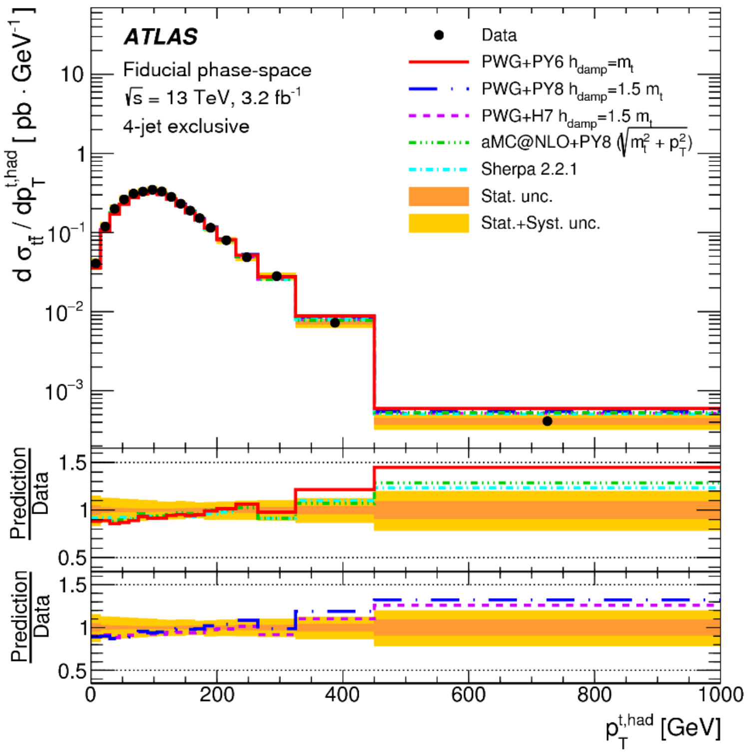
Kinematics quantities of interest, for various jet configurations

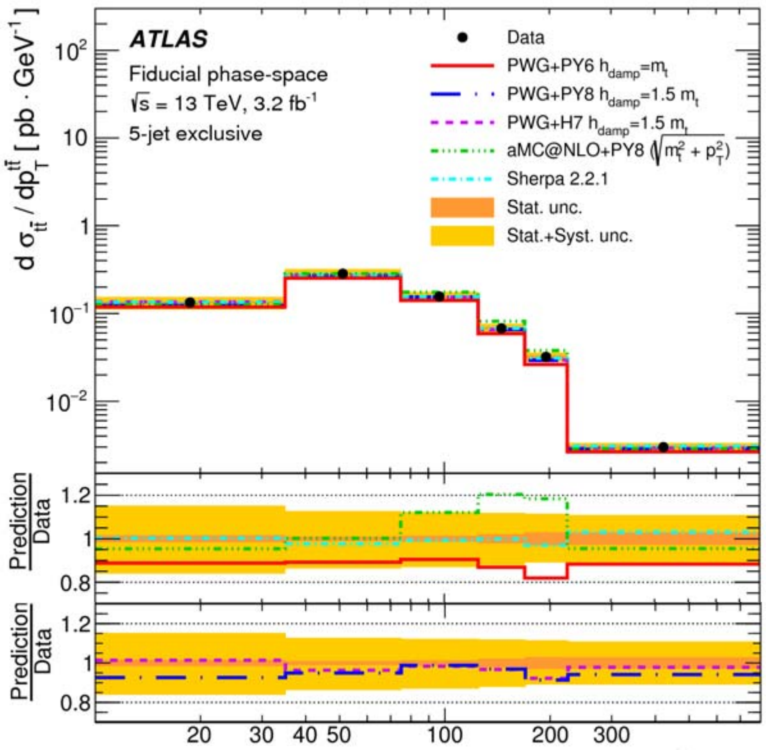


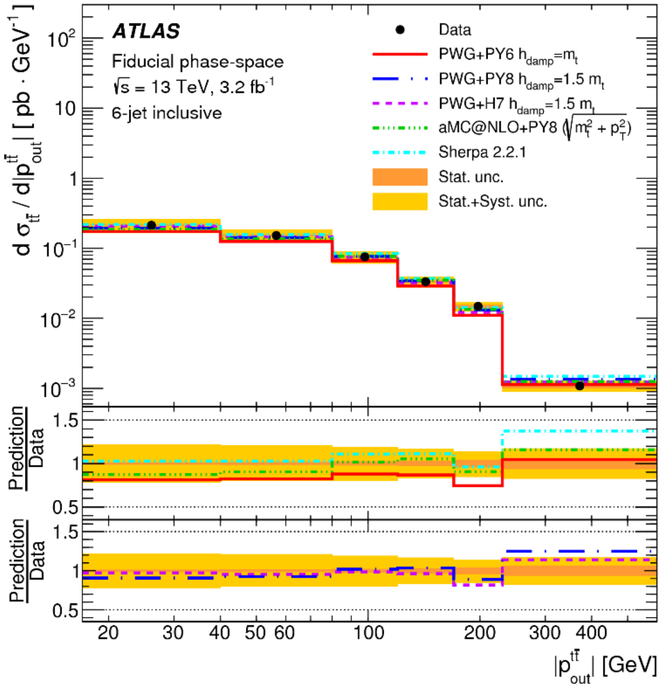




Flatter than in 4-jet exclusive



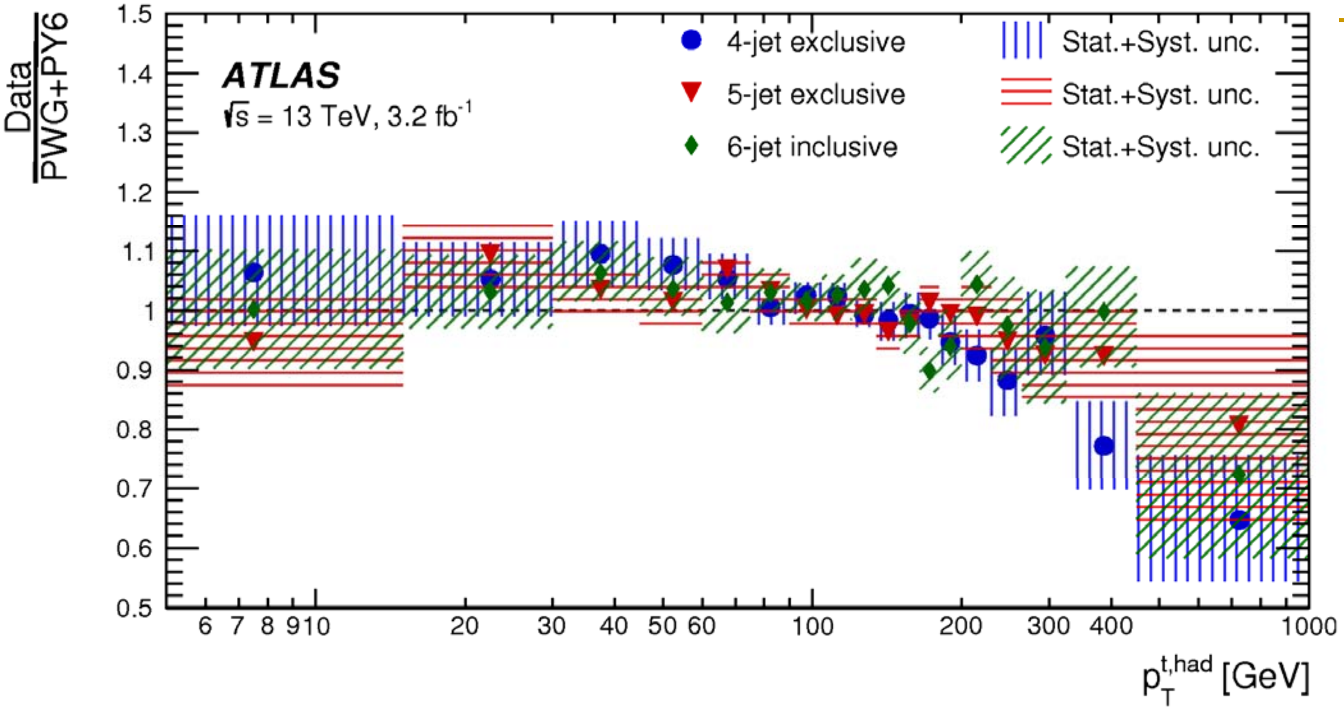


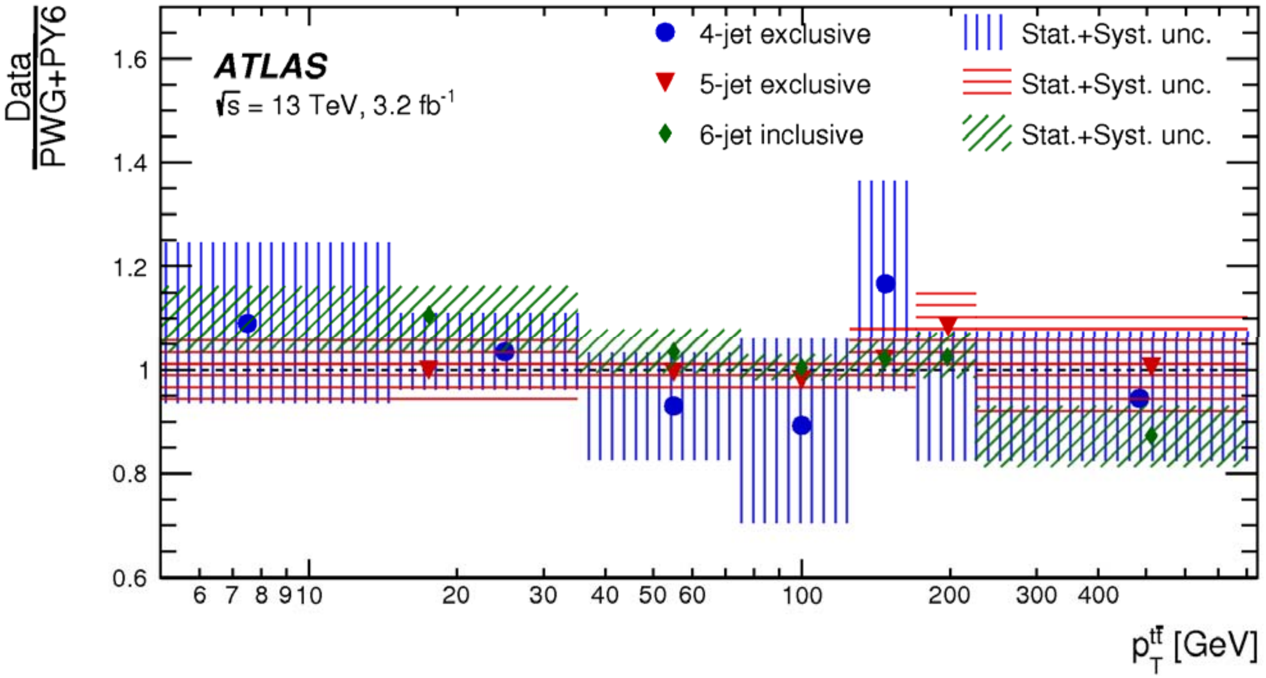


Absolute cross-sections

	4-jet exclusive		5-jet exclusive		6-jet inclusive	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Powheg+Pythia6	23.4/17	0.14	14.1/17	0.66	14.8/17	0.61
Powheg+Pythia6 (radHi)	23.4/17	0.14	14.9/17	0.60	15.9/17	0.53
Powheg+Pythia6 (radLo)	25.6/17	0.08	16.5/17	0.49	16.5/17	0.49
Powheg+Pythia8 ($h_{\mathrm{damp}} = m_t$)	22.7/17	0.16	16.9/17	0.46	18.3/17	0.37
Powheg+Pythia8 ($h_{\mathrm{damp}} = 1.5\,m_t$)	20.4/17	0.25	15.6/17	0.56	18.8/17	0.34
Powheg+Pythia8 (radHi) ($h_{\mathrm{damp}} = 3\,m_t$)	17.8/17	0.40	16.3/17	0.50	19.3/17	0.31
Powheg+Pythia8 (radLo) ($h_{\mathrm{damp}} = 1.5\,m_t$)	21.1/17	0.22	17.8/17	0.40	17.5/17	0.42
Powheg+Herwig7	16.6/17	0.48	12.1/17	0.80	12.8/17	0.75
Powheg+Herwig++	19.1/17	0.33	20.7/17	0.24	28.1/17	0.04
MadGraph5_aMC@NLO+Herwig++	16.3/17	0.50	11.5/17	0.83	23.9/17	0.12
MadGraph5_aMC@NLO+Pythia8 ($H_{\mathrm{T}}/2$)	20.3/17	0.26	21.9/17	0.19	22.5/17	0.17
MadGraph5_aMC@NLO+Pythia8 ($\sqrt{m_t^2 + p_{\mathrm{T}}^2}$)	20.7/17	0.24	18.1/17	0.38	28.5/17	0.04
Sherpa 2.2.1	21.8/17	0.19	20.0/17	0.28	17.5/17	0.42

Comparison of the measured fiducial phase space normalised differential cross sections as a function of $p_T^{t,had}$ and the predictions from several MC generators in different n-jet configurations. For each prediction a χ^2 and a p-value are calculated using the covariance matrix of the measured spectrum. The number of degrees of freedom (NDF) is equal to the number of bins in the distribution minus one.

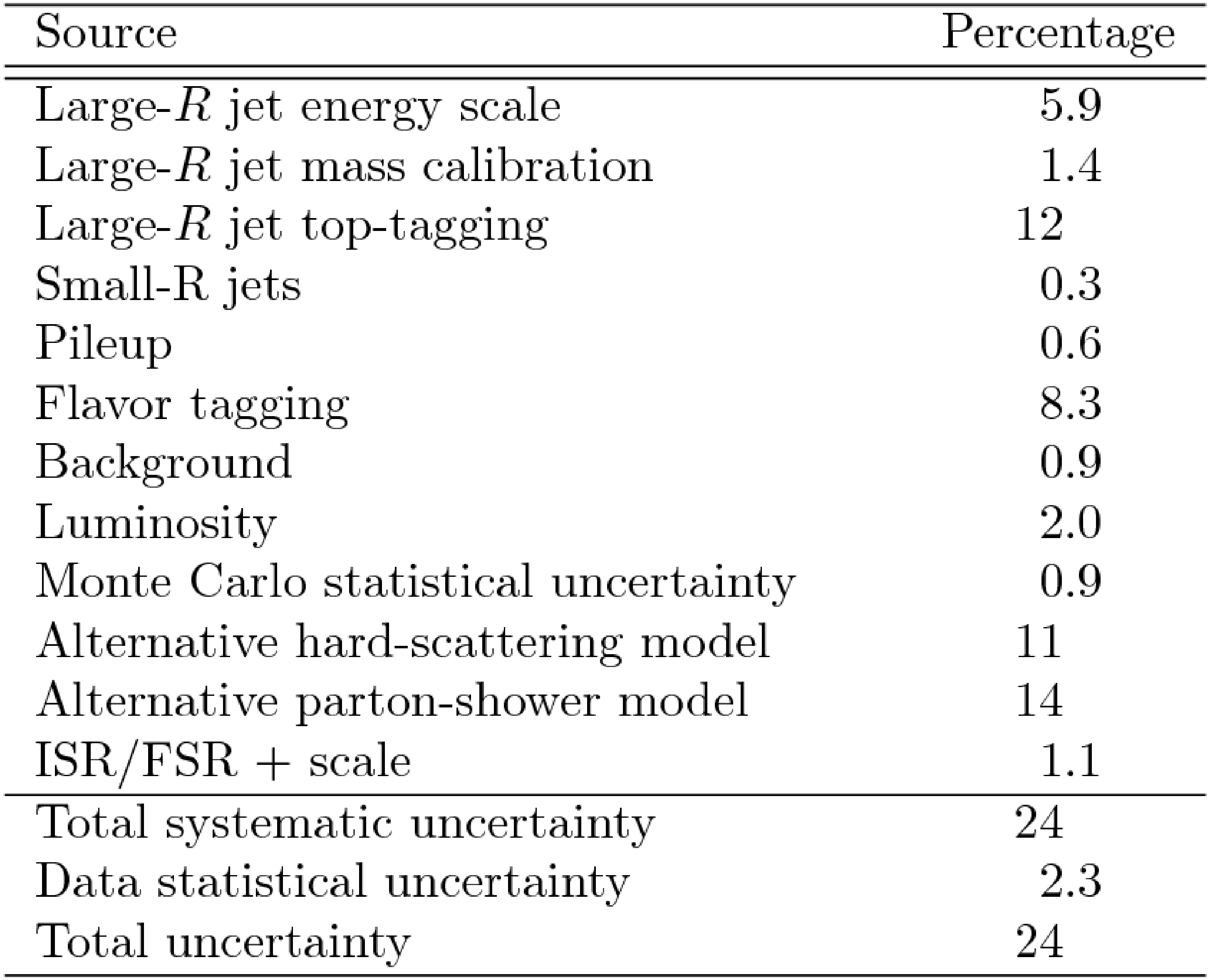




Comparison of all
Jet configurations with
PowHeg + Pythia6

Differential $t\bar{t}$ cross-sections of boosted top quarks in all-hadronic final states - Submitted to PRD (arXiv: 1801.02052)

- Dataset: $\mathcal{L} \sim 36.1\ \mathrm{fb}^{-1}$ @ 13 TeV
- Events contain two large-R jets, with pT > 500 and 350 GeV
  - Boosted regime ⟶ $t\bar{t}$ production in TeV scale range - many theory uncertainties
- Use rapidity variables (in lab and CM frame) to study production
  - $y^* = (y^{t,1} - y^{t,2})/2$, $-y^*$, $\chi^{tt} = e^{2|y^*|}$ (non-SM processes tend to peak at low χ^{tt})
    - y^* is in the $t\bar{t}$ CM frame, whereas $y^{t,1(2)}$ are in the lab frame
  - $y^{tt}_B = (y^{t,1} + y^{t,2})/2$ measures the longitudinal movement in the lab frame and is sensitive to PDFs
- Other variables include mass, p_T, H_T, rapidity, $\Delta\varphi$, p_{out} of the $t\bar{t}$ system, and $\cos\theta^*$ (in the Collins-Soper frame)



Source	Percentage
Large-R jet energy scale	5.9
Large-R jet mass calibration	1.4
Large-R jet top-tagging	12
Small-R jets	0.3
Pileup	0.6
Flavor tagging	8.3
Background	0.9
Luminosity	2.0
Monte Carlo statistical uncertainty	0.9
Alternative hard-scattering model	11
Alternative parton-shower model	14
ISR/FSR + scale	1.1
Total systematic uncertainty	24
Data statistical uncertainty	2.3
Total uncertainty	24