Top quark precision measurements with the ATLAS experiment at the LHC

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Introduction

- The top quark is the heaviest known fundamental particle and with a large coupling to the SM Higgs boson and is predicted to have large couplings to hypothetical new particles
- The top quark has a very short lifetime, and is the only quark that decay before forming hadronic bound states
- Measurable top properties like mass, width and couplings are crucial inputs to the SM
- Understanding top production is crucial for many searches for rare SM processes and physics beyond the SM
- The LHC is a Top factory, Run 2 has produced over 10^8 top quarks

Results presented

Measurement of the $t\bar{t}$ production cross section at $\sqrt{s} = 5.02\,\mathrm{TeV}$ using di-leptonic events on $257\,\mathrm{pb}^{-1}$

ATLAS-CONF-2021-003

Measurement of the $t\bar{t}$ production cross section at $\sqrt{s} = 13\,\mathrm{TeV}$ in the lepton+jets channel on $139\,\mathrm{fb}^{-1}$

Phys. Lett. B 810 (2020) 135797,arXiv:2006.13076

Top quark mass measurement using soft muon tags in the $t\bar{t} \rightarrow$ lepton+jets channel with semileptonic decays at $\sqrt{s} = 13\,\mathrm{TeV}$ on $36.1\,\mathrm{fb}^{-1}$

ATLAS-CONF-2019-046

Test of the lepton universality of τ and μ couplings using di-leptonic $t\bar{t}$ events at $\sqrt{s} = 13\,\mathrm{TeV}$ on $139\,\mathrm{fb}^{-1}$

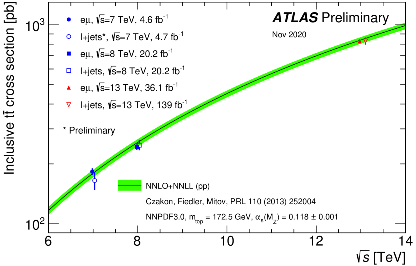
Accepted by Nature Physics, arXiv:2007.14040

$t\bar{t}$ production cross section: Introduction

Top quarks at the LHC are primarily produced in quark-antiquark pairs and form an important background in many searches for physics beyond the SM

Predictions for the inclusive $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ available at NNLO including NNLL are in excellent agreement with measurements from ATLAS and CMS at $\sqrt{s} = 7, 8$ and $13\,\mathrm{TeV}$

For $t\bar{t}$ production, the lower $\sqrt{s}$ value of $5.02\,\mathrm{TeV}$ increases the fraction of $q\bar{q}$ initiated events to about 25% compared to 11% at $\sqrt{s}$=$13\,\mathrm{TeV}$



ATL-PHYS-PUB-2020-029

Complementary to the larger samples at $7, 8$ and $13\,\mathrm{TeV}$, potential for additional constraints on PDFs

Analysis strategy

The $t\bar{t}$ production cross section is extracted from a fit of the number of dilepton events with one or two b-tagged jets

Data and nominal $t\bar{t}$ sample

2017 data (5.02 TeV, 257 pb^{-1})
PowhegBox NLO + Pythia8, NNPDF3.0NLO

Event selection $t\bar{t} \to W^+ bW^- \bar{b} \to ll'\nu\bar{\nu}b\bar{b}$

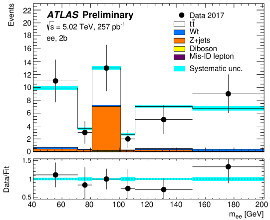
e-μ, e-e and μ-μ channels, oppositely charged leptons
1 or 2 b-tagged jets (DL1r, 85%)

Tagging equations

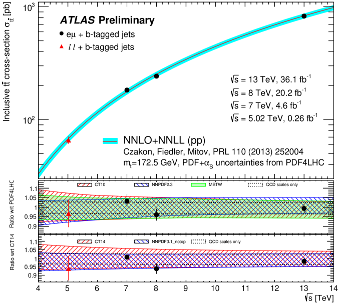
Relate the number of events with one (N_1) and two (N_2) b-tagged jets with $\sigma_{t\bar{t}}$, the combined acceptance and b-tagging efficiencies (ϵ_b^{ll}) and normalization of the Z+jet background (R_1^Z, R_2^Z)

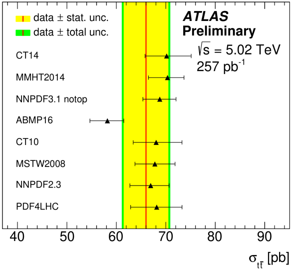
Maximum likelihood fit

Poisson likelihood, comparing N_1 and N_2 for each channel and each dilepton mass bin to the prediction
Free parameters $\sigma_{t\bar{t}}$, ϵ_b^{ll}, R_1^Z, R_2^Z
Systematic uncertainties are evaluated by repeating the fit with changed inputs



Uncertainty	σ (%)
Data statistics	6.8
generator	1.2
hadronisation	0.2
Initial/final state radiation	1.0
heavy-flavour production	0.2
Parton distribution functions	0.3
Electron energy scale	0.1
Electron energy resolution	0.1
Electron identification	0.6
Electron charge misidentification	0.0
Electron isolation	0.5
Muon momentum scale	0.1
Muon momentum resolution	0.0
Muon identification	0.3
Muon isolation	0.6
Lepton trigger	0.2
Jet energy scale	0.1
Jet energy scale extrapolation	0.0
Jet energy resolution	0.1
Pileup jet veto	0.0
b-tagging efficiency	0.1
b-tag mistagging	0.1
E_T^{miss} soft particle modelling	0.1
Single-top cross-section	1.0
Single-top/ interference	0.2
Single-top modelling	0.4
Z+jets extrapolation	0.7
Diboson cross-sections	0.3
Misidentified leptons	0.7
Simulation statistics	0.2
Integrated luminosity	1.8
Beam energy	0.3
Total uncertainty	7.5





$\sigma_{t\bar{t}} = 66.0 \pm 4.5(\text{stat.}) \pm 1.6(\text{syst.}) \pm 1.2(\text{lumi}) \pm 0.2(\text{beam})\,\text{pb}$ ($\pm 7.5\%$)

Compatible with the NNLO+NNLL QCD prediction of $\sigma_{t\bar{t}} = 68.2^{+5.2}_{-5.3}\,\text{pb}$

Compatible with all the PDF sets considered

Products of jet acceptance and b-tagging efficiencies are compatible with each other and the prediction

Consistent scale factors for the Z+jets background compatible with unity

Analysis strategy

The $t\bar{t}$ production cross section is extracted from a fit of A, m_{lj}^{min} and $\Delta R_{bjj}^{\text{avg}}$ in the lepton+jets channel

Data and nominal $t\bar{t}$ sample

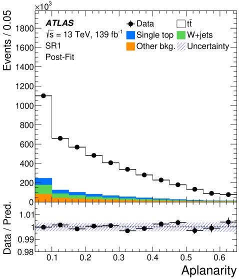
2015-2018 data ($13\,\text{TeV}, 139\,\text{fb}^{-1}$)
PowhegBox NLO+Pythia8, NNPDF3.0NLO

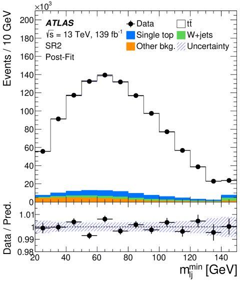
Event selection

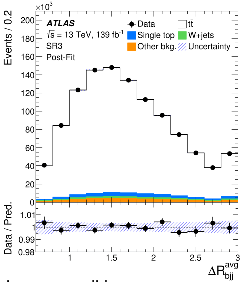
$==$ 1 electron or muon
≥ 4 jets (anti-kt $R = 0.4$)
$1, 2$ b-jets (MV2c10 at 60%, ghost matching)
SR 1/2/3: $\geq 4/4/\geq 5$ jets, 1/2/2 b-jets

Profile likelihood fit

SR1: A, SR2: m_{lj}^{min}, SR3: $\Delta R_{bjj}^{\text{avg}}$
Systematic uncertainties as NPs





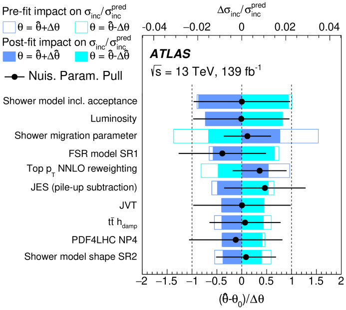


Aplanarity $A = \frac{3}{2}\lambda_3$, λ_3: smallest eigenvalue of $S^{\alpha\beta} = \sum_i p_i^\alpha p_i^\beta / \sum_i |p_i|^2$
m_{lj}^{min}: minimum mass over all lepton-jet pairs
ΔR_{bjj}^{avg}: avg. angular distance between the constituents from a hadronically decaying top candidate

$$\sigma_{\text{fid}} = 110.7 \pm 0.05(\text{stat.})^{+4.5}_{-4.3}(\text{syst.}) \pm 1.9(\text{lumi})\,\text{pb} = 110.7 \pm 4.8\,\text{pb}\ (\pm 4.3\%)$$

$$\sigma_{inc} = 830 \pm 0.4(\text{stat.}) \pm 36(\text{syst.}) \pm 14(\text{lumi})\,\text{pb} = 830 \pm 38\,\text{pb}\ (\pm 4.6\%)$$

In agreement with the theoretical NNLO+NNLL prediction of $\sigma_{t\bar{t}} = 832^{+20}_{-29}(\text{scale}) \pm 35(\text{PDF} + \alpha_S)$

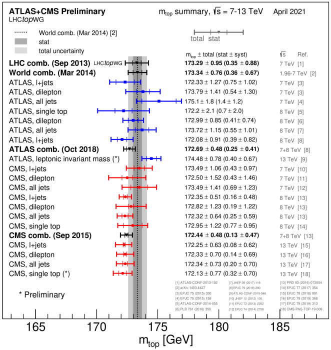


Largest uncertainties from shower/hadronization modeling and scale variations

Integrated luminosity is the highest ranked experimental uncertainty

- Large top mass plays a role in much of the dynamics of elementary particles via loop diagrams
- Top mass affects very significantly the radiative corrections to the Higgs boson and W boson, establishing a relationship that can be used for precision tests of consistency of the SM
- Precise measurement of the top quark mass is required to predict the evolution of the Higgs quartic coupling at high scales

- Direct reconstruction from its decay products and indirect measurements from top quark production cross sections or kinematic distributions
- Partial, leptonic-only, invariant mass reconstruction with less sensitivity to jet energy calibration/resolution and top production modeling compared to standard direct reconstruction methods



ATL-PHYS-PUB-2021-015

Analysis strategy

The MC mass is extracted from a fit to the $m_{l\mu}$ distributions in a $t\bar{t}$ enriched region

Data and nominal $t\bar{t}$ sample

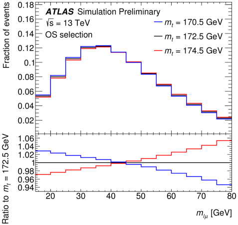
2015-2016 data ($13\,\mathrm{TeV}$, $36.1\,\mathrm{fb}^{-1}$)
Pohweg-Box NLO+Pythia8, NNPDF3.0

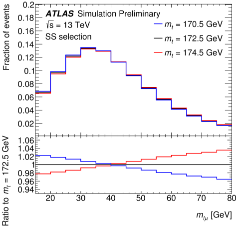
Event selection

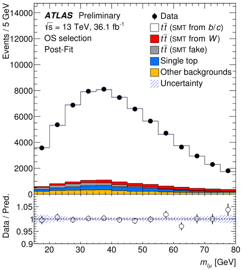
Lepton-jets channel
$==1$ lepton with $p_T > 27\,\mathrm{GeV}$
≥ 4 jets with $p_T > 30\,\mathrm{GeV}$
≥ 1 SMT-tagged jet
SMT muon: tight with $p_T > 8\,\mathrm{GeV}$ and $\Delta R_{\mu,\mathrm{jet}} < 0.4$

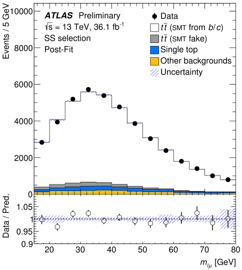
Profile likelihood fit

Poisson likelihood with Gaussian NPs for systematics
Binned templates for various top quark masses $\in$,$[165.0, 180.0]\,\mathrm{GeV}$









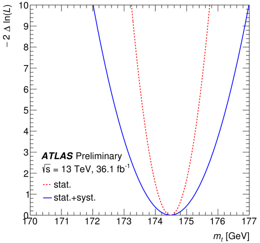
Top quark mass: Results ATLAS-CONF-2019-046

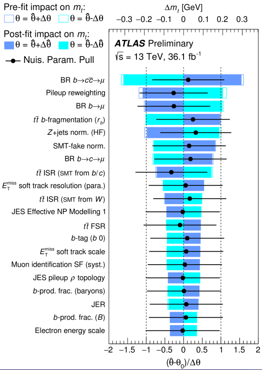
$m_t = 174.48 \pm 0.40(\text{stat}) \pm 0.67(\text{syst})\,\text{GeV}$

$m_t = 174.48 \pm 0.78\,\text{GeV}\ (\pm 0.45\%)$

Most precise single measurement

Consistent at the level of 2.2σ with the current ATLAS combination of $m_t = 172.69 \pm 0.48\,\text{GeV}$





Main sources of systematic uncertainties

- b-fragmentation and decay
- Pileup and backgrounds
- $t\bar{t}$ modeling

Lepton universality: Introduction arXiv:2007.14040

Lepton-flavor universality states that the couplings of the electroweak gauge bosons (W,Z) to charged leptons, g_l ($l = e, \mu, \tau$) are independent of the mass of the leptons

This assumption is tested by measuring the ratio of the fraction of on-shell W boson decays, branching ratios (B), to τ-leptons and muons, $R(\tau/\mu) = B(W \to \tau\nu_\tau)/B(W \to \mu\nu_\mu)$

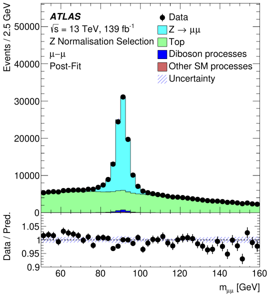
Given the large $B(t \to Wq)$, close to 100%, $t\bar{t}$ production gives a very large sample of W boson pairs

The displacement of the τ decay vertex and the muon transverse momentum (p_T) spectra are used to distinguish between muons from the $W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$ and $W \to \mu\nu_\mu$ processes

$R(\tau/\mu)$ has been measured by four experiments at LEP, yielding a combined value of 1.070 ± 0.026, which deviates from the SM expectation by 2.7σ

The equivalent ratio for the two light generations, $R(\mu/e)$, has been found to be consistent with the SM prediction at the 1% level at LEP, LHCb and ATLAS

Lepton universality: Measurement arXiv:2007.14040



Analysis strategy

$R(\tau/\mu)$ is extracted from a fit of the p_T^μ and d_0^μ distributions of the probe μ in di-leptonic $t\bar{t}$ events

Data and nominal $t\bar{t}$ sample

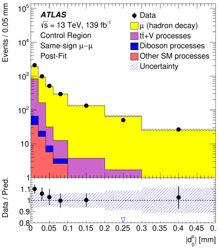
2015-2018 data ($13\,\mathrm{TeV}, 139\,\mathrm{fb}^{-1}$)
PowhegBox NLO + Pythia8, NNPDF3.0NLO
NNLO reweighting on top quark p_T

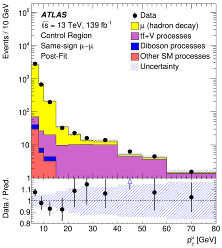
Event selection

e-μ or μ-μ with oppositely charged leptons
Tag e or μ with $p_T > 27\,\mathrm{GeV}$
Probe μ with $p_T > 5\,\mathrm{GeV}$
≥ 2 b-tagged jets (MV2c10, 70% WP)
μ-μ-channel: $m_{\mu\mu} \notin [85, 95]\,\mathrm{GeV}$

Profile likelihood fit

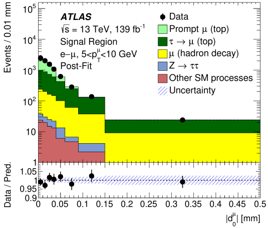
$R(\tau/\mu) = \mu_{\tau\to\mu}/\mu_{(\mathrm{prompt})}$, $k(t\bar{t})$
NPs for systematic uncertainties
48 bins of the probe muons (3 p_T^μ, 8 $|d_0^\mu|$)
6 signal regions (2 channels, 3 p_T^μ regions)
2 control regions for $Z \to \mu\mu$ w/o $m_{\mu\mu}$ criterion and $\mu_{(\mathrm{had})}$ with same-sign leptons

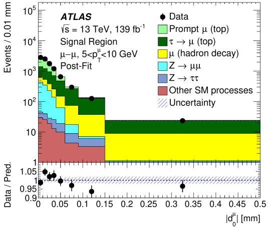




Lepton universality: Results

arXiv:2007.14040





Source	Impact on $R(\tau/\mu)$
Prompt d_0^μ templates	0.0038
$\mu_{(prompt)}$ and $\mu_{(\tau\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
$\mu_{(had.)}$ normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
$\mu_{(had.)}$ parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{(\tau\to\mu)}$ and $\mu_{(had.)}$ d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

$R(\tau/\mu) = 0.992 \pm 0.013$

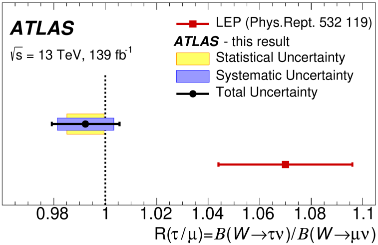
$R(\tau/\mu) = 0.992 \pm 0.007(\text{stat}) \pm 0.011(\text{syst})$

Agreement with the SM expectation of equal couplings and the hypothesis of lepton-flavor universality

$\mu_{(\text{prompt})}$ ($\mu_{(\tau\to\mu)}$) dominates at low (high) $|d_0^\mu|$

$\mu_{(\text{had})}$ most important for low p_T^μ

Leading uncertainties from the imperfect knowledge of the tail of the $|d_0^\mu|$ distribution



Summary

- Many analyses with increasingly high precision and increasingly sophisticated interpretations at the LHC Top factory
- The inclusive top quark pair production cross section $\sigma_{t\bar{t}}$ at $\sqrt{s} = 5.02\,\mathrm{TeV}$ has been measured with a relative uncertainty of 7.5% to be consistent with theoretical QCD calculations at NNLO
- The inclusive top quark pair production cross section $\sigma_{t\bar{t}}$ at $\sqrt{s} = 13\,\mathrm{TeV}$ has been measured with a relative uncertainty of 4.6% to be consistent with theoretical QCD calculations at NNLO
- SMT top quark mass measurement is the most precise single measurement to date of the top quark mass from direct reconstruction
- The measured ratio of the rate of decay of W bosons to τ-leptons and muons agrees with the hypothesis of universal lepton couplings

Further recent Top publications

Title	$\sqrt{s}$ (TeV)	L (fb^{-1})	arXiv	Journal
Measurement of the $t\bar{t}t\bar{t}$ production cross section	13	139	-	ATLAS-CONF-2021-013
Measurement of ttZ cross sections in Run 2	13	139	arXiv:2103.12603	Submitted to EPJC
Evidence for $t\bar{t}t\bar{t}$ production	13	139	arXiv:2007.14858	EPJC 80(2020)1085
Measurements of combined $t\bar{t}\gamma + tW\gamma$ cross sections in the e-μ channel	13	139	arXiv:2007.06946	JHEP09(2020)049
Measurement of the Wt single top cross section	8	20	arXiv:2007.01554	Submitted to EPCJ
Measurement of the $t\bar{t}$ production cross-section in the lepton+jets channel	13	139	arXiv:2006.13076	PLB 810(2020)135797
Measurement of the $t\bar{t}$ production cross section and lepton differential distributions in dilepton events	13	36	arXiv:1910.08819	EPJC 80(2020)528
Top-quark pair differential cross-sections in the resolved hadronic channel	13	36	arXiv:2006.09274	JHEP 01(2021)033
ATLAS+CMS $t\bar{t}$ W helicity combination	8	20	arXiv:2005.03799	JHEP 08(2020)51
Observation of tZq single top	13	139	arXiv:2002.07546	JHEP 07(2020)124

The search for rare top production and decay processes with the ATLAS experiment at the LHC by Anil Sonay

Full list of ATLAS top public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults