Top quark precision measurements with the ATLAS experiment at the LHC

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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 $\sqrt{s} = 5.02$ TeV using di-leptonic events on 257 pb$^{-1}$

*ATLAS-CONF-2021-003*

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


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

*ATLAS-CONF-2019-046*

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

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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 TeV.

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

Complementary to the larger samples at 7, 8 and 13 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 $t\bar{t} \rightarrow W^+ bW^- \bar{b} \rightarrow ll' \nu \bar{\nu} b\bar{b}$
$e-\mu$, $e-e$ and $\mu-\mu$ 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 ($\epsilon_b^{ll}$) 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 $\sigma_{t\bar{t}}$, $\epsilon_b^{ll}$, $R_1^Z$, $R_2^Z$

Systematic uncertainties are evaluated by repeating the fit with changed inputs
$\sigma_{t\bar{t}} = 66.0 \pm 4.5\text{(stat.)} \pm 1.6\text{(syst.)} \pm 1.2\text{(lumi)} \pm 0.2\text{(beam)} \text{ pb (} \pm 7.5\% \text{)}$

Compatible with the NNLO+NNLL QCD prediction of $\sigma_{t\bar{t}} = 68.2^{+5.2}_{-5.3}$ 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 $Z+\text{jets}$ background compatible with unity
Analysis strategy

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

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

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

Event selection

- $\geq 1$ electron or muon
- $\geq 4$ 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: $m_{lj}^{\text{min}}$, SR3: $\Delta R_{bjj}^{\text{avg}}$

Systematic uncertainties as NPs

Aplanarity $A = \frac{3}{2} \lambda_3$, $\lambda_3$: smallest eigenvalue of $S^{\alpha\beta} = \sum_i p_i^{\alpha} p_i^{\beta} / \sum_i |p_i|^2$

$m_{lj}^{\text{min}}$: minimum mass over all lepton-jet pairs

$\Delta R_{bjj}^{\text{avg}}$: avg. angular distance between the constituents from a hadronically decaying top candidate
\[ \sigma_{\text{fid}} = 110.7 \pm 0.05(\text{stat.})^{+4.5}_{-4.3}(\text{syst.}) \pm 1.9(\text{lumi}) \text{ pb} = 110.7 \pm 4.8 \text{ pb} (\pm 4.3\%) \]
\[ \sigma_{\text{inc}} = 830 \pm 0.4(\text{stat.}) \pm 36(\text{syst.}) \pm 14(\text{lumi}) \text{ pb} = 830 \pm 38 \text{ pb} (\pm 4.6\%) \]

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.
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 TeV, 36.1 fb\(^{-1}\))
Pohweg-Box NLO+Pythia8, NNPDF3.0

Event selection
Lepton-jets channel
\( \geq 1 \) lepton with \( p_T > 27 \text{ GeV} \)
\( \geq 4 \) jets with \( p_T > 30 \text{ GeV} \)
\( \geq 1 \) SMT-tagged jet
SMT muon: tight with \( p_T > 8 \text{ GeV} \)
and \( \Delta R_{\mu,\text{jet}} < 0.4 \)

Profile likelihood fit
Poisson likelihood with Gaussian NPs for systematics
Binned templates for various top quark masses \( \in [165.0, 180.0] \text{ GeV} \)
\( m_t = 174.48 \pm 0.40 \text{(stat)} \pm 0.67 \text{(syst)} \text{ GeV} \)

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

Most precise single measurement

Consistent at the level of 2.2\( \sigma \) 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-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 $\tau$-leptons and muons,

$$R(\tau/\mu) = \frac{B(W \to \tau \nu_{\tau})}{B(W \to \mu \nu_{\mu})}$$

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 $\tau$ 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 $1.070 \pm 0.026$, which deviates from the SM expectation by $2.7\sigma$.

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

Analysis strategy

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

Data and nominal \( t\bar{t} \) sample

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

Event selection

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

Profile likelihood fit

\[ R(\tau/\mu) = \mu_{\tau \to \mu/\mu(\text{prompt})}, k(t\bar{t}) \]
NPs for systematic uncertainties
48 bins of the probe muons (3 \( p_T^{\mu} \), 8 \( |d_0^{\mu}| \))
6 signal regions (2 channels, 3 \( p_T^{\mu} \) regions)
2 control regions for \( Z \rightarrow \mu\mu \) w/o \( m_{\mu\mu} \) criterion and \( \mu(\text{had}) \) with same-sign leptons
$R(\tau/\mu) = 0.992 \pm 0.013$

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

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 $p_T$

Leading uncertainties from the imperfect knowledge of the tail of the $|d_0^\mu|$ distribution
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 $\sqrt{s} = 5.02\,\text{TeV}$ 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 $\sqrt{s} = 13\,\text{TeV}$ 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 $\tau$-leptons and muons agrees with the hypothesis of universal lepton couplings
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