Top quark precision measurements with the ATLAS experiment

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On behalf of the ATLAS collaboration

DIS and related subjects 2022
The top quark

By far the heaviest elementary particle: $m_t = 172.69 \pm 0.48$ GeV

- Coupling to the Higgs boson $y_t \sim 1$
  - connection to EW symmetry breaking

- Short lifetime $\tau \approx 10^{-25}$ s
  - decay before hadronise
  - decay as a quasi free quark
  - spin information and polarisation are accessible

High production rate at the LHC

- produced $> 100$ M top quarks pairs in Run 2

$\Rightarrow$ Unique opportunity to test deviations from the SM predictions and BSM
Precision measurements overview

**Part 1:** differential cross section measurements of $t\bar{t}$ in two different channels, defined by decay modes of the W-bosons from top-quark decay:

- lepton+jets
- all hadronic

**Part 2:** top-quark properties

- energy asymmetries in $t\bar{t}j$
- polarisation

Processes discussed today
Boosted $t\bar{t}$ differential cross section in the $\ell + \text{jets}$ channel

- Select $\ell + \text{jets}$ events with $p_{T}^{t,h} > 335$ GeV → boosted top-quark

- Measure 1D and 2D differential cross-sections
  - kinematics of the top quark
  - and additional radiation

- Interpret the distribution of $p_{T}^{t,h}$ in an EFT:
  - SMEFT@NLO 1.0.0
  - $C_{tG}$ and $C_{tq}^{(8)}$
Jet energy correction

Reduce the impact of uncertainties from Jet energy scale:

- Employ a parameter (JSF) sensitive to the $m_{t,h}$
- JSF absorbs the jet energy scale difference between data and simulation

\[ m_{t,h} = 93.61 + 75.55 \cdot \text{JSF} \]

- Use $m_{t,h}$ in data to determine the JSF
  - JSF$_{\text{data}} = 0.99965 \pm 0.00087$ (stat.)
- reduce the uncertainty $\pm 4.2\% \implies \pm 0.7\%$
Results: Differential cross-sections

- top $p_T$ is softer in data than simulation
- reweighting the MC predictions to the NNLO parton-level improves the agreement with data
- sensitive to additional radiation
- none of the tested models provides a good description of all the measured observables
Interpretation in effective field theory

Interpretation of differential $p_T^{t,h}$ measurements in EFT framework

- Probing two EFT coefficients

- Interpretation in $\Lambda^{-2}$ and $\Lambda^{-4}$ models

<table>
<thead>
<tr>
<th>Model</th>
<th>$C_i (\Lambda/\text{TeV})^2$</th>
<th>Marginalised 95% intervals</th>
<th>Individual 95% intervals</th>
<th>Global fit 95% limits $[111]^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Expected</td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>$\Lambda^{-4}$</td>
<td>$C_{tG}$</td>
<td>$[-0.44, 0.35]$</td>
<td>$[-0.53, 0.21]$</td>
<td>$[-0.44, 0.28]$</td>
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<tr>
<td></td>
<td>$C_{tq}^{(8)}$</td>
<td>$[-0.57, 0.17]$</td>
<td>$[-0.60, 0.13]$</td>
<td>$[-0.57, 0.18]$</td>
</tr>
</tbody>
</table>

limits on $C_{tq}^{(8)}$ are competitive with global fit

* arxiv:2105.00006
Boosted $t\bar{t}$ differential cross section in the all-hadronic channel

**ATLAS-CONF-2021-050**

- select all-hadronic events with two boosted top-quarks:

  \[ p_T^{t,1} > 500 \text{ GeV} \quad \text{and} \quad p_T^{t,2} > 350 \text{ GeV} \]

- measure 1D, 2D and 3D differential cross-sections
  - compare to NLO and NNLO predictions
  - unfold to particle and parton level

- Interpret of differential $p_T^{t,1}$ cross-section measurements in an EFT
Boosted $t\bar{t}$ differential cross section in the all-hadronic channel

**Leading top $p_T$/ particle-level**

- better agreement with more ISR predictions than with the nominal for many distributions

**Fiducial parton-level total $\sigma_{t\bar{t}}$**

- better agreement with NNLO predictions than NLO
Part 2: top-quark properties

- energy asymmetries in $t \bar{t} j$
- top quark polarisation
Energy asymmetry

Select boosted $t\bar{t} + j$ events in the semi-leptonic decay channel

- measure energy asymmetry for the first time

$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}$$

- $\Delta E = E_t - E_{\bar{t}}$
- $\theta_j$ the jet scattering angle w.r.t the beam axis

- Set EFT limits on this asymmetry measurement
Results: energy asymmetry

\[ A_E(\theta_j) : \text{from unfolded } \Delta E \text{ distributions in } \theta_j \text{ bins} \]

- largest asymmetry in the second \( \theta_j \) bin, the jet is emitted perpendicular to the beam:
  - From zero: measured asymmetry differ by 2.1 sigma
- measurement agrees with NLO prediction
- experimental uncertainty is dominated by data statistics
Results: EFT interpretations

Energy asymmetry is sensitive to chirality and colour charges of top quark:
- Interpretation in SMEFT framework
- Probing six Wilson coefficients

- $A_E$ probes new directions in the parameter space of Wilson coefficients, complementing other observables as the rapidity asymmetry

Strict limits on colour singlet coefficients

2D constraints
Part 2: top-quark properties

- energy asymmetries
- top quark polarisation
Top-quark polarisation

- unique chance to measure top polarisation in single top-quark events
  - highly polarised top quarks

- first measurement of the full polarisation vector
  - in the t-channel
  - for both top and anti top quarks
  - use angular distributions of the top decay products

- differential cross sections are extracted for these angular variables

- sensitive to EFT effects in $Wtb$ vertex

arxiv:2202.11382
Result: measurement of the top-quark polarisation

Template fit of the lepton angle octant (Q) in top rest frame

First measurement ever!

- systematics are mainly dominated by jet energy resolution
- strong polarisation in the $z$-direction and little in other directions
- Excellent agreement with the SM NNLO predictions

### Parameter | Extracted value
---|---
$P_x^t$ | $+0.01 \pm 0.18$
$P_y^t$ | $-0.02 \pm 0.20$
$P_y^t$ | $-0.029 \pm 0.027$
$P_z^t$ | $-0.007 \pm 0.051$
$P_{z'}^t$ | $+0.91 \pm 0.10$
$P_{z'}^t$ | $-0.79 \pm 0.16$
Results: differential cross-sections and EFT limits

- differential cross-sections as a function of $\cos \theta_{\ell \bar{\chi}}, \cos \theta_{\ell \bar{\psi}}, \cos \theta_{\ell \bar{\zeta}}$

  $\Delta \sigma$ as a function of $\cos \theta_{\ell \bar{\chi}}$

- set limits on Wilson coefficients

  $\Delta \sigma$ as a function of $\cos \theta_{\ell \bar{\chi}}$

  global $p - value$ for top and antitop combined Powheg+Pythia8 of 0.93

- best limits for $C_{tW}$ so far from HEP experiments!
- consistent with the SM predictions
Conclusion

Several new ATLAS top cross-section and property measurements

- Improved precision of previous measurements
- Explored new measurements (energy asymmetry)
- Differential cross sections are able to distinguish the predictions from different MC models
  - Input for MC parameters tuning

- Results interpreted in EFT

➢ Run-III will bring even higher precisions!
Backup: top-quark polarisation

The $\ell$ angle octant in top rest frame

Signal region is divided in terms of the sign of $\cos \theta_{\ell X} \Rightarrow 8$ bins
- $\hat{z}'$ direction: is that of the spectator quark in the top-quark rest frame.
- $\hat{x}'$ direction lies in the production plane
- $\hat{y}'$ direction is perpendicular to the production plane