Recent highlights of top-quark physics with the ATLAS detector

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The top quark: a unique particle

- Most massive elementary particle known to date. Special role in many theories beyond the Standard Model
- Short-lived, decays before hadronising. Possible to study the properties of a bare quark
- Precision tests of perturbative QCD
- Main background in many BSM searches
- Essential to study Higgs properties, measure top Yukawa coupling

This talk focuses on some of the most recent top quark (+ friends) results by ATLAS with the full Run-2 13 TeV data
Top quark pairs + friends

- Studying processes with $0(5)$ of magnitude difference in production rate
- Plethora of measurements available: top-quark properties production/decays, associated production, couplings, ...

![Top Quark Production Cross Section Measurements](image-url)

- Properties of W-boson from $t\bar{t}$ events
- Scrutinise production of top+X processes
- Access to the even more rare $t\bar{t}t\bar{t}$ process
Studying $t\bar{t} + Z/\gamma$ process: what and why?

- Rare processes that **test the electroweak couplings of the top quark to bosons**
- Test higher order theoretical calculations and Monte Carlo simulations to improve the understanding of the modelling
- **Irreducible background** to several searches for BSM phenomena as well as to measurements of important SM processes (e.g. $t\bar{t}H$)
- **Sensitive to new physics**: eg. Effective Field Theory interpretations
General strategy: inclusive and differential cross sections

- **Strategy**: focus on leptonic (e, µ) decays of top quarks (and Z boson)
  - Smaller BR than hadronic decays, smaller backgrounds

- **Inclusive cross section**
  - Profile likelihood fit → Allows to constrain systematic uncertainties, improve precision
  - Include signal and control regions to reduce dependency on the backgrounds

- **Differential cross section measurements**
  - Unfolding: correct for detector efficiencies ($\epsilon^l$), acceptances ($f_{acc}^j$, $f_{match}^j$) and migration ($M_{ij}$) to particle or parton level in full or fiducial phase space (requirements similar to those at detector level)
\(t\bar{t}\gamma + tW\gamma\) cross section measurements, JHEP 09 (2020) 049

- Fiducial parton-level cross-section measurements on the \(e\mu\) channel
  - Small BR but cleanest \(t\bar{t}\) decay channel

- Profile likelihood fit to \(S_T\)
  \[
  \sigma_{\text{fid}} = 39.6 \pm 0.8^{\text{stat}} + 2.5^{\text{syst}} \text{ fb}
  \]
  (\(~6\%\) precision)

- Compare to full NLO calculation for \(pp \rightarrow e\mu
\nu\nu b\bar{b}\gamma\) (JHEP 1810 (2018) 158)
  \[
  \sigma_{\text{NLO}} = 38.50^{+0.56}_{-2.18}^{\text{scale}} + 1.04^{\text{PDF}} \text{ fb}
  \]

- Dominant uncertainties: signal and background modelling
$t\bar{t}\gamma + tW\gamma$: absolute and norm. differential cross sections

- Variables: photon $p_T$ and $|\eta|$, $\Delta R(\gamma, \ell)_{\text{min}}$, $\Delta \phi(\ell, \ell)$ and $|\Delta \eta(\ell, \ell)|$

<table>
<thead>
<tr>
<th>Predictions</th>
<th>$p_T(\gamma)$ (abs.) $\chi^2$/ndf $p$-value</th>
<th>$\Delta \phi(\ell, \ell)$ (norm.) $\chi^2$/ndf $p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory NLO</td>
<td>16.0/16 0.45</td>
<td>5.8/9 0.76</td>
</tr>
<tr>
<td>MG5+PYTHIA8</td>
<td></td>
<td>30.8/9 &lt;0.01</td>
</tr>
<tr>
<td>MG5+HERWIG7</td>
<td></td>
<td>31.6/9 &lt;0.01</td>
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</tbody>
</table>
**$t\bar{t}Z$ cross-section measurements, ATLAS-CONF-2020-028**

- Most sensitive 3 and 4 lepton ($e$, $\mu$) channels
- Requirements on number of jets, $b$-tagged jets, leptons imposed to define signal/control regions
  - Dominant backgrounds: $WZ/ZZ+\text{light jets}$
- Profile likelihood fit based on the event yields in each region

\[
\sigma_{\text{fid}} = 1.05 \pm 0.05^{\text{(stat)}} \pm 0.09^{\text{(syst)}} \text{ pb} \quad \sim 10\% \text{ precision}
\]

\[
\sigma_{NLO+NLL} = 0.86^{+0.07}_{-0.09} \text{ (scale)} \pm 0.03 \text{ (PDF + } \alpha_S \text{) pb} \quad \text{[JHEP 08 (2019) 039]}
\]
**$t\bar{t}Z$: absolute and norm. differential cross sections**

- **Fiducial region unfolded at particle and parton levels**
- **Performed in different channels: $3\ell$, $4\ell$ or $3\ell + 4\ell$ combination**
- **Functions of kinematic variables of the $Z$ boson, $t\bar{t}$ system, angular differences between objects, etc.**
- **Compared to NLO MC generators and calculations at NLO, NLO+NLL, nNLO**
Search for SM $t\bar{t}t\bar{t}$ production, arXiv:2007.14858, accepted by EPJC

- Tiny cross section in SM: $\sigma_{t\bar{t}t\bar{t}}^{SM} \sim 12 \text{ fb@13 TeV}$
- ... and very complex final state
- Many BSM models predict an increase:
  Particles decaying to top quarks or modified couplings, massive coloured bosons, composite Higgs/top, extra dimensions, SUSY...
- Measurements can be used to constrain $y_t$
Search for SM $t\bar{t}t\bar{t}$ production: strategy

- $\ell^{\pm}\ell^{\pm}$ or $\geq 3\ell$: 12% of total BR, but low background contamination
- Exploit jet multiplicity, jet flavour and event kinematics to separate signal/background events
  - Signal region: at least 6 jets and at least 2-bjets, $H_T > 500$ GeV
- Main backgrounds:
  - $t\bar{t} + Z/H+$jets: MC estimate
  - $t\bar{t}W$ and non-prompt backgrounds: normalisations determined in CRs

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ATLAS $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

- Pre-Fit
- Data / Pred.
- Sum of b-tag scores
- ATLAS $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
- CR $t\bar{t}W$
- Post-Fit
- Data / Pred.
- $\Sigma p_T^\ell$ [GeV]
Search for SM $t\bar{t}t\bar{t}$ production: results

Signal extraction

- BDT used in signal region to separate $t\bar{t}t\bar{t}$ and background
- Simultaneous fit of signal region and 4 control regions

$$\sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6} \text{ fb}$$

First evidence of $t\bar{t}t\bar{t}$ production with a significance of 4.4 $\sigma$ compared to 2.4 $\sigma$ expected

- Dominated by statistical uncertainties
- Main systematic uncertainties: $t\bar{t}W$ background

- Universality of the coupling of $\ell^\pm$ to $W$ boson is a fundamental property of the SM
- Some disagreement (2.7$\sigma$) of the on-shell $W \rightarrow \tau\nu$ results seen at LEP
- Tested via $R(\tau/\mu) = B(W \rightarrow \tau\nu)/B(W \rightarrow \mu\nu)$
- Main challenge: differentiate between $W \rightarrow \tau\nu \rightarrow \mu\nu\nu\nu$ and $W \rightarrow \mu\nu$

\[ \rightarrow \text{Use } p_T \text{ and transverse impact parameter of the muons } |d_0^{\mu}| \]
Measurement of lepton flavour universality: strategy

- **Event selection**: dileptonic $t\bar{t}$ events

- $|d_0^{\mu}|$ is the key variable: distance of closest approach of muon tracks in transverse plane wrt beamline
  - Shape of the distribution from $Z \rightarrow \mu\mu$ data events for prompt muons
  - Major backgrounds estimated using control regions in data
    - $Z + 2b$-tagged jets in the $\mu\mu$ channel, muons from hadron decays
Measurement of lepton flavour universality: results

- Profile likelihood fit to $|d_0^\mu|$ distribution in regions of muon $p_T$ and decay channel ($e\mu$, $\mu\mu$)

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

(precision of 1.3%)

- Leading systematic uncertainties: description of $|d_0^\mu|$ tail, parton shower uncertainties and muon identification/isolation

- Most precise result up to date and in agreement with the SM hypothesis

\begin{center}
\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{ATLAS $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$}
\end{figure}
\end{center}
Summary

- Presented highlights of top-quark results with the full Run 2 data
- $t\bar{t}\gamma$ and $t\bar{t}Z$ inclusive and differential measurements in fiducial phase space (absolute and normalised)
  - Results compared with latest MC and higher order theory prediction: results compatible within uncertainties
    → Important to improve their modelling, explore parameters of EFT and other BSM models
- Evidence for the 4-top quark production has been achieved with 4.3$\sigma$ significance!
- Most precise measurement of $R(\tau/\mu)$: Lepton flavour universality in agreement with the SM