Differential Top Cross-section and $t\bar{t}+X$ Measurements at ATLAS
Pheno2018, Pittsburgh PA

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on behalf of the ATLAS Collaboration

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May 8th, 2018
• ATLAS has a rich and varied top physics program

• I don’t have time to cover everything! I will focus instead only on the most recent results at $\sqrt{s} = 13$ TeV

• Differential Cross-Sections:
  - Dilepton
  - Lepton+Jets (Resolved+Boosted)
  - All Hadronic (Boosted)

• Differential $t\bar{t}$+jets

• Measurement of $t\bar{t}+W$, $t\bar{t}+Z$

  I will not cover here $t\bar{t}+H$: see talk by G. Piacquadio tomorrow afternoon in the Higgs session
I consider myself something of a moral relativist.
Why do measurements of $t\bar{t}$ processes? [1/2]

The top quark is unique in the SM due to its large mass:
- decay before hadronisation
  - only quark that can be studied in isolation
  - precision QCD test
  - Experimental studies are now measuring to sub percent level in many cases
- same order as V.E.V in SM
  - $m_t \approx 173$ GeV, $v = 246$ GeV
  - Direct sensitivity to new physics
  - $t\bar{t}(+X)$ precision measurements are one of the most likely places for it to manifest!

$$m_t = \frac{y_t v}{\sqrt{2}}$$

$$\Delta m_h^t \sim -\frac{m^2}{v^2} \frac{\Lambda}{4\pi^2}$$

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Why do measurements of $t\bar{t}$ processes? [2/2]

- Major background to many interesting SM and exotic searches
  - Not always well described in current MC generators
  - Precision measurements crucial input to MC tuning efforts!

- Precision data very useful to theorists:
  - Constraining EFT operators: 
    - TopFitter
    - Bylund et al
    - Saavedra et al
  - Gluon PDF at large $x$: 
    - Czakon et al
  - Highly sensitive to NNLO effects: 
    - Czakon et al
Differential Cross-Sections

Not this kind of differential
Goldilocks and the Three Decay Modes

The $t\bar{t}$ process can be divided into three signatures, depending on the decays of the $W$ bosons.

ATLAS has performed measurements in all three decay modes.

Each channel comes with its own set of challenges and is sensitive to different parts of phase space.

<table>
<thead>
<tr>
<th></th>
<th>Dilepton</th>
<th>Lepton+Jets</th>
<th>All-Hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branching Ratio</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Trigger</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
The Analyses

**Dilepton: 2 of these**
- Reconstruct $t\bar{t}$ system with neutrino weighting

**All-Hadronic: 2 of these**
- Reduce combinatorics by targeting boosted

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**Lepton+Jets Resolved**
- Utilise both reconstruction techniques in same paper
- Unfold also in bins of $N_{jets}$ (resolved only)

**Lepton+Jets Boosted**

- ▶ Dilepton
- ▶ L+Jets Resolved + Boosted
- ▶ L+Jets Resolved in N(Jets)

- ▶ All-Hadronic

- ▶ L+Jets Resolved in N(Jets) using 3.2fb$^{-1}$ from 2015
- ▶ All-Hadronic using 36fb$^{-1}$ from 2015+2016
- ▶ Share common unfolding to fiducial volume

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I’ve chosen to focus today on $p_T$ distributions, where the most interesting results$^1$ are: many more available in the papers!

$^1$In my opinion!
Differential Cross-Section Systematics

Of course systematics are analysis dependent, but there are common themes
- $t\bar{t}$ Modelling, including ME and PS, are always among the largest systematics
- Jet energy scale important, especially in the boosted analyses
- Contributions from flavor tagging, lepton ID more analysis dependent
MC generally predicts harder spectrum than is observed
- as observed previously by both ATLAS and CMS
- Similar slope seen in both dilepton and lepton+jets, resolved and boosted
- Less obvious in all-had, but uncertainties are larger
- MC Generators also often disagree with each other
- Lepton+jets boosted gives highest reach in $p_T$ so far
A way out? Top $p_T$ Corrections

- We have reason to believe that the NNLO QCD and NLO EW corrections could account for the slope in top $p_T$
  - LHCTopWG comparisons at 8 TeV show good agreement with NNLO calculations (though $p_T$ range is limited)
  - EW Corrections have also been shown to be $p_T$ dependent and in the direction of better agreement with data
  - Recent CMS result suggests maybe this is not enough

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p_{T}\bar{t}t\text{ Lepton+Jets, Binned in N(Jets)}

- Binning variables in N(Jets) and unfolding separately can reveal previously unseen discrepancies
- MG5_aMC@NLO+Pythia8 in 4jet exclusive shows a big slope that is less dramatic at higher multiplicity
- Powheg+Pythia8 shows a slope in ≥6 jets that is not present at lower multiplicity

Note the ratio pad Y axis ranges!

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$t\bar{t}+V$
\( \sigma_{t\bar{t}} \simeq 800\text{pb}, \sigma_{t\bar{t}W(Z)} \simeq 200\text{fb} ! \)

\( t\bar{t}V (V=W^\pm, Z) \) processes observed with 7.1\( \sigma \) significance in Run1

Today: first 13 TeV measurement with 3.2fb\(^{-1} \)
Strategy: split into many regions based on leptons, $N_{jets}$, $N_b$ – tags and fit simultaneously

- Validation Regions (VR) to check fake estimate (not included in fit)
- Control Regions (CR) to control diboson normalisations
- Signal Regions (SR) focusing on one of $t\bar{t}W$ ($2\mu$, $3\ell$noZ), $t\bar{t}Z(3\ell$, $4\ell$)
Dilepton Regions

- **2µSS Validation Region**
  - no $E_T^{miss}$ cut, $==1$b-tag

- **2µSS Signal Region with $\geq 2$b-tags targeting $t\bar{t}W$**

- Other dilepton regions used as VRs to check fakes estimates for 3L/4L regions
**Trilepton Regions**

- **3L-WZ Control Region** for floating WZ normalisation in fit
  - OSSF in Z-mass window, $==0b$-tags
- SRs split by jet, b-tag multiplicities, OSSF Z-mass window (targeting $t\bar{t}Z$)
- One SR with Z-mass veto of OSSF leptons (targeting $t\bar{t}W$)
**Tetralepton Regions**

- All regions targeting clean but low BR $t\bar{t}Z$
- 4L-ZZ-CR for floating ZZ normalisation in fit - 2 OSSF pairs in Z-mass window
- 4L SRs split by lepton flavor, b-tag multiplicity
**$t\bar{t}V$ Fit Results**

- **Observed (Expected) Significances:**
  - $t\bar{t}Z$: 3.9σ (3.4σ)
  - $t\bar{t}W$: 2.2σ (1.0σ)

- **$WZ$ norm**: 1.11 ± 0.30
- **$ZZ$ norm**: 0.94 ± 0.17

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**Uncertainty Table**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{t\bar{t}Z}$</th>
<th>$\sigma_{t\bar{t}W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.6%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Reconstructed objects</td>
<td>8.3%</td>
<td>9.3%</td>
</tr>
<tr>
<td>Backgrounds from simulation</td>
<td>5.3%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Fake leptons and charge misID</td>
<td>3.0%</td>
<td>19%</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>2.3%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Total systematic</td>
<td>11%</td>
<td>22%</td>
</tr>
<tr>
<td>Statistical</td>
<td>31%</td>
<td>48%</td>
</tr>
<tr>
<td>Total</td>
<td>32%</td>
<td>53%</td>
</tr>
</tbody>
</table>

**Analysis statistically dominated with 3.2fb$^{-1}$**
Summary

YEAH

SCIENCE
Summary

- Top quark physics is a crucial area of the LHC physics menu, both as an SM test and a BSM window.
- I have presented just a small taste of the ATLAS Top Physics program, focusing on $t\bar{t}(+X)$ production at $\sqrt{s} = 13$ TeV.
- We find generally good agreement with the Standard Model.
  - But the top $p_T$ spectrum slope remains.
- We are entering the precision measurement regime for $t\bar{t}+X$ physics, including $t\bar{t}+\text{jets}$ and $t\bar{t}+V$.

Keep an eye out for the many more developments to come.
Backup
Boosted Top Tagger

- Scan over combinations of substructure variables
  - Best combination over full $p_T$ range and for 50% and 80% WPs: jet mass and $\tau_{32}$
- Define $p_T$ dependent cuts for 50% and 80% WPs
  - In this measurement, we use the 80% WP

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Early RunII Tagger Pub Note

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**ATLAS Preliminary Simulation**

Scan over combinations of substructure variables
- Best combination over full $p_T$ range and for 50% and 80% WPs: jet mass and $\tau_{32}$
- Define $p_T$ dependent cuts for 50% and 80% WPs
  - In this measurement, we use the 80% WP

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**ATLAS Preliminary Simulation**

80% efficiency
- optimal $\tau_{32}$ cut
- regularized cut

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**ATLAS Preliminary Simulation**

80% efficiency
- optimal Mass cut
- regularized cut

---

**ATLAS Preliminary Simulation**

80% efficiency
- optimal Mass cut
- regularized cut
Common Unfolding Procedure

- Using the Iterative "Bayesian" method in RooUnfold with 4 iterations
- Master formula:

\[
\frac{d\sigma^{\text{fid}}}{dX^i} \equiv \frac{1}{\mathcal{L} \cdot \Delta X^i} \cdot f^{\text{eff}}_i \cdot \sum_j M^{-1}_{ij} \cdot f^{\text{acc}}_j \cdot (N^{\text{reco}}_j - N^{\text{bkg}}_j)
\]

(1)

\[
f^{\text{eff}}_i \equiv \left( \frac{N^{\text{part}}_i}{N^{\text{reco}\&\text{part}}_i} \right)^i, \quad f^{\text{acc}}_j \equiv \left( \frac{N^{\text{reco}\&\text{part}}_j}{N^{\text{reco}}_j} \right)^j
\]
Uncertainties : Lepton+Jets

- Small-R jet (resolved) and large-R jet (boosted) dominant
  - Energy scale/resolution (both), b-tagging (resolved), JSS modelling (boosted)
- Generator systematics important in both analyses
  - e.g. Powheg vs aMC@NLO, Pythia vs Herwig…
Top $p_T$ : Resolved and Boosted in Lepton+Jets

- $p_T$ ranges are complementary
- Very similar trend in overlapping region between resolved and boosted reconstruction techniques

**ATLAS**

$\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
Top $p_T$ : Binned in $N_{jets}$

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

Data

- 4-jet exclusive
- 5-jet exclusive
- 6-jet inclusive

Stat. + Syst. unc.
The full spectrum of (normalised) top $p_T$ results
**tt+V Signal Region Definitions**

2μSS: $2 \times \mu \ p_T > 25 \text{ GeV}, \ E_T^{\text{miss}} > 40 \text{ GeV}, \geq 2\text{-tag}, \text{ veto } 3\text{rd } \ell \ p_T > 7 \text{ GeV}

<table>
<thead>
<tr>
<th>Variable</th>
<th>3ℓ-Z-1b4j</th>
<th>3ℓ-Z-2b3j</th>
<th>3ℓ-Z-2b4j</th>
<th>3ℓ-noZ-2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading lepton</td>
<td></td>
<td></td>
<td>$p_T &gt; 25 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>Other leptons</td>
<td></td>
<td></td>
<td>$p_T &gt; 20 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>Sum of lepton charges</td>
<td></td>
<td></td>
<td>$\pm 1$</td>
<td></td>
</tr>
<tr>
<td>Z-like OSSF pair</td>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>&lt; 10 \text{ GeV}$</td>
<td>$</td>
</tr>
<tr>
<td>$n_{\text{jets}}$</td>
<td>$\geq 4$</td>
<td>3</td>
<td>$\geq 4$</td>
<td>$\geq 2 \text{ and } \leq 4$</td>
</tr>
<tr>
<td>$n_{b-\text{jets}}$</td>
<td>1</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
</tr>
</tbody>
</table>

| Region | Z$_2$ leptons | $p_T^{34}$ | $|m_{Z_2} - m_Z|$ | $E_T^{\text{miss}}$ | $n_{b-\text{tags}}$ |
|--------|----------------|------------|----------------|------------------|-----------------|
| 4ℓ-DF-1b | $e^\pm \mu^\mp$ | $> 35 \text{ GeV}$ | - | - | 1 |
| 4ℓ-DF-2b | $e^\pm \mu^\mp$ | - | - | - | $\geq 2$ |
| 4ℓ-SF-1b | $e^\pm e^\mp, \mu^\pm \mu^\mp$ | $> 25 \text{ GeV}$ | $\begin{cases} > 10 \text{ GeV} \\ < 10 \text{ GeV} \end{cases}$ | $\begin{cases} > 40 \text{ GeV} \\ > 80 \text{ GeV} \end{cases}$ | 1 |
| 4ℓ-SF-2b | $e^\pm e^\mp, \mu^\pm \mu^\mp$ | - | $\begin{cases} > 10 \text{ GeV} \\ < 10 \text{ GeV} \end{cases}$ | $\begin{cases} > 40 \text{ GeV} \end{cases}$ | $\geq 2$ |
tt+V Run1 and Run2 Comparisons

ATLAS

* Madgraph5_aMC@NLO calculation

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