Measurement of colour flow in $t\bar{t}$ events with the ATLAS detector

ATLAS-CONF-2017-069

Fabian Wilk
on behalf of the ATLAS collaboration
Introduction

- Colour connection of hard objects affects energy distribution within and between jets

Goal: Extract information about **connection type and properties**
- Can be used for **Monte-Carlo** validation / tuning, ...
- Allow to construct truly orthogonal event selection observable 
  e.g. for assigning $b$'s in $t\bar{t}H(\rightarrow b\bar{b})$

*New* first measurement of this type at 13 TeV

The Jet Pull

- Measure quantities derived from **jet pull vector**
  \[ p_T \text{-weighted radial jet moment} \]

\[ \vec{P}(J_1) = \sum_{i \in J_1} p_T^i \cdot |\vec{r}_i| \vec{r}_i \]

\[ \rightarrow \text{jet pull vector magnitude } |\vec{P}| \]

\[ \Delta \phi = \phi - \phi_{J_1} \]

\[ \Delta y = y - y_{J_1} \]
The Jet Pull

- Measure quantities derived from **jet pull vector**
  \[ p_T \text{-weighted radial jet moment} \]

\[ \vec{P}(J_1) = \sum_{i \in J_1} p_T^i \cdot |\vec{r}_i| \vec{r}_i \]

\[ \rightarrow \text{jet pull vector magnitude } |\vec{P}| \]

\[ \vec{C}(J_1, J_2) = \vec{J}_2 - \vec{J}_1 \]

\[ \theta_P (J_1, J_2) = \angle \left( \vec{P}(J_1), \vec{C}(J_1, J_2) \right) \]

\[ \rightarrow \text{jet pull angle } \theta_P \]

Legend
- Pull Vector \( \vec{P}_1 \)
- Jet Connection Vector \( \vec{C}(J_1, J_2) \)
- Pull Angle \( \theta_P \) (\( J_1 \) w.r.t. \( J_2 \))
- Constituent of \( J_1 \) (size weighted by \( p_T \))

\[ \Delta \phi = \phi - \phi_{J_1} \]

\[ \Delta y = y - y_{J_1} \]
Analysis Strategy

1. Apply event selection for $t\bar{t} \rightarrow \ell + \text{jets}$ signal
2. Select target jets for calculation
   - Probe true colour connection
   - Select two leading non-$b$-tagged jets: $j_W^1, j_W^2$
   - Probe remnant colour flow across event
   - Select two leading $b$-tagged jets: $j_b^1, j_b^2$

3. Calculate observables for selected jets, measure detector-level spectra
   → Use jet-associated tracks, previous measurement w/ calo clusters ▶ Phys. Lett. B750 475
   \[
   \theta_P\left(j_W^1, j_W^2\right) \quad \theta_P\left(j_W^2, j_W^1\right) \quad |\vec{P}\left(j_W^1\right)|
   \]
   \[
   \theta_P\left(j_b^1, j_b^2\right)
   \]

4. Remove detector effects from measurement by unfolding to particle-level
   → use D’Agostini iterative bayesian technique

5. Compare normalised particle-level spectra to simulation-based predictions

Selection

Event Selection

- $\ell = 1$ lepton ($p_T > 27\text{ GeV}, |\eta| < 2.5$)
- $\ell = 0$ veto lepton ($p_T > 25\text{ GeV}, |\eta| < 2.5$)
- $\geq 4$ jets ($p_T > 25\text{ GeV}, |\eta| < 2.5$)
- $\geq 2$ $b$-tags (70% eff. WP)
- $E_T^{\text{miss}} > 20\text{ GeV}$

$\rightarrow$ estimated signal fraction $\sim 89\%$

Results

- Uncertainties dominated by signal modelling
- Statistical uncertainty sub-dominant

Angle: Predictions suggest stronger effect than observation
→ more sloped pull angle

Magnitude: Data favours larger value
→ “wider” jets

- Mostly poor modelling from MCs
- Powheg+Herwig7 generally does a good job

Results

- Uncertainties dominated by signal modelling
- Statistical uncertainty sub-dominant
- As expected, very flat distribution
- Agreement reversed:
  - Powheg+Herwig7 models observation poorly
  - Other predictions offer much better description

Results

- Comparison to maximally violating exotic ("colour-flipped") colour flow model: replace $W_{\text{Had}}$ by ad-hoc colour-octet

- Predicted colour flow shows significantly less sloped pull angle

- Goodness-of-fit tests show data prefers SM-like distribution over exotic ... but Powheg+Pythia8 does not provide a good description either

Conclusion

- A measurement of colour flow using jet pull properties with $36.1 \text{ fb}^{-1}$ of 13 TeV $pp$ data measured by the ATLAS experiment was presented
- Detector-level spectra are unfolded to particle-level using iterative bayesian technique
- Normalised fiducial spectra are compared to various predictions obtained from MC

- **An improved precision** respective to 8 TeV measurement is achieved
- Several Monte-Carlo predictions show poor modelling of jet pull vector properties
  - We can barely exclude the exotic colour model against our SM predictions
- **No one-fits-all prediction:**
  - Powheg+Herwig7 offers best description of pull angle from $W$-jets but worst for $b$-jets

- Measurement uncertainty dominated by signal modelling uncertainties
- Low statistical uncertainty suggests **future doubly-differential measurement**

Backup
### Event Selection Yields

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>1026000 ± 95000</td>
</tr>
<tr>
<td>$t\bar{t}V$</td>
<td>3270 ± 250</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>1711 ± 97</td>
</tr>
<tr>
<td>Single-top</td>
<td>48400 ± 5500</td>
</tr>
<tr>
<td>Diboson</td>
<td>1440 ± 220</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>27700 ± 4700</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>8300 ± 1400</td>
</tr>
<tr>
<td>NP/Fake leptons</td>
<td>53000 ± 30000</td>
</tr>
</tbody>
</table>

#### Total Expected

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Expected</td>
<td>1170000 ± 100000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>1153003</td>
</tr>
</tbody>
</table>

→ estimated signal fraction ~ 89%
### Systematic Uncertainty Breakdown

<table>
<thead>
<tr>
<th></th>
<th>$\Delta \theta_p (j_1^W, j_2^W)$ [%]</th>
<th>$\theta_p (j_1^W, j_2^W)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0 – 0.21</td>
<td>0.21 – 0.48</td>
</tr>
<tr>
<td>Hadronisation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generator</td>
<td>0.63</td>
<td>0.22</td>
</tr>
<tr>
<td>Colour Reconnection</td>
<td>0.11</td>
<td>0.26</td>
</tr>
<tr>
<td>$b$-Tagging</td>
<td>0.35</td>
<td>0.12</td>
</tr>
<tr>
<td>Non-Closure</td>
<td>0.25</td>
<td>0.07</td>
</tr>
<tr>
<td>ISR / FSR</td>
<td>0.32</td>
<td>0.12</td>
</tr>
<tr>
<td>Other</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>JER</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>JES</td>
<td>0.13</td>
<td>0.06</td>
</tr>
<tr>
<td>Tracks</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Syst.</td>
<td>0.97</td>
<td>0.52</td>
</tr>
<tr>
<td>Stat.</td>
<td>0.22</td>
<td>0.18</td>
</tr>
<tr>
<td>Total</td>
<td>0.99</td>
<td>0.55</td>
</tr>
</tbody>
</table>

- Signal modelling uncertainties (generator, hadronisation, ...) evaluated using alternate MC

Measurement of colour flow in $t\bar{t}$ events with the ATLAS detector
### $\chi^2$ Goodness-of-Fit Test Results

| Sample               | $\theta_P(j^W_1, j^W_2)$ | $\theta_P(j^W_2, j^W_1)$ | $\theta_P(j^b_1, j^b_2)$ | $|\vec{P}(j^W_1)|$ |
|----------------------|---------------------------|---------------------------|---------------------------|---------------------|
|                      | $\chi^2$/NDF  | $p$-value | $\chi^2$/NDF  | $p$-value | $\chi^2$/NDF  | $p$-value | $\chi^2$/NDF  | $p$-value |
| Powheg+Pythia8       | 50.7 / 3  | $< 0.001$ | 20.5 / 3  | $< 0.001$ | 1.5 / 3  | 0.690 | 26.2 / 4  | $< 0.001$ |
| Powheg+Pythia6       | 24.0 / 3  | $< 0.001$ | 8.2 / 3  | 0.041 | 3.0 / 3  | 0.385 | 9.7 / 4  | 0.045 |
| aMC@NLO+Pythia8      | 6.2 / 3   | 0.104 | 4.6 / 3  | 0.200 | 1.9 / 3  | 0.597 | 18.4 / 4  | 0.001 |
| Powheg+Herwig7       | 2.5 / 3   | 0.478 | 2.1 / 3  | 0.543 | 5.7 / 3  | 0.128 | 10.0 / 4  | 0.041 |
| Sherpa               | 23.4 / 3  | $< 0.001$ | 11.7 / 3  | 0.008 | 0.2 / 3  | 0.974 | 14.6 / 4  | 0.006 |
| Powheg+Pythia8*      | 21.0 / 3  | $< 0.001$ | 20.5 / 3  | $< 0.001$ | 0.9 / 3  | 0.821 | 13.0 / 4  | 0.011 |
| Flipped Powheg+Pythia8* | 48.1 / 3  | $< 0.001$ | 35.6 / 3  | $< 0.001$ | 2.8 / 3  | 0.427 | 18.5 / 4  | $< 0.001$ |

When comparing the data with the prediction for the exotic flipped colour flow model, the model itself is considered as an additional source of signal modelling uncertainty and thus added to the covariance matrix. Calculations which include this additional systematic are marked with *.