Colour Flow between Jets

- Jets carry colour, and are thus **colour connected** to other colour-charged objects
  - Pairing of connection depends on nature of decaying particles

![Singlet](image1)  
**Singlet**

![Octet](image2)  
**Octet**

- Particles created during hadronization should be concentrated along angular region spanned by the colour connected partons
  - Transverse jet profiles should not be round
  - Shape influenced by direction of colour flow!
Colour Flow between Jets

- Jets carry colour, and are thus **colour connected** to other colour-charged objects
  - Pairing of connection depends on nature of decaying particles

  ![Singlet](example-singlet.png)
  Example: $t\bar{t}H$

  ![Octet](example-octet.png)
  Example: $t\bar{t}g$

- Particles created during hadronization should be concentrated along angular region spanned by the colour connected partons
  - Transverse jet profiles should not be round
  - Shape influenced by direction of colour flow!
Colour Flow Observable

- Construct a local observable, constructed from particles within a chosen jet: **Jet pull**
- Pick a pair of jets in the event
- Build vectorial sum of jet components:

\[ \vec{p} = \sum_i \frac{E_T^i |r_i|}{E_T^{jet}} \vec{r}_i \]

- \( \vec{r}_i \): position of jet component i relative to center of jet
- \( E_T^i \): transverse energy of component i
- \( E_T^{jet} \): transverse energy of jet

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Gallicchio, Schwartz, PRL 105, 022001 (2010)
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Colour Flow Observable

- Chosen particles can be constructed from:
  - Clusters of calorimeter cells
    - Gives energy components
  - Or tracks ("charged-particles pull")
    - Momentum instead of energy sum

\[ \vec{p} = \sum_i \left( p_T^i \frac{r_i}{p_T^{jet}} \right) \]

- \( r_i \): position of jet component \( i \) relative to center of jet
- \( p_T^i \): transverse momentum of component \( i \)
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- Earlier ATLAS analysis showed: charged-particle pull has better sensitivity due to better track resolution

Gallicchio, Schwartz, PRL 105, 022001 (2010)

PLB 750, 475-493 (2015)
**Colour Flow in Top**

- Use top events as laboratory to test new tools

Gallichio, Schwartz, PRL 105, 022001 (2010)

Jet pull: vectorial sum of components within each jet → **jet pull angle**: angle wrt. connection line of pair of jets
Event Selection

- Select semileptonic $t\bar{t}$ events
  - Clean sample for colour flow studies
  - 2 jets from $W$ boson: jets from colour singlet
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Exact 1 charged electron or muon

Missing transverse energy from neutrino

At least 4 jets
Event Selection

- Select semileptonic $t\bar{t}$ events
  - Clean sample for colour flow studies
  - 2 jets from $W$ boson: jets from colour singlet

- Exact 1 charged electron or muon
- Missing transverse energy from neutrino
- At least 4 jets
- At least 2 of the jets b-tagged
  (jets identified as coming from hadronisation of $b$ quark)
Consider 4 observables in latest ATLAS 13 TeV analysis

- Two non-b-tagged jets:
  - Relative jet pull angles
    - From highest-$p_T$ jet to $2^{nd}$ highest and vice versa
  - Jet pull magnitude

- Two b-tagged jets
  - Relative jet pull angle
Signal and Background

- Event selection results in sample rich in $t\bar{t}$ events
- Background-modeling:
  - Most backgrounds modeled with MC and theory prediction
  - Fake leptons modeled with data-driven method


Yvonne Peters
Particle-level and Corrections

- Correcting observables to particle-level
  - Using stable particles with lifetimes >30 ps
- Background subtracted from data
- Iterative Bayesian unfolding
  - Migration matrix derived from t\bar{t} MC

\[\begin{tabular}{cccc}
9.13 & 11.47 & 20.95 & 58.45 \\
\pm 0.06 & \pm 0.06 & \pm 0.08 & \pm 0.14 \\
9.76 & 17.29 & 57.94 & 15.02 \\
\pm 0.05 & \pm 0.06 & \pm 0.12 & \pm 0.06 \\
17.04 & 57.35 & 17.56 & 8.06 \\
\pm 0.06 & \pm 0.11 & \pm 0.06 & \pm 0.04 \\
61.84 & 19.63 & 11.15 & 7.37 \\
\pm 0.12 & \pm 0.07 & \pm 0.05 & \pm 0.04 \\
\end{tabular}\]
Analysis Strategy

- Experimental **systematic uncertainties**, signal modeling uncertainties, background modeling uncertainties and unfolding procedure uncertainties are taken into account.

- **Normalised distributions** extracted
  - Reduced uncertainty from normalization.

- Comparison of **unfolded distributions** for two scenarios:
  - 1. Various different MC generators
  - 2. SM $t\bar{t}$ with a colour-flipped MC
    - **Colour-flipped**: replace colour-singlet W boson with ad-hoc colour-octet “W” by flipping colour-string.

- Colour-flip diagram:
  - Original diagram:
    - $t \rightarrow W^+ b \rightarrow \bar{q}' q'
    - $q \rightarrow \bar{q}' q', \bar{q} \rightarrow q, q' \rightarrow b$
  - Colour-flip:
    - Replace the original colour-singlet W boson with a colour-octet “W” by flipping the colour-string.
## Systematics: Example

<table>
<thead>
<tr>
<th>Source</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>0.55</td>
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</tr>
<tr>
<td>Generator</td>
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</tr>
<tr>
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<td>0.16</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Other</td>
<td>0.02</td>
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</tr>
<tr>
<td><strong>Syst.</strong></td>
<td>0.88</td>
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Results: Comparison to MCs

- MC modeling has room for improvement
- Different MC model different distributions more or less well
- Within uncertainties, a single generator cannot describe all observables
Results: Comparison to Colour-Flip Model

- Colour-flipped model disfavoured more by the data than SM
  (for this distribution $\chi^2$/NDF: 45.3/3; SM Powheg+Pythia8: 17.1/3)

Two measurements performed in ATLAS
- 8 TeV: using calorimeter jets and charged particles from track-info
- 13 TeV: only charged objects with track only

Using $t\bar{t}$ events as laboratory to test QCD colour connections

Comprehensive analysis performed on 13 TeV ATLAS data
- Considering 4 different observables related to jet pull

Could do measurement with more data
- Or other observables?
- Using particle flow?
- Jet pull in boosted objects?!
Backup
Colour coherence: QCD predicts increase of radiation where colour connection exists

Hadronization: Particles building up between colour-connected partons

Gluon: color octet

Quark: color triplet
### Chi2

<table>
<thead>
<tr>
<th>Sample</th>
<th>$W_{\text{Had Pull}}$</th>
<th>$W_{\text{All Pull Angles}}$</th>
<th>$W_{\text{Had Pull Angles}}$</th>
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<tr>
<td></td>
<td>$\chi^2$/NDF $p$-value</td>
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<td>Powheg+Pythia8</td>
<td>92.4/10 &lt; 0.001</td>
<td>78.6/9 &lt; 0.001</td>
<td>64.0/6 &lt; 0.001</td>
<td>119.4/13 &lt; 0.001</td>
</tr>
<tr>
<td>Powheg+Pythia6</td>
<td>51.2/10 &lt; 0.001</td>
<td>42.3/9 &lt; 0.001</td>
<td>28.6/6 &lt; 0.001</td>
<td>54.6/13 &lt; 0.001</td>
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<tr>
<td>MG5_aMC+Pythia8</td>
<td>34.1/10 &lt; 0.001</td>
<td>14.5/9 0.104</td>
<td>12.0/6 0.062</td>
<td>54.7/13 &lt; 0.001</td>
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<tr>
<td>Powheg+Herwig7</td>
<td>36.8/10 &lt; 0.001</td>
<td>40.9/9 &lt; 0.001</td>
<td>6.3/6 0.396</td>
<td>95.2/13 &lt; 0.001</td>
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<tr>
<td>Sherpa</td>
<td>60.0/10 &lt; 0.001</td>
<td>27.5/9 0.001</td>
<td>26.6/6 &lt; 0.001</td>
<td>62.8/13 &lt; 0.001</td>
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<tr>
<td>Powheg+Pythia8*</td>
<td>90.5/10 &lt; 0.001</td>
<td>77.9/9 &lt; 0.001</td>
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<tr>
<td>Flipped Powheg+Pythia8*</td>
<td>660.1/10 &lt; 0.001</td>
<td>171.6/9 &lt; 0.001</td>
<td>164.3/6 &lt; 0.001</td>
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