Recent Jet Substructure Results from the LHC
APS Division of Particles of Fields

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on behalf of the ATLAS and CMS Collaborations

Tuesday, August 4, 2015
The field of **jet substructure** is an active field of research with a fast pipeline from new ideas to experimental results.

**In Theory** → **In Principle** → **In Practice**

**Phenomenology Studies**

**Performance Studies**

**BSM Searches**

**SM Measurements**

New ways of thinking about jet sub/super structure

Understanding the detector response

Constraining models of (B)SM!


ATLAS-CONF-2014-048

ATLAS Simulation Preliminary

\( \sqrt{s} = 8 \text{ TeV} \)

<table>
<thead>
<tr>
<th>Cluster Energy (GeV)</th>
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Run Number 204668
Event Number 104923301

Clusters (size = log(E))

Jet Axes

Pull Vector (x 100)

\( p_T^{J_1} \sim p_T^{J_2} \sim 50 \text{ GeV} \)

\( m_{J_1J_2} \sim 70 \text{ GeV} \)
<table>
<thead>
<tr>
<th>Property</th>
<th>Substructure Variable(s)</th>
<th>Performance Result</th>
<th>Search Result</th>
<th>Measurement Results</th>
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<tr>
<td>Color(flow)*</td>
<td>Jet Pull</td>
<td>CMS-PAS-JME-14-002</td>
<td>CMS-PAS-EXO-12-055 (and others)</td>
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<td>(and others)</td>
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*Focus of this talk - no time to cover everything!
**Colorflow with the Jet Pull**

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

Jet Pull Angle \((\theta_p)\) = direction the radiation from one jet leans relative to another jet.

**Legend**
- \(\theta_p\) Pull Angle
- Constituent of \(J_1\) (size weighted by \(p_T\))

**Schematic from** arXiv:1506.05629
Tag-and-look
(tag-and-probing will come later!)

Can study the jet pull angle in top quark events where we expect non-trivial shapes for W jets and b-jets.

Similar results from ATLAS:
CONF-2013-048 and 1506.05629

These shapes seem to be well re-produced by the simulation!
Colorflow Tagging for BSM Searches

Jet pull is used in several CMS searches for boosted bosons in the high $p_T$ but still resolved regime.

Color flow is subtle, so needs to be combined in an MVA.

Tagger: dijet mass jet pull angle
dijet $m/p_T$ $q/g$ tags mass drop
Colorflow Tagging for an SM Measurement

ATLAS has measured the pull angle in top events

Quantified sensitivity of a dijet resonance color representation

(in this case, a $W$ boson)
Two big challenges in this measurement:

- Nearly uniform (but backgrounds are small!)

Resolution is comparable to the range

→ ATLAS Colorflow in backup
There are severe subtleties in the measurement: e.g. what is the jet axis?

Jets are corrected to point to the primary vertex, but it is crucial that their constituents are also corrected!
Can **significantly** (~3σ) distinguish a singlet $W$ from an octet $W$.

Furthermore the unfolded data are public for future model comparisons.

N.B. **track-based** is more sensitive than **calorimeter-based**.
\[ Q_j = \frac{1}{(p_{Tj})^\kappa} \sum_{i \in Tr} q_i \times (p_T^i)^\kappa \]

\( \kappa \) is a regularization parameter - controls sensitivity to soft radiation.

\( \kappa \) is a free scaling parameter, and

\( X \) is a regularization parameter -

\( \kappa \in [0.3, 1.0] \)

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Tag-and-probe

Tag the charge of $W \rightarrow l\nu$ and then probe the charge of $W \rightarrow jj$ in top quark pair production.

Significant difference between $W^+$ and $W^-$, though subtle; well-reproduced by the simulation.

**Similar results from ATLAS:**
- ATLAS-CONF-2013-086
- ATLAS-PERF-2014-002
**ATLAS** has measured the jet charge in dijet events.

Non-trivial change in the mean jet charge as a function of $p_T$ because the up-quark jet fraction increases.

Furthermore, there have been recent calculations which we can put to the test!
**Unfold** to facilitate model/calculation comparisons.

Increases due to more up-quark jets

Resolution degrades at high $p_T$

→ ATLAS Jet Charge in backup
The number of charged particles increases with $p_T$ and their tracks become straighter. One way to study the modeling of the merging is to look at the charged-energy fraction.

→ ATLAS Jet Charge in backup
The unfolded data are compared to various models.

- Systematically lower mean in the simulation
- Significant variation with PDF, CTEQ6L1 best description of the data
- Sensitive to amount of radiation in the shower (depends on $\kappa$)
Charge Tagging a SM Measurement

Question: accounting for PDFs, does jet charge depend on $p_T$? (recent theory calculation: yes!)

$$\langle Q_i \rangle \approx \sum_f \alpha_{f,i} \bar{Q}_f (1 + c_f \log(p_{T,i}/\bar{p}_T))$$

Can exploit the $\eta$-dependence of the flavor fractions to extract the up- and down-quark jet charge in each $p_T$ bin.
Boson type tagging performance

Another use for jet charge (and jet mass and b-tagging):
Distinguishing $W$ bosons from $Z$ bosons

- ATLAS Preliminary $e+\mu$
  $\sqrt{s} = 8$ TeV, $\int L dt = 20.3$ fb$^{-1}$
  Entries / 5 GeV

Jet Mass

- 2012 Data
- Total SM
- $t\bar{t}$ Boosted $W$
- $t\bar{t}$ b-Contaminated
- $t\bar{t}$ Other
- Single Top
- W+jets
- multijets

Data / MC

- ATLAS Preliminary $e+\mu$
  $\sqrt{s} = 8$ TeV, $\int L dt = 20.3$ fb$^{-1}$
  Entries / 0.16 e

Jet Charge

- 2012 Data
- $t\bar{t}$ Boosted $W$
- Other

Data / MC

→ ATLAS W/Z in backup

→ ATLAS-PERF-2015-02

$\sqrt{s} = 8$ TeV, $\int L dt = 20.3$ fb$^{-1}$

$50 \text{ GeV} < m_{\text{jet}} < 120$ GeV

Lepton Charge $> 0$

Lepton Charge $< 0$

Jet Charge ($\kappa=0.5$) [e]
Boson type tagging performance

Rejection of \( \sim 10 \) at 50\% Z efficiency

Potential uses

WZ/WW cross section

Classifying diboson resonances

Flavor-changing-neutral currents

\[ \text{\rightarrow ATLAS W/Z in backup} \]

Mass the most powerful variable, but gain from combining!

Results: Performance curve

ATLAS Simulation Preliminary

\( b \)-tagging best at low efficiency

No discrimination

- M (Jet Mass)
- M+Q
- M+B
- \( Q \) (b-tagging)
- \( Q+B \)
- \( M+Q+B \)
So far, focused on discriminating particles of the same type (boson versus boson, quark versus quark)

When a heavy particle (W/Z/h/t) is \textit{boosted}, jet substructure can improve over standard \textit{resolved} techniques.

A lot of dedicated work to distinguish W/Z/h/t from quark/gluon jets. Just enough time to flash results.
Both ATLAS and CMS have conducted extensive studies of $W$ tagging optimization

CMS has further measured the tagger efficiency in boosted $W$ bosons from top quark events.
Many uses of tagging boosted bosons for searches; e.g. the ATLAS diboson resonance search.

Stay tuned for Run II!

Tagger: subjet momentum balance, jet mass, and n_{track}
Top Quark Tagging Performance

There are more handles for top tagging due to its three-prong structure which includes b-quarks (subjett b-tagging!).

![Graph showing top quark tagging performance](image-url)

- ATLAS Collaboration, "Performance of Boosted W Boson Identification with the ATLAS Detector", ATL-
- D. Bertolini, P. Harris, M. Low and N. Tran, "Pileup Per Particle Identification", JHEP
- ATLAS Collaboration, "Flavor Tagging with Track Jets in Boosted Topologies with the ATLAS Detector",
- CMS Collaboration, "Performance of b tagging at
- ATLAS Collaboration, "Performance of boosted top quark identification in 2012 ATLAS data", ATLAS-
- J. Thaler and K. Van Tilburg, "Identifying Boosted Objects with N-subjettiness", JHEP
- ATLAS Collaboration, "Performance of shower deconstruction in ATLAS", ATLAS-CONF-2014-003,
- Top row: top tagging performance in ATLAS using trimmed anti-
- 600 GeV jets (right) [7].
Top Quark Tagging in Action

Top quark pair resonance search

Tagger: $k_t$ splitting scale and jet mass
careful treatment of electrons-in-jets!

arXiv:1505.07018

Top quark pair resonance search

Tagger: $k_t$ splitting scale and jet mass
careful treatment of electrons-in-jets!
Higgs Tagging Performance

The key is subjet (double) $b$-tagging

$$HH \rightarrow \bar{b}b\bar{b}b$$

Challenge: select axes correlated with the $b$-hadron direction - use the last jet clustering step

except for very high eff., subjet $b$-tagging outperforms fat jet $b$-tagging

**CMS Simulation Preliminary**

<table>
<thead>
<tr>
<th>Tagging efficiency ($H\rightarrow b\bar{b}$)</th>
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</thead>
<tbody>
<tr>
<td>Misid. probability (Inclusive QCD)</td>
</tr>
</tbody>
</table>

- $AK R=0.8$, $300<p_T<500$ GeV/$c$
- $75<m_{\text{pruned}}<135$ GeV/$c^2$
- "inclusive vertexing" ghost-associate tracks

CMS-PAS-BTV-13-001

*BTV-13-001 CA8

Last update: (11/2014 [CMS] and 9/2014 [ATLAS])
Higgs Tagging in Action

Tagger: trimmed jet mass and (R=0.3) track-jet b-tagging

track jets are the ATLAS approach to a calo jet-independent and b-hadron direction correlated algorithm
Outlook

Many sophisticated and powerful techniques already tested and tried in the 8 TeV data.

Gearing up now for boosted object tagging and substructure studies at 13 TeV!
This note is organized as follows. Section 3 formally defines the jet pull angle and sets the notation and nomenclature. Section 4 describes all of the simulation and data samples. Section 5 details the object and event selection. Truth studies are shown in Section 6, data/MC control plots are in Section 7 and the analysis strategy is outlined in Section 8. Section 9 lists and describes all of the systematic uncertainties considered in the analysis. The results for the unfolded distribution and comparisons to beyond the SM leading order color flow models are in Section 10. Section 11 contains conclusions and future outlook. Following the conclusions are a series of appendices with additional studies related to both experimental and theoretical (modeling) considerations.

3 Jet Pull Definition

The pull vector for a given jet $J$ is defined as

$$X_i^J \sim \mathbf{r}_i,$$

where the sum runs over constituents of the jet $J$ and $\mathbf{r}_i = (y_i, \phi_i)$ with respect to the position of the jet axis in rapidity ($y$) - azimuthal angle ($\phi$) space. Given the pull vector for jet $J_1$, a variable sensitive to the underlying color connections to another jet $J_2$ is the angle the pull vector for $J_1$ makes with respect to the vector connecting $J_1$ and $J_2$ in ($y$, $\phi$) space. This is shown graphically in Fig. 1 and will be called the pull angle and denoted $\theta_p(J_1, J_2)$. The pull angle is symmetric around zero when it takes values between $-\pi$ and $\pi$, and so henceforth, $\theta_p(J_1, J_2)$ refers to the modulus of the angle in ($y$, $\phi$) space with $0 < \theta_p \leq \pi$.

$$\Delta \phi = \phi - \phi_{J_1}$$

$$\Delta y = y - y_{J_1}$$
Colorflow Backup

Boosted Boson Type Tagging

Jet ETmiss

SLAC, Stanford University

March 26, 2014

Benjamin Nachman and Ariel Schartzman

ATLAS

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Data

$t\bar{t}$

Powheg+Pythia6

Flipped $t\bar{t}$

Powheg+Herwig

SM $t\bar{t}$

Charged particles $\theta_p(J_1,J_2)$ [rad]/$\pi$

MC/Data

0.95 0.9 0.95 1

0 0.2 0.4 0.6 0.8 1

All particles $\theta_p(J_1,J_2)$ [rad]/$\pi$

MC/Data

0.95 0.9 0.95 1

0 0.2 0.4 0.6 0.8 1

Boosted Boson Type Tagging

Jet $E_T^{miss}$

SLAC, Stanford University

March 26, 2014

Benjamin Nachman and Ariel Schartzman

B. Nachman (SLAC)

March 26, 2014 1 / 21

ATLAS Simulation
\( \sqrt{s} = 8 \text{ TeV} \)

- **All-particles**
- **All-particles** (Before Origin Correction)

Normalized to Unity

Reconstructed - Particle-Level \( \theta_p \text{ [rad]/\pi} \)

ATLAS Simulation
\( \sqrt{s} = 8 \text{ TeV} \)

- **All-particles**
- **Charged-particles**

Normalized to Unity

Reconstructed - Particle-Level \( \theta_p \text{ [rad]/\pi} \)
Events / 0.001

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Data

Standard Model

$\bar{t}\bar{t}$

Single Top

$W+\text{jets}$

Fake Leptons

$Z+\text{jets}$

Dibosons

Data/SM

Charged Particles |$v_{||}(J_{||})$|
Colorflow Backup


<table>
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<tr>
<th>$\theta_p^{all}(J_1, J_2)$ [rad]/$\pi$</th>
<th>$\theta_p^{charged}(J_1, J_2)$ [rad]/$\pi$</th>
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Statistical Bin-Bin Correlation
Boosted Boson Type Tagging
Jet ETmiss
SLAC, Stanford University
March 26, 2014
Benjamin Nachman and Ariel Schartzman

B. Nachman (SLAC)

ATLAS
$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Data
Powheg+Pythia6
Flipped $t\bar{t}$

ATLAS
$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Data
Powheg+Pythia6
Flipped $t\bar{t}$

All particles $\theta_p(J_1,J_2)$ [rad]/$\pi$

Charged particles $\theta_p(J_1,J_2)$ [rad]/$\pi$
Colorflow Backup

Boosted Boson Type Tagging

Jet ETmiss

SLAC, Stanford University

March 26, 2014

Benjamin Nachman and Ariel Schartzman

B. Nachman (SLAC)

March 26, 2014 1 / 21


Colorflow Backup
Colorflow Backup


<table>
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<tr>
<th>Process</th>
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<td>$Wt$-channel single top</td>
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<td>$s$- and $t$-channel single top</td>
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<td>$Z$+jets</td>
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<td>CT10 [20,21] CTEQ6L1 [23] -</td>
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<td>AUET2 [28]</td>
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<td>CT10</td>
<td>-</td>
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### Boosted Boson Type Tagging

Jet $E_{T\text{miss}}$

SLAC, Stanford University

March 26, 2014

Benjamin Nachman and Ariel Schartzman

---

**Table: Colorflow Backup**

<table>
<thead>
<tr>
<th>$\Delta \theta_p^{\text{charged}}$ [%]</th>
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---

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup


ATLAS Preliminary Simulation
\( \sqrt{s} = 8 \text{ TeV} \)
50 GeV < \( p_T < 100 \) GeV

Jet Charge (\( \kappa = 0.5 \)) [e]
Jet Charge Backup

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup


\[ \langle \Sigma \text{ Matched charged } p_T / \Sigma \text{ charged } p_T \rangle \]

\[ \langle \Sigma \text{ track } p_T / \text{ Jet } p_T \rangle \]

\[ \sqrt{s} = 8 \text{ TeV} \]

Pythia 8.175 CT10 AU2

\[ = 8 \text{ TeV}, \quad L_{\text{int}} = 20.3 \text{ fb}^{-1} \]

- 2012 Data
- Pythia (Detector Level)
- Herwig (Detector Level)
- Pythia (Particle Level)
- Herwig (Particle Level)
Jet Charge Backup

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup

Jet Charge Backup


**ATLAS** Preliminary
$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
CT10 + Pythia8 Flavor Fractions

![Graph showing scale violation parameter vs. κ](attachment:image.png)
<table>
<thead>
<tr>
<th>Trigger threshold [GeV]</th>
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<th>Luminosity [fb(^{-1})]</th>
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<tbody>
<tr>
<td>25</td>
<td>[50,100]</td>
<td>(7.84 \times 10^{-5})</td>
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<tr>
<td>55</td>
<td>[100,136]</td>
<td>(4.42 \times 10^{-4})</td>
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<td>80</td>
<td>[136,190]</td>
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<td>110</td>
<td>[190,200]</td>
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<td>145</td>
<td>[200,225]</td>
<td>(3.63 \times 10^{-2})</td>
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<td>180</td>
<td>[225,250]</td>
<td>(7.88 \times 10^{-2})</td>
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<td>220</td>
<td>[250,300]</td>
<td>(2.61 \times 10^{-1})</td>
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<td>280</td>
<td>[300,400]</td>
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<td>360</td>
<td>(\geq 400)</td>
<td>20.3</td>
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Jet Charge Backup


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<th>Average Jet Charge</th>
<th>Jet $p_T$ Range [100 GeV]</th>
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<td>[0.5,1] [1,2] [2,3] [3,4] [4,5] [5,6] [6,8] [8,10] [10,12] [12,15]</td>
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### Standard Deviation

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W/Z Tagger Backup

Boosted Boson Type Tagging

Jet ETmiss

SLAC, Stanford University

March 26, 2014

Benjamin Nachman and Ariel Schartzman

W/Z Tagger Backup

ATLAS Simulation Preliminary
\( \sqrt{s} = 8 \text{ TeV} \) PYTHIA \( W' \rightarrow WZ \)

200 GeV < \( p_T^V < 400 \) GeV

\( Z \)

\( W^+ \)

\( W^- \)
W/Z Tagger Backup

W/Z Tagger Backup


**ATLAS Simulation Preliminary**

\( \sqrt{s} = 8 \text{ TeV}, \text{ PYTHIA } W' \rightarrow WZ \)

200 GeV < \( p_T \) < 400 GeV

- \( Z \rightarrow b\bar{b} \)
- \( Z \rightarrow c\bar{c} \)
- \( Z \rightarrow \text{light} \)
- \( W \rightarrow cX \)
- \( W \rightarrow \text{light} \)

**ATLAS Simulation Preliminary**

\( \sqrt{s} = 8 \text{ TeV}, \text{ PYTHIA } W' \rightarrow WZ \)

200 GeV < \( p_T \) < 400 GeV

- \( Z \rightarrow b\bar{b} \)
- \( Z \rightarrow c\bar{c} \)
- \( Z \rightarrow \text{light} \)
- \( W' \rightarrow cX \)
- \( W' \rightarrow \text{light} \)
W/Z Tagger Backup

W/Z Tagger Backup

W/Z Tagger Backup

W/Z Tagger Backup

W/Z Tagger Backup

W/Z Tagger Backup

W/Z Tagger Backup

ATLAS Preliminary e+μ
\( \sqrt{s} = 8 \text{ TeV}, \int L \, dt = 20.3 \text{ fb}^{-1} \)

- 2012 Data
- Total SM
- \( \bar{t}t \) Boosted W
- \( \bar{t}t \) b-Contaminated
- \( \bar{t}t \) Other
- Single Top
- W+jets
- multijets

W/Z Tagger Backup

W/Z Tagger Backup

W/Z Tagger Backup

ATLAS Simulation Preliminary

Hadronic W, 200 GeV < $p_T$ < 400 GeV
Correlation: 0.00

ATLAS Simulation Preliminary

Hadronic Z, 200 GeV < $p_T$ < 400 GeV
Correlation: 0.00

W/Z Tagger Backup

W/Z Tagger Backup

W/Z Tagger Backup