Measurements of jet substructure observables and jet fragmentation at the LHC

SUSY 2019

David W. Miller
on behalf of the ATLAS and CMS Collaborations

Enrico Fermi Institute

May 21, 2019
The current era of particle physics

For the first time in the history of particle physics, the collision energy is well above the scale of electroweak symmetry breaking and $\Lambda_{QCD}$.

Lorentz-boosted objects are an *inevitability* for SM processes & new physics!
The current era of particle physics

For the first time in the history of particle physics, the collision energy is well above the scale of electroweak symmetry breaking and $\Lambda_{QCD}$.

Lorentz-boosted objects are an *inevitability* for SM processes & new physics!
Searches are pushing the boundaries of hadronic final states

Rich final states, new techniques, and motivated benchmark scenarios.
Hadronic final states: major part of LHC physics program

- Major background to new physics, even in the case of EWK-oriented searches
- Wealth of interesting physics & precision tests in QCD(+EWK) processes
- **Boosted hadronic object tagging critical for high-mass SUSY sensitivity**
$m_{jj} = 9.3$ TeV, with $p_T^{\text{jet}} = 2.9$ TeV $\rightarrow$ more than $35 \times m_W$!

($p_T^{\text{jet}} \gg m_W/Z/Higgs/top$)
Essential to measure and understand jet substructure

Run 2 LHC: $\mathcal{L}_{\text{inst}} = 2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} = 0.02 \text{ pb}^{-1} \text{s}^{-1} = 6 \text{ kHz of dijet events}$

Standard Model Production Cross Section Measurements

*ATLAS* Preliminary

Run 1,2 $\sqrt{s} = 7,8,13$ TeV

Status: July 2018
Highlights in this talk

1. Precision mass and fragmentation measurements using light QCD processes
   - STDM-2017-16 (ATLAS)
   - arXiv:1807.05974 (CMS)
   - arXiv:1711.08341 (ATLAS)

2. Jet substructure measurements in $\bar{t}t$ events
   - 1903.02942 (ATLAS)
   - arXiv:1808.07340 (CMS)
   - 1805.02935 (ATLAS)

3. Properties of $b\bar{b}$ resonances
   - arXiv:1812.09283 (ATLAS)
   - arXiv:1709.05543 (CMS)
ATLAS soft drop jet mass measurement

\[ \min(p_{T,j_1}, p_{T,j_2}) \quad \frac{p_{T,j_1} + p_{T,j_2}}{z_{\text{cut}}} > \left( \frac{\Delta R_{12}}{R_0} \right)^{\beta} \]

\[ \text{Soft drop grooming} \]

\[ \text{Soft drop } R = 0.8 \text{ jet mass: } \beta = 0, 1, 2 \]

- Higher \( \beta \) implies softer grooming
- Non-perturbative effects less well-modeled
Soft drop grooming

\[
\frac{\min(p_{T,j_1}, p_{T,j_2})}{p_{T,j_1} + p_{T,j_2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta
\]

Soft drop \( R = 0.8 \) jet mass: \( \beta = 0, 1, 2 \)
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\[ \text{Soft Drop Groomed Mass} \]

\( \text{Soft Drop, } z_{\text{cut}} = 0.1, \beta = 0 \)
13 TeV, \( pp \rightarrow Z+j, p_{Tj} > 500 \text{ GeV}, R = 0.8 \)

\[ \text{Non-perturbative Resummation} \]

\[ \text{Fixed-order} \]

\[ \text{Herwig++ (no had+ue)} \]
\[ \text{Herwig++ (had+ue)} \]
\[ \text{NNLL matched} \]
Soft drop grooming

\[
\text{min}(p_{T,j_1}, p_{T,j_2}) < z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta
\]

\[
\frac{p_{T,j_1} + p_{T,j_2}}{p_{T,j_1} + p_{T,j_2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta
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Jet substructure at the LHC – SUSY 2019

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**Soft drop grooming**

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**Soft drop \( R = 0.8 \) jet mass: \( \beta = 0, 1, 2 \)**

- Higher \( \beta \) implies softer grooming
- Non-perturbative effects less well-modeled
**CMS soft drop jet mass measurement**

- JHEP 11 (2018) 113
- (arXiv:1807.05974)

### Ungroomed $R = 0.8$ jet mass
- Higher syst. uncertainty: $\sim 10\%$ vs. $\sim 3\%$
- Significant Sudakov peak

### Soft drop $R = 0.8$ jet mass: $\beta = 0$
- Sudakov peak suppressed
- Similar agreement with MC models
Ungroomed $R = 0.8$ jet mass

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**Soft drop jet mass measurement uncertainty comparisons**

### ATLAS uncertainty
- “Bottom-up” uncertainties based on calorimeter clusters and $E/p$
- Determined in QCD dijet samples

### CMS uncertainty
- “Top down” uncertainties based on comparison of $W$ mass peak
- Determined in $t\bar{t}$ samples
Top quark pair events are an ideal proving ground for measurements of jet substructure

- Plentiful process, and key background for many new physics searches
- High purity, and relatively orthogonal event selection criteria (for lepton+jets samples)
- Multiple jet flavors involved: $b$, $q$, $g$
- Two resonances, $W$ & $t$, including colorless object
Structures of small-radius $R = 0.4$ jets

- IRC safe **angular** and **counting** observables that are sensitive to multi-prong vs. single prong decays
- **Wide-angle & high-multiplicity** structures least well-described by MC
Structures of small-radius $R = 0.4$ jets

- Soft-drop observables delated to energy partitioning and angular structures are very well-described
- Sensitive to very different physics: $\Delta R_g$ is particularly sensitive to $\alpha_S$
**CMS jet substructure measurements in resolved $t\bar{t}$ events**

![Graph showing CMS measurement of $\alpha_S$ from bottom-quarks in $t\bar{t}$ sample](image)

**Measurement of $\alpha_S$ from bottom-quarks in $t\bar{t}$ sample**

- $\alpha_S$ scan allows for best-fit value $\alpha_S(m_Z) = 0.115^{+0.015}_{-0.013}$
- Dominated by FSR scale uncertainties

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**ATLAS jet substructure measurements in resolved $t\bar{t}$ events**

- Large-radius jet substructure for: $W$, top, and light quark jets!
  - Semi-leptonic selections for $W$ and top jets in $t\bar{t}$ events
  - Dijet selection for light quark jets in QCD events

8 observables for $W$, top, QCD jets
- Modeling can differ significantly
  - Complex angular structures modeled well
  - $N$-body structure modeling harder

Validation regions (VR) are used to confirm the predictions from the CRs.
Large-radius jet substructure for: $W$, top, and light quark jets!

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arXiv:1903.02942

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[Energy-correlation ratio]

- ATLAS $\sqrt{s} = 13$ TeV, 33 fb$^{-1}$
- Dijet selection, anti-$k_T$, $R = 1.0$, $p_T > 450$ GeV
- Soft drop $\beta = 0$, $z_{\text{cut}} = 0.1$

**D. W. Miller (EFI, Chicago; ATLAS) Jet substructure at the LHC – SUSY 2019**

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[Energy-correlation ratio]

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Validation regions (VR) are used to confirm the predictions from the CRs.
Important discrimination for BSM physics tagging!

- Clear differences in boosted jet shapes and substructures
- Many of these are already used or soon to be used in searches for SUSY at large masses (and thus with significant Lorentz boosts!)
- Detailed measurements and MC tuning essential for optimizing physics performance of both measurements and searches
ATLAS & CMS jet measurements of boosted $b\bar{b}$ final states


Careful measurement required for understanding Higgs couplings

Backgrounds, calibration, $b$-tagging, jet substructure all come together
ATLAS & CMS jet measurements of boosted $b\bar{b}$ final states

**Critical process for deep understanding of Standard Model**

- Gluon splitting is a fundamental component of QCD
- Careful measurement required for understanding Higgs couplings
- Backgrounds, calibration, $b$-tagging, jet substructure all come together
- **Important to constrain difficult bckgs to sophisticated searches!**

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Gluon splitting to $b\bar{b}$ is present in almost any search with $N_{b\text{-jet}} \geq 2$

- Angular properties measured in dedicated sample
- Basic modeling of $\Delta R$ is good, but decay plane more difficult
**ATLAS measurements of g → b\bar{b}**

*Phys. Rev. D 99 (2019) 052004*  
*arXiv:1812.09283*

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**Momentum sharing and invariant mass**

- Kinematic measurements extend to the study of the **fragmentation** of the gluon using $z = p_{T,2}/p_T$ and the **invariant mass** of the $b\bar{b}$ system.
- Low $z$ and $m_{b\bar{b}}$ exhibit some mismodeling, otherwise good.
**CMS studies of Z → b\bar{b}**

- **Phys. Rev. Lett. 120 (2018) 071802**

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**Observation of Z → b\bar{b}**

- **Impressive & successful Z → b\bar{b} observation**
- **Soft-drop grooming and energy-energy correlations** critical to mitigating multijet background

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Jet substructure at the LHC – SUSY 2019  
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20 / 23
Jet fragmentation function \( \zeta = \frac{p_T^{\text{particle}}}{p_T^{\text{jet}}} \)

- Measurements up to very high \( p_T^{\text{jet}} \): 2–2.5 TeV
- Tuned PYTHIA and Herwig++ model data well, Sherpa less so
Charged particle multiplicity in forward vs. central dijets

- Rapidity used to isolate quark-like vs. gluon-like “topics”.

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Summary and conclusions

- **New physics searches with sensitive hadronic final state observables based on jet substructure are pushing sensitivities well above 2 TeV**
- **Detailed measurements of both QCD and EWK processes of the SM needed**
  - Interesting in their own right to shed light on the SM in extreme regions of phase space
  - Improve search sensitivity by demonstrating robustness, systematics, and MC modeling issues
- **Extensive jet substructure and properties measurement campaign to expand with Run 2 data and Run 3**
  - Rarer QCD and QCD+EWK processes now accessible
  - Needed for Higgs physics program as well as search program
Additional Material
Backup slides and additional information

- ATLAS soft drop jet mass measurement
- CMS soft drop jet mass measurement
- ATLAS jet substructure measurements in $t\bar{t}$ events
- CMS jet substructure measurements in $t\bar{t}$ events
- ATLAS measurements of jet fragmentation
**ATLAS soft drop jet mass measurement**

(arXiv:1711.08341)

ATLAS

\[ \frac{d\sigma}{d\log_{10}(m_{\text{soft drop}}/p_T)} \]

**ATLAS**

\[ \mu s = 13 \text{ TeV, } 32.9 \text{ fb}^{-1} \]

Anti-\(k_T\), \(R=0.8\), \(p_T^{\text{lead}} > 600 \text{ GeV}, \text{ Data}\)

Soft drop \(\beta = 0, z_{\text{cut}} = 0.1\)

Soft drop \(\beta = 2, z_{\text{cut}} = 0.1\)

\[ 600 < p_T / \text{GeV} < 650 \times 10^0 \]
\[ 650 < p_T / \text{GeV} < 700 \times 10^1 \]
\[ 700 < p_T / \text{GeV} < 750 \times 10^2 \]
\[ 750 < p_T / \text{GeV} < 800 \times 10^3 \]
\[ 800 < p_T / \text{GeV} < 850 \times 10^4 \]
\[ 850 < p_T / \text{GeV} < 900 \times 10^5 \]
\[ 900 < p_T / \text{GeV} < 950 \times 10^6 \]
\[ 950 < p_T / \text{GeV} < 1000 \times 10^7 \]
\[ 1000 < p_T / \text{GeV} < 2000 \times 10^9 \]

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CMS soft drop jet mass measurement

### ATLAS jet substructure measurements in resolved $\bar{t}t$ events

**D. W. Miller (EFI, Chicago; ATLAS)**

**Jet substructure at the LHC – SUSY 2019**

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<table>
<thead>
<tr>
<th>Jet Substructure Selections</th>
<th>Detector Level</th>
<th>Particle Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dijet selection:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two trimmed anti-$k_t$ $R = 1.0$ jets</td>
<td>$p_T &gt; 200$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Leading-$p_T$-trimmed anti-$k_t$ $R = 1.0$ jet</td>
<td>$p_T &gt; 450$ GeV</td>
<td></td>
</tr>
<tr>
<td>Top and $W$ selections:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exactly one muon</td>
<td>$p_T &gt; 30$ GeV</td>
<td>$p_T &gt; 30$ GeV</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>z_0\sin(\theta)</td>
</tr>
<tr>
<td>Anti-$k_t$ $R = 0.4$ jets</td>
<td>$p_T &gt; 25$ GeV</td>
<td>$p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>JVT output $&gt; 0.5$ (if $p_T &lt; 60$ GeV)</td>
<td></td>
</tr>
<tr>
<td>Muon isolation criteria</td>
<td>If $\Delta R(\mu,\text{jet}) &lt; 0.04 + 10$ GeV /$p_T,\mu$: muon is removed, so the event is discarded</td>
<td>None</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}, m_T^W$</td>
<td>$E_T^{\text{miss}} &gt; 20$ GeV , $E_T^{\text{miss}} + m_T^W &gt; 60$ GeV</td>
<td></td>
</tr>
<tr>
<td>Leptonic top</td>
<td>At least one small-radius jet with $0.4 &lt; \Delta R(\mu,\text{jet}) &lt; 1.5$</td>
<td></td>
</tr>
<tr>
<td>Top selection:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leading-$p_T$-trimmed anti-$k_t$ $R = 1.0$ jet</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>$\Delta R(\text{large-radius jet, } b\text{-tagged jet}) &lt; 1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Delta \phi(\mu, \text{large-radius jet}) &gt; 2.3$</td>
<td></td>
</tr>
<tr>
<td>$W$ selection:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leading-$p_T$-trimmed anti-$k_t$ $R = 1.0$ jet</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>$1 &lt; \Delta R(\text{large-radius jet, } b\text{-tagged jet}) &lt; 1.8$</td>
<td></td>
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<tr>
<td></td>
<td>$\Delta \phi(\mu, \text{large-radius jet}) &gt; 2.3$</td>
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</table>
Correlations of jet substructure observables

- Deciding on observables to use in search is complex, understanding the correlations among them can be an important consideration
- Systematic uncertainties & complexity of results also important
ATLAS jet fragmentation measurements

- Excellent experimental control of charged particle measurements
- Systematic uncertainties at the level of 1–2%

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Excellent experimental control of charged particle measurements

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