Measurement of jet substructure observables using the ATLAS detector

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Miguel Villaplana
INFN

on behalf of the ATLAS Collaboration

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Outlook

- The Soft Drop algorithm
- Measurement of the soft-drop jet mass
- Measurement of substructure variables in ttbar and inclusive jet events
- New event generator configurations for the modelling of jet production
Jet substructure

- Jet substructure techniques are paramount to deal with boosted objects in the LHC

- New measurements of jet substructure are also solidifying our understanding of the internal structure of jets and the theory of QCD
  - $k_T$ splitting scales in $Z \rightarrow ll$ events at 8 TeV with the ATLAS detector. (JHEP08 (2017) 26)
  - **Soft-drop jet mass at 13 TeV.** (Phys. Rev. Lett. 121, 092001)
  - Measurement of substructure variables in $t\bar{t}$bar and inclusive jet events. (arXiv:1903.02942)
  - Multijet simulation for 13 TeV ATLAS analyses. (ATL-PHYS-PUB-2019-017)

- Non-negligible differences are observed between data and MC simulations

- Can constrain both analytic calculations in perturbative regime and soft-hadronic activity in non-perturbative region
Soft Drop

- Jet substructure tests QCD in a regime where a fixed-order is insufficient
  - Sensitive to soft and collinear radiation

- A precise analytic calculation of substructure variables (beyond leading log) not possible due to the presence of non-global logarithmic resummation terms (NGLs).
  - Related to particles radiating out of and then into jet

- A perfect example is jet mass

- Soft drop. JHEP 1405 (2014) 146
  - Jet grooming procedure that removes energy related to soft parton emission and pile-up
  - Formally insensitive to NGLs

- The distribution of the soft-drop mass has now been calculated at
  - NLO with NLL. JHEP07(2016)064
  - LO with NNLL. JHEP07(2017)132
The Soft Drop algorithm

- Take a jet, re-cluster its constituents with C/A, and go backwards in the C/A clustering sequence

![Diagram of jet clustering](image)

- If \( \frac{\min(p_T,1,p_T,2)}{p_T,1+p_T,2} > z_{cut} \left( \frac{\Delta R_{12}}{R} \right)^\beta \) then the jet is a soft drop jet.

- Otherwise, the highest \( p_T \) sub-jet is taken as a new candidate and the procedure is iterated.

- \( z_{cut} \) sets the scale of energy removal. Higher \( z_{cut} \) means more energy removed by grooming.

- \( \beta \) determines the sensitivity to wide-angle radiation.
  - Larger \( \beta \) means smaller fraction of soft small-angle radiation removed -> less grooming.
ATLAS measurement of the soft-drop jet mass

Soft-drop jet mass measurement

- Using anti-$k_T$ R=0.8 jets built from locally calibrated calorimeter-cell clusters

- Lowest un-prescaled trigger (400 GeV) and $p_{T,1} > 600$ GeV

- Dijet topologies: $p_{T,1}/p_{T,2} < 1.5$ for two leading jets

- Measuring dimensionless mass parameter, $\rho = m_{\text{softdrop}} / p_T^{\text{ungroomed}}$
  - Weak dependence on $p_T$
  - Distribution of $\log_{10}(\rho^2)$ studied for $\beta = 0, 1, 2$ and $z_{\text{cut}} = 0.1$

- Simultaneously unfolding in $\log_{10}(\rho^2)$ and jet $p_T$ distributions using Pythia LO predictions

- Three distinct regions
  - Non-perturbative region: $\log_{10}(\rho^2) < -3.7$ (soft and collinear emissions)
  - Resummation region: $-3.7 < \log_{10}(\rho^2) < -1.7$ (resummation dominates)
  - Fixed-order region: $\log_{10}(\rho^2) > -1.7$ (wide-angle hard gluon emissions)
Results

- Distributions normalised to data in resummation region
- MC generators do an excellent job of describing data over entire mass range
- Good agreement between data and analytic calculations in resummation and fixed-order regions
- Largest difference between MC and analytic predictions in non-perturbative regime
  - Effect larger for higher $\beta$ (smaller fraction of soft energy removed)
- Including non-perturbative effects improves the accuracy of the NLO+NLL prediction
ATLAS measurement of jet-substructure observables in ttbar and inclusive jet events

arXiv:1903.02942
Overview

- JSS variables are used extensively for top/W/Z and Higgs tagging
- No ATLAS unfolded measurement of variables at 13 TeV
- Useful for MC model and tagger developments
- A set of softdrop-groomed variables can be calculated analytically
  - strong theoretical motivation
- Large-radius jet substructure for: W, top, and light quark jets!
  - Semi-leptonic selections for W and top jets in ttbar events
  - Dijet selection for light quark jets in QCD events
- 8 observables for top, W and QCD jets
Observables

- (generalised) N-subjetiness

\[ \tau_N^{(\beta)} = \frac{1}{d_0} \sum_i p_{Ti} \min \{(\Delta R_{1,i})^\beta, (\Delta R_{2,i})^\beta \cdots (\Delta R_{N,i})^\beta\} \]

  - A set of N subjet axis are defined using the exclusive k_t algorithm.

- Normalised energy correlation functions (and ratios)

\[ e_2^\beta = \frac{1}{p_t^2} \sum_{j \in J} p_{Tij} R_{ij}^\beta \quad e_3^\beta = \frac{1}{p_t^3} \sum_{j < k \in J} p_{Tij} p_{Tjk} R_{ij}^\beta R_{jk}^\beta R_{ik}^\beta \]

  - Subjet-independent way to discriminate between a “two-pronged” jet and a single prong parton initiated jet.
  - Ratio of energy correlation functions:

\[ D_2^{\beta} = \frac{e_3^\beta}{(e_2^\beta)^3}, \quad C_2^{\beta} = \frac{e_3^\beta}{(e_2^\beta)^2} \]

- Les Houches angularity (LHA)

  - Used in various quark/gluon discrimination studies with \( \kappa = 1 \) and \( \beta = 0.5 \)

\[ \chi_\beta^{\kappa} = \sum_{i \in \text{jet}} \left( \frac{p_{Ti}}{\sum_{i \in \text{jet}} p_{Ti}} \right)^\kappa \left( \frac{R_{iT}}{R} \right)^\beta \]
Results

- Unfolded to particle level with Bayesian method

Pythia8 does best for light quark/gluon observables
- Herwig7 very different from data
- No meaningful differences seen between different hadronization models used in Sherpa
- Shifted peak suggest excess gluon radiation in predictions
Results

- Important discrimination for BSM physics tagging
- Clear differences in boosted jet shapes and substructures
- Detailed measurements and MC tuning essential for optimizing physics performance of both measurements and searches
Multijet simulation for 13 TeV ATLAS Analyses

ATL-PHYS-PUB-2019-017
Overview

- Measurement of the inclusive jet spectrum at 13 TeV
  - provide interesting inputs for the understanding of basic physics modelling features such as the parton shower or the hadronization model

- Measurement in distributions of global event observables and jet substructure variables

- Compared to different MC samples:
  - Pythia 8.230
  - Madgraph + Pythia 8.212
  - Herwig 7.1.3
    - PS: angular-ordered and dipole
  - Powheg + Pythia 8.230
  - Sherpa 2.2.5
    - Hadronization: cluster fragmentation (AHADIC) and string fragmentation (Lund)

- For this analysis, all jets (R=0.4) fulfilling $p_T > 100$ GeV and $|\eta| < 2.5$ are considered.
Results

- Fraction of $p_T$ in the outer band of the jets ($r=0.2$)
  - The green bands show the PS uncertainties for Pythia
  - The vertical error bars represent the stat. uncertainties

- MG5_aMC@NLO and Powheg predict narrower jets than Pythia 8
  - but compatible within the Pythia 8 shower uncertainties

- Herwig:
  - dipole parton shower predicts systematically narrower jets than Pythia 8
  - angular-ordered showers give, on average, wider energy distributions inside the jet cone

- Both Sherpa samples provide a very similar prediction to that of Pythia 8
Conclusions

- Jet substructure studies are essential to find new physics in post-Higgs era
- Proper estimation of uncertainties, and robustness against pile-up is critical
- Need measurements, and best possible MC modeling

Presented recent ATLAS measurements of substructure observables

- **Soft-drop jet mass at 13 TeV.** (Phys. Rev. Lett. 121, 092001)
  - Good agreement between data and calculations in resummation and fixed-order regions
  - MC generators do better in non-perturbative region
  - Results to be used to constrain future calculations and MC generator predictions

- **Measurement of jet substructure observables at 13 TeV.** (arXiv:1903.02942)
  - Uncertainties small enough to have discriminating power between the various MC models
    - useful to improve modeling
  - Help understand limitations of searches with boosted topologies
  - Improve the design and performance of tagging algorithms

- **Multijet simulation for 13 TeV ATLAS Analyses.** (ATL-PHYS-PUB-2019-017)
  - Significant differences in the description of substructure observables such as the jet mass found at low $p_T$ in both hadronization models implemented in Sherpa.
  - Both Herwig samples give very different descriptions of the jet shapes
    - the dipole parton shower giving significantly wider jets than the angular-ordered counterpart
Thanks
The Large Hadron Collider (LHC)
The ATLAS detector

- A Toroidal LHC ApparatuS
  - 44 m long, 25 m of diameter
  - 4 layers of detectors

- Inner detector
  - pixel, strip, TRT

- Electromagnetic calorimeter

- Hadronic calorimeter

- Muon detector
LHC and ATLAS performance

- At LHC two bunches of protons collide every 25 ns (40 MHz)
- LHC design instantaneous luminosity: $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

- Hard collisions -> between two elementary components of the protons (q or g)
- Other components of the same hadrons produce “underlying event”
- Several collision events per proton bunch crossing “pile-up events”
LHC and ATLAS performance

- Current center of mass energy $\sqrt{s}=13$ TeV
- Originally expected to get up to 120 fb$^{-1}$ by the end of 2018
- $\sim 160$ fb$^{-1}$ (!!) of proton-proton collision data registered by ATLAS in Run-II
What is a jet?

- At short distances quarks and gluons move as quasi-free particles (asymptotic freedom)
- When they are energetic, they produce bremsstrahlung cascades of gluons and q\bar{q} pairs, which then hadronise
- We see jets of tightly collimated hadrons

- There are a lot at the LHC! (dominant high $p_T$ process)
- Jet properties reflect those of the quarks and gluons which originated them
- A good handle to test the QCD sector of the SM over several orders of magnitude
  - Proton structure (PDF)
  - Strong coupling constant, $\alpha_s$
  - Perturbative QCD effects
  - Fragmentation/Hadronization effects
Jet reconstruction

- Sequential recombination algorithms most popular in the LHC era (G. Salam, arXiv:0906.1833)
- Collinear and infrared safe!

- The clustering inverts the parton shower by combining the constituents of the jet according to subsequent ‘distance’ criteria

\[
\begin{align*}
    d_{ij} &= \min(p_{T_{i}}^{2n}, p_{T_{j}}^{2n}) \times \frac{\Delta R_{i,j}^2}{R^2} \\
    d_{iB} &= p_{T}^{2n}
\end{align*}
\]

- Inclusive jet reconstruction: clustering continues until the minimum distance is found to be \(d_{iB}\)

  - **(n=1) \(k_t\):** Softest pair of constituents clustered first. Follows IR and collinear splittings.
  - **(n=0) Cambridge-Aachen (C/A):** Closest pair of constituents clustered first. Mimics angular-ordered parton shower.
  - **(n=-1) anti-\(k_t\):** Hardest constituent clustered with closest neighbour. Regularly shaped jets.
Jet substructure

● Classical “resolved” algorithms run into problems for highly boosted final states

● A large radius jet of $R > 2m/p_T$ can contain all decay products of a given particle
  ○ Top quark, Higgs/W/Z bosons, new heavy particles ...

● Internal structure of the large R jet shows interesting features that can be used to identify the origin of the jet
  ○ distinguish multi-jet background from signals
Jets in ATLAS

- Jet production is the dominant high-$p_T$ process in the LHC

- Jet observables play an important role in the study of:
  - The structure of the proton
  - The color interaction and its coupling strength $\alpha_s$

- Anti-$k_T$ jets

- Built considering topological clusters of calorimeter cells

- Clusters corrected for pileup prior to jet building

- Multi-stage calibration scheme

- Larger energy scale uncertainty than photons
ATLAS measurement of the soft-drop jet mass
Uncertainties

- Many uncertainties cancel since $p$ is a ratio

- QCD modeling uncertainties dominate
  - Particularly large at low mass where non-perturbative effects are largest

- Cluster energy uncertainties
  - Large at lower masses
    - Low cluster multiplicity
  - Also important at higher masses
    - Energy of hard prongs dominates the mass resolution instead of the opening angle

- Other uncertainties are subdominant
  - Pile-up negligible as expected
Unfolding

- Pythia used as nominal
  - Sherpa and Herwig++ to evaluate uncertainty

- Particle-level selection as close as possible to detector-level
  - Jets built using the same algorithm
  - Events must pass the same dijet requirement
  - Additional correction for the acceptance included

- $\log_{10}(\rho^2)$ and $p_T$ unfolded simultaneously

- Example of response matrix for the combined $p_T$ and $\log_{10}(\rho^2)$ bins
  - Each group of 10 bins corresponds to a different $p_T$ bin
  - Each bin within the $p_T$ bin corresponds to 10 evenly spaced bins in $\log_{10}(\rho^2)$
  - The bins are normalized so that the z-axis corresponds to the probability of a jet lying in a particular truth bin, given its reconstructed bin

- There are substantial migrations between the detector- and particle-level distributions, which cause large off-diagonal terms in the unfolding matrix especially at low values of $\log_{10}(\rho^2)$
Results: $\log_{10}(\rho^2)$ vs $p_T$

- $\log_{10}(\rho^2)$ for the $p_T$ bins used in the analysis (from 600 GeV up to 2000 GeV)
- As expected, there is no strong dependence on $p_T$
- Distributions normalised to data in resummation region
- MC generators do an excellent job of describing data over entire mass range
Results

- Good agreement between data and analytic calculations in resummation region
  - and fixed-order region for NLO calculations
- Including non-perturbative effects improves the accuracy of the NLO+NLL prediction
• Largest difference between data and MC/analytic predictions in non-perturbative regime
  ○ Effect larger for higher $\beta$ (smaller fraction of soft energy removed)
ATLAS measurement of jet-substructure observables
in ttbar and inclusive jet events
arXiv:1903.02942
<table>
<thead>
<tr>
<th>Process</th>
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<th>Version</th>
<th>PDF</th>
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<th>Use</th>
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<td>Two trimmed anti-$k_t$ $R = 1.0$ jets</td>
<td>$p_T &gt; 200$ GeV, $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
<td>$p_T &gt; 200$ GeV, $</td>
<td>\eta</td>
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<td>Exactly one muon</td>
<td>$p_T &gt; 30$ GeV, $</td>
<td>\eta</td>
<td>&lt; 2.5$, $</td>
<td>z_0 \sin(\theta)</td>
<td>&lt; 0.5$ mm and $</td>
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<td>\eta</td>
<td>&lt; 4.4$, JVT output $&gt; 0.5$ (if $p_T &lt; 60$ GeV)</td>
<td>$p_T &gt; 25$ GeV, $</td>
<td>\eta</td>
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<td>Muon isolation criteria</td>
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<td>$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>
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<td><strong>Leptonic top</strong></td>
<td>At least one small-radius jet with $0.4 &lt; \Delta R(\mu, \text{jet}) &lt; 1.5$</td>
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<td><strong>Top selection:</strong></td>
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<tr>
<td>Leading-$p_T$-trimmed anti-$k_t$ $R = 1.0$ jet</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.5$, $p_T &gt; 350$ GeV, mass $&gt; 140$ GeV, $\Delta R(\text{large-radius jet, }b\text{-tagged jet}) &lt; 1$, $\Delta \phi(\mu, \text{large-radius jet}) &gt; 2.3$</td>
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<td><strong>$W$ selection:</strong></td>
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<tr>
<td>Leading-$p_T$-trimmed anti-$k_t$ $R = 1.0$ jet</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.5$, $p_T &gt; 200$ GeV, mass $&gt; 60$ GeV and mass $&lt; 100$ GeV, $1 &lt; \Delta R(\text{large-radius jet, }b\text{-tagged jet}) &lt; 1.8$, $\Delta \phi(\mu, \text{large-radius jet}) &gt; 2.3$</td>
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</table>
Cluster and large R systematics dominate in all topologies
  ○ Largest effect on the majority of measured distributions from cluster energy smearing (CES)
Results

**ATLAS**

$\sqrt{s} = 13$ TeV, 33 fb$^{-1}$

Dijet selection, anti-$k_T$ R = 1.0, $p_T > 450$ GeV

Soft drop $\beta = 0$, $z_{cut} = 0.1$

- Data
- Pythia8
- Herwig7
- Sherpa (cluster)
- Sherpa (string)

**Top selection**

$\sqrt{s} = 13$ TeV, 33 fb$^{-1}$

Anti-$k_T$ R = 1.0, $p_T > 350$ GeV

Soft drop $\beta = 0$, $z_{cut} = 0.1$

- Data
- Powheg + Pythia8
- Powheg + Herwig7
- MG5 aMC + Pythia8
- Sherpa

**W selection**

$\sqrt{s} = 13$ TeV, 33 fb$^{-1}$

Anti-$k_T$ R = 1.0, $p_T > 200$ GeV

Soft drop $\beta = 0$, $z_{cut} = 0.1$

- Data
- Powheg + Pythia8
- Powheg + Herwig7
- MG5 aMC + Pythia8
- Sherpa

**ATLAS**

$\sqrt{s} = 13$ TeV, 33 fb$^{-1}$

Anti-$k_T$ R = 1.0, 1 jet

Soft Drop $\beta = 0$, $z_{cut} = 0.1$

- W selection
- Top selection
- Dijet selection
Results

\begin{align*}
\text{ATLAS} & \quad \sqrt{s} = 13 \text{ TeV}, 33 \text{ fb}^{-1} \\
\text{Top selection} & \quad \text{Anti-}k_t, \ p_T > 350 \text{ GeV} \\
& \quad \text{Soft drop} \beta = 0, \ z_{\text{cut}} = 0.1
\end{align*}

\begin{align*}
\text{ATLAS} & \quad \sqrt{s} = 13 \text{ TeV}, 33 \text{ fb}^{-1} \\
\text{Dijet selection} & \quad \text{Anti-}k_t, \ p_T > 450 \text{ GeV} \\
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& \quad \text{Soft drop} \beta = 0, \ z_{\text{cut}} = 0.1
\end{align*}
Multijet simulation for 13 TeV ATLAS Analyses

ATL-PHYS-PUB-2019-017
Overview

- Jet shape: normalized $p_T$ flow inside the jet cone as a function of the angular distance to the jet axis
- Two versions:
  - the differential jet shape is defined as the fraction of $p_T$ in a circular crown of width $\Delta r$ at a distance $r < R$ of the jet centroid
    \[
    \rho(r) = \frac{1}{\Delta r} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)}
    \]
  - the integrated jet shape is defined as the cumulative distribution $\rho(r)$. Geometrically, it can be regarded as the fraction of momentum in circles of radius $r < R$ taken from the jet axis
    \[
    \Psi(r) = \frac{p_T(0, r)}{p_T(0, R)}
    \]
- Both are sensitive to the kinematics of the jet under study.
  - the radiation around the original parton becomes more collimated when increasing the jet $p_T$, giving higher values of $\rho(r)$ for small values of $r$ and also higher values of $\Psi(r)$ overall
Results

- Pythia 8 shower uncertainty largest at low $p_T$, but negligible at mid/high $p_T$
- Powheg + Pythia 8
  - reduced impact of the combined ME+PS uncertainties at low $p_T$ (one extra parton included at ME at LO)
  - uncertainty slightly increases as a function of the jet $p_T$ (due to the increase in PDF uncertainty)
- Sherpa two different hadronization models show differences of up to 45%
  - low $p_T$ jets described by the cluster model are more collimated than their string model counterparts
    - as the mass distribution peaks at lower values