Studies of Jet Shapes and Substructure with the ATLAS Experiment

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The internal structure of jets produced in proton-proton collisions at 7 TeV centre-of-mass energy provides a direct test of QCD which is largely orthogonal to other measurements of jets. The ATLAS experiment at the CERN LHC has measured a number of distributions related to the distribution of energy inside jets including jet shapes, fragmentation functions, masses and substructure variables.

1 Introduction

The ATLAS detector observes proton-proton collisions provided by the CERN Large Hadron Collider [1]. The results presented here use the 2010 ATLAS dataset, consisting of 35 pb^{-1} of collisions with a centre-of-mass energy of 7 TeV. A key feature of the ATLAS detector is excellent calorimeter granularity. The electromagnetic calorimeter has granularity ranging from 0.025×0.025 to 0.1×0.1 in the $\eta - \phi$ plane. The finest region of the hadronic calorimeter has granularity of 0.1×0.1.

Measurements of jet production at ATLAS have contributed to the understanding of QCD at higher energies than ever before explored at a hadron collider. In addition to testing the production of jets however, it is also informative to look inside jets at their internal structure. The structure of jets is influenced by a wide range of physics, such as fragmentation and hadronisation, and also hard physics, colour connections, underlying-event, pile-up and heavy particle production. Measurements of the internal structure of jets therefore help test models of all these processes. Additionally, for the first time at the LHC heavy particle production in jets can often include W and Z-bosons and top quarks.

2 Jet Shapes

Jet shapes determine the fraction of the p_{T} of a jet which is within an annulus centred on the jet radius. Formally quantities are defined such as:

$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N^{\text{jet}}} \sum_{\text{jets}} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)}.$$

Where R is the radius of the jet and r is a distance from the jet axis, both defined in the $y - \phi$ plane. $p_T(a, b)$ is a function which gives the total p_T of particles which are between a and

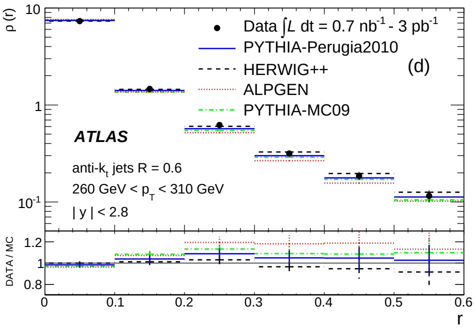

Figure 1: The measured differential jet shape, $\rho(r)$, in inclusive jet production. Error bars indicate the statistical and systematic uncertainties added in quadrature [3].

b away from the jet axis. It can be seen from this definition that ρ is the density of energy at a certain distance from the jet axis in $y - \phi$ space.

ATLAS has measured $\rho(r)$ for anti-k_t [2] jets with R-parameters of 0.4 and 0.6, corrected for detector effects and compared the resulting distributions to a number of predictions from Monte Carlo packages [3]. Figure 1 shows some of these results. Although there is clearly variation between different Monte Carlo models and tunings, the distributions are generally well reproduced.

3 Jet Fragmentation

An alternative way to study the internal structure of jets is to study the momenta of individual particles inside jets. Specifically, for a jet with four-momentum $\overline{p}_{\mathrm{jet}}$ and a charged particle inside the jet with four-momentum $\overline{p}_{\mathrm{ch}}$, the following variables are defined:

$$z = \frac{\overline{p}_{\mathrm{jet}} \cdot \overline{p}_{\mathrm{ch}}}{|\overline{p}_{\mathrm{jet}}|^2} \qquad p_{\mathrm{T}}^{\mathrm{rel}} = \frac{|\overline{p}_{\mathrm{ch}} \times \overline{p}_{\mathrm{jet}}|}{|\overline{p}_{\mathrm{jet}}|} \, .$$

These quantities represent the projection of the momentum of the charged particle along and transverse to the jet axis respectively. Differential cross-sections are defined as:

$$F(z, p_{\mathrm{Tjet}}) = \frac{1}{N_{\mathrm{jet}}} \frac{dN_{\mathrm{ch}}}{dz} \quad \text{and} \quad f(p_{\mathrm{T}}^{\mathrm{rel}}, p_{\mathrm{Tjet}}) = \frac{1}{N_{\mathrm{jet}}} \frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}^{\mathrm{rel}}} \, .$$

ATLAS has measured these differential cross-sections for anti-k_t jets with and R-parameter of 0.6, corrected for detector effects [4]. Figure 2 shows a sample of these measurements compared to predictions from Monte Carlo packages. Again there are differences between the predictions of different Monte Carlo generators and tunings however all models correctly predict the overall shape of the distributions.

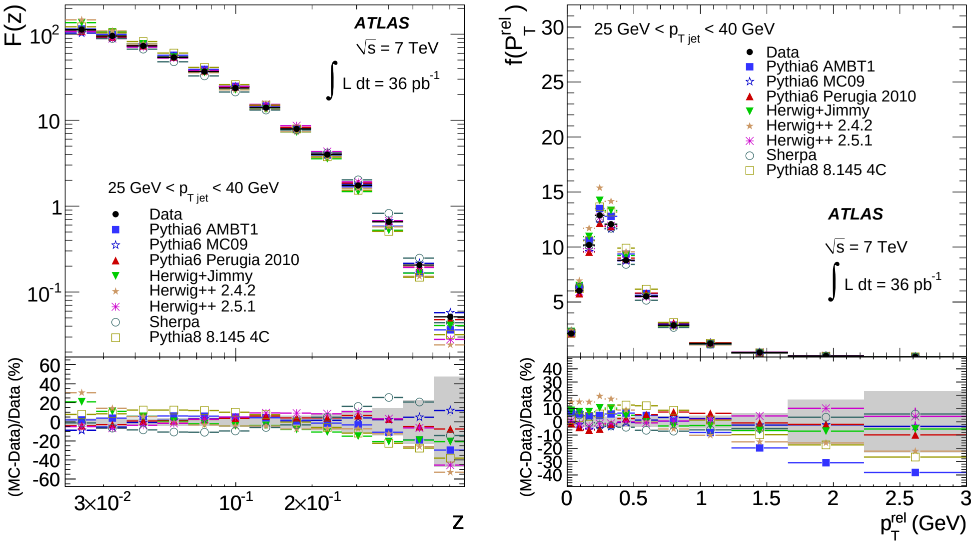

Figure 2: The measured differential cross-sections as a function of z (left) and p_{T}^{rel} (right) for anti-k_t jets with R-parameter 0.6 in the p_{T} range 25 to 40 GeV[4].

4 Jet Mass and Substructure

Recent phenomenological studies [5] have highlighted the potential for studies of jet mass and substructure in searches for new physics. Generally these searches centre on the idea that heavy particles such as W and Z bosons, top quarks and Higgs bosons could be produced with large Lorentz boosts at the LHC. At sufficiently large boosts, the decay products are collimated such that they are identified as a single jet in a detector. This type of jet has an invariant mass close to that of the parent particle and also distinctive internal structure which can be used to discriminate against jets from purely light QCD processes. Often these searches focus on larger radius jet algorithms in order to capture a whole heavy-particle decay.

ATLAS has measured a number of quantities related to this topic in anti-k_t jets with R-parameter of 1.0 and Cambridge-Aachen [6, 7] jets with R-parameter of 1.2 [8]. Jet mass is defined simply as the mass component of the jet four-momentum. Also measured was jet mass after the jet had been subjected to a procedure known as “splitting and filtering” [9]. This procedure searches through the clustering history of a jet to identify interesting structure and retains only radiation likely to relate to this structure, reducing the effective area of the jet. Additionally two variables designed to identify jets containing heavy particles, N-subjettiness [10] and k_t splitting scales [11] were measured. Finally the pile-up dependence of mean mass was also explored.

Two example results can be seen in Figure 3, which shows the jet mass distributions for Cambridge-Aachen jets with an R-parameter of 1.2 before and after applying the splitting and filtering procedure. HERWIG++ 2.4.2 does not describe the jet mass before splitting and filtering. However, differences between Monte Carlo generators and the data are significantly reduced by the application of the splitting and filtering procedure, implying that this procedure reduces sensitivity to soft physics.

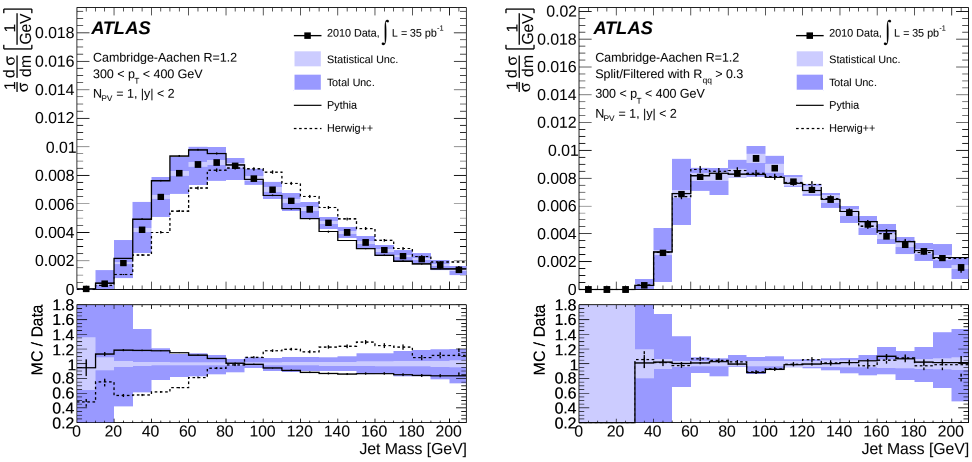

Figure 3: The measured differential cross-sections as a function of jet mass for Cambridge-Aachen jets with R-parameter 1.2 (left) and the same jets after the application of splitting and filtering (right) in the p_{T} range 300 to 400 GeV[8].

5 Conclusions

The study of the internal structure of jets is an interesting opportunity to test our understanding of QCD in new ways. ATLAS has measured a number of quantities relating to the internal structure of jets, including jet shapes, fragmentation functions, mass and substructure variables. These measurements make it possible to improve Monte Carlo models and tunings which is crucial for ATLAS as many new physics searches rely on accurate models of QCD backgrounds.

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