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Measurement of jet properties with the ATLAS detector

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The average charge and the multiplicity of charged hadrons within a jet provide new insights into the modeling of strong interactions. The jet charge can also be used to tag hadronically decaying gauge bosons and the number of charged particles within a jet provides a powerful means to distinguish gluon-initiated from quark-initiated jets. The ATLAS collaboration has used a selection of di-jet events in 20.3 fb^{-1} of data collected at a center-of-mass energy of 8 TeV to measure the average charged-particle multiplicity and the transverse-momentum weighted average charge of the hadrons within the jets, separately for the more central and the more forward jets and as a function of the jet transverse momentum. The results have been compared with calculations at next-to-leading order (NLO) in pQCD and with predictions of MC generators interfaced with various parton distribution functions and underlying-event tunes.

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The strong interaction intervenes in various ways at multiple scales in every single LHC event [1]. At large distance scales (corresponding to $\Lambda \lesssim 1$ GeV), theoretical predictions from quantum chromodynamics (QCD) cannot be obtained from a perturbative expansion of the Hamiltonian. The description of proton distribution functions (PDFs), gluon fragmentation, or hadrons formation (hadronization) must therefore involve phenomenological modelings and ancillary measurements, with their corresponding uncertainties. The transition between large distance and short distance scales can be perturbatively described using the DGLAP evolution equations. To account for this, event generators and cross section calculations must be supplemented with parton shower or resummation algorithms introducing extra assumptions, approximations, and parameter dependences in the calculation, leading to extra uncertainties on the various predictions. For example, parton showers are formulated using a soft and collinear approximation, their kernel functions are calculated at leading order, and they require a choice of ordering parameters affecting the predictions. It is of prime importance for the LHC physics program and its discovery potential to be able to test and improve the modeling of these large-to-small distance QCD corrections.

The Pythia [2] and Herwig [3] generators use different approaches to model these effects. For example, Pythia (version 8.175) uses a p_T-ordered parton shower, natural for a shower partly based on a dipole subtraction approach, while Herwig++ (version 2.63) uses an angular-ordered parton shower, designed to deal with quantum interferences between multiple parton emissions. In addition, these two generators differ in their fragmentation model (Lund string linear confinement model for Pythia; cluster pre-confinement model for Herwig), and in their multiple interaction tunings (Pythia uses the many parameters AU2 or A14 ATLAS-based tunes, while Herwig uses the fewer parameters EE3 or EE5 tunes). Many physics quantities, such as the number of charged particles in an event, are sensitive to these differences. It can lead to possibly large uncertainties on the predictions on di-jet invariant mass distributions, missing transverse momentum-related (E_T^{miss}) observables, or cross section predictions for events with large jet rapidity gap, to name a few. To improve the theoretical description of these quantities, measurements of observables sensitive to charged-particle multiplicity in events involving hadronic jets must be performed with the highest possible precision.

Using 20 fb^{-1} of 8 TeV data, ATLAS performed two sets of measurements sensitive to the charged-particle multiplicity inside jets:

- The average jet charged-particle multiplicity $< n_{charged} >$ defined as the number of particles fiducial to a jet leaving a track in the detector with a transverse momentum above a certain threshold $p_{T,min}^{track}$ [4];
- The jet charge defined as the momentum-weighted sum of the charge q_i of particle i in a jet J: $Q_J = \frac{1}{(p_{T,J})^\kappa} \sum_{i \in tracks} q_i \times (p_{T,i})^\kappa$, where the parameter κ regulates the sensitivity of the jet charge to very soft particles. The jet charge being a quantity that varies from event to event, ATLAS measured [5]:
  - the average jet charge μ_{Q_J} as a function of the p_T of the jet
  - the standard deviation of the jet charge σ_{Q_J} as a function of the p_T of the jet.

The right panel of Fig. 1 presents the comparison of the average jet charged-particle multiplicity measurement results, after unfolding, to the Pythia 8 predictions for three different transverse momentum thresholds. We can see that the average number of tracks in a jet increases with the p_T of the jet. This is expected because higher p_T jets will be produced in events with higher Q^2, and so will involve higher parton emission, and more energy stored in the gluon field before it fragments. The left panel of Fig. 1 presents the comparison of average jet charge measurement results for more forward jets with predictions for various κ values. The increase in the jet charge fraction with the p_T of the jet that can be observed correlates with an enhancement of the PDF up-flavor at increasing jet p_T for higher rapidity jets. The most striking feature of these two plots is however the very strong discrepancy observed between data and predictions, even if these discrepancies get somewhat reduced when very soft activity is suppressed by a higher p_T threshold on the jet charged-particle multiplicity or by a higher κ parameter in the jet charge definition. The question is then to determine which QCD effect(s) is (are) mismodeled in the simulation used for the predictions.

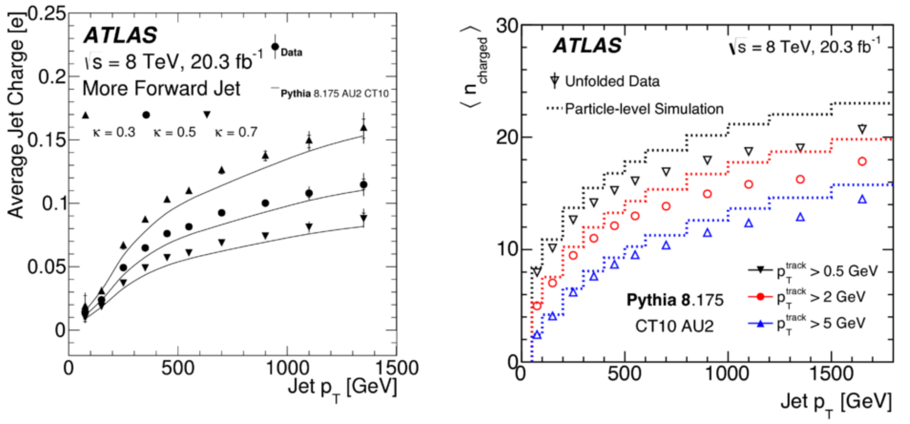

Figure 1: Comparison between Pythia 8 (v1.875) predictions and the unfolded measurement results obtained from ATLAS 8 TeV data for different observables. Left: The observable is the average jet charge for various κ parameter values (0.3, 0.5 and 0.7) for more forward jets [5]. Right: The observable is the charged-particle multiplicity in a jet for various values of the charged-particle p_T thresholds (0.5 GeV, 2.0 GeV and 5.0 GeV) [4].

First, it was verified that varying the PDF does not improve the agreement between data and predictions. To study the impact of the final-state parton radiation modeling on the description of the average jet-charge observables, Pythia 6 RadHi and RadLow parton shower tunes [6] are compared to the measurement results. In these tunes, the scale at which α_S is obtained is varies by half (RadLow) and by two (RadHi) reducing or enhancing the final-state parton radiation from the main quark initiating the jets. The impact of the fragmentation and hadronization are studies by comparing Pythia 8 to Herwig++ predictions, for a compatible level of final-state radiation, but using a different parton shower ordering parameter. The results of these comparison are presented in Fig. 2. The left panel of this figure indicates that for low κ values, the average jet charge is quite sensitive to the modeling of fragmentation and hadronization, but not to variations in the final-state parton radiation. On the other hand, the right panel indicates that for larger value of κ, the average jet charge is very sensitive to amount of final-state parton radiation included in the predictions, and much less sensitive to the fragmentation and hadronization models used to yield the jets from the partons. The same observations can also be made from the comparison of the jet charge standard deviation distribution to the predictions, as can be seen in Fig. 3. Results indicate that the Pythia 8 fragmentation and hadronization models yield a better description of ATLAS data than Herwig++. However, Pythia's default parton shower tune slightly overestimates the amount of gluon emission needed to provide a good description of the average and standard deviation jet charge when the the very soft activity is suppressed by using a large κ factor. Very similar conclusions can be obtained from the average charged-particle multiplicity inside jets. As can be seen in Fig. 4, predictions largely vary when the amount of final state radiation is varied, with data favoring less radiation than what is included in the default Pythia 6 P2012 tune. In addition, this figure indicates that $< n_{charged} >$ is not wildly sensitive to the underlying event tune used to obtain the predictions. Finally, it features a dependence on the fragmentation and hadronization model used in the predictions, agreeing better with Pythia at low jet p_T, but with Herwig++ at high jet p_T.

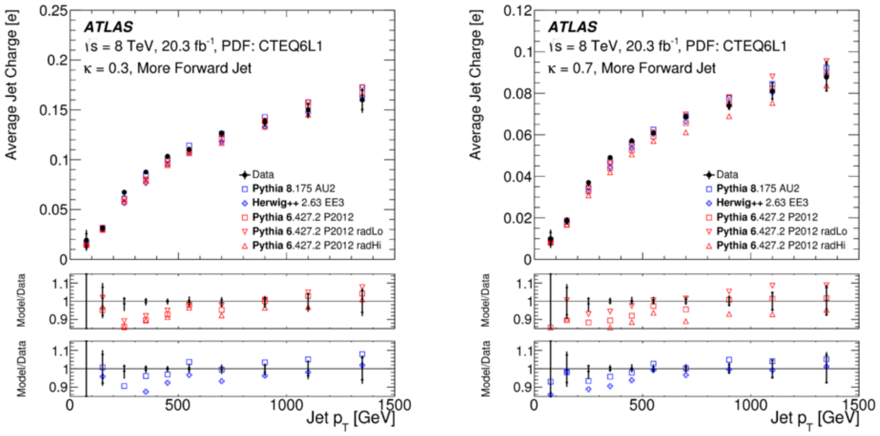

Figure 2: The average of the jet charge distribution in units of the positron charge for (left) κ=0.3; and (right) κ=0.7 comparing various QCD MC models and tunes for the more forward jet [5]. The crossed lines in the bars on the data indicate the statistical uncertainty and the full extent of the bars is the sum in quadrature of the statistical and systematic uncertainties.

In addition of allowing for tests of various QCD effects implemented in event generators, and to offer observables suitable for the tuning of fragmentation, hadronization and parton shower model free parameters, these observables are sensitive to the parton content of protons. The average charged-particle multiplicity in a jet has the tendency to be larger for gluon than for quark jets because of their larger color factor, while the average jet charge is different for jets originating from up and down quarks. Assuming the flavor-fraction provided by PDF predictions for various parton flavor initiating a jet, these observables could be used to tag the flavor of light jets. As can be seen on the left panel of Fig. 5, the measurement of the average jet charge demonstrates that this observable can be used to separate up-quark jets from down-quark jets. This jet tagging is essentially independent of the value given to the κ parameter defining the observable. Similarly, the average charged-particle multiplicity in a

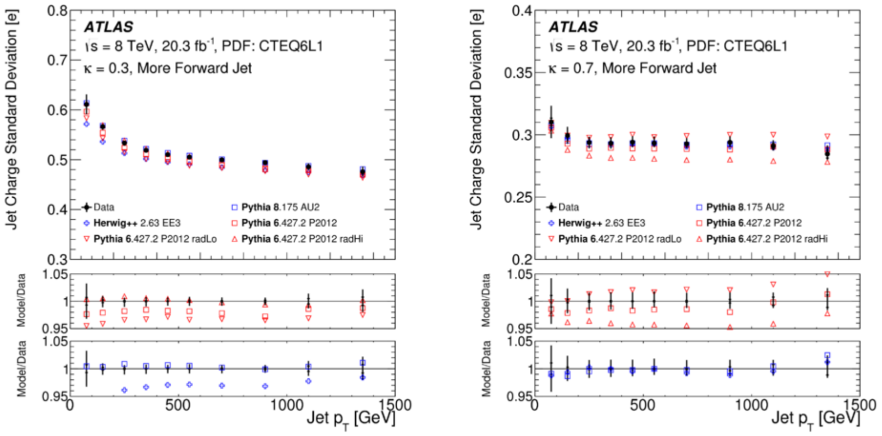

Figure 3: The standard deviation of the jet charge distribution in units of the positron charge for (left) κ=0.3; and (right) κ=0.7 comparing various QCD MC models and tunes for the more forward jet [5]. The crossed lines in the bars on the data indicate the statistical uncertainty and the full extent of the bars is the sum in quadrature of the statistical and systematic uncertainties.

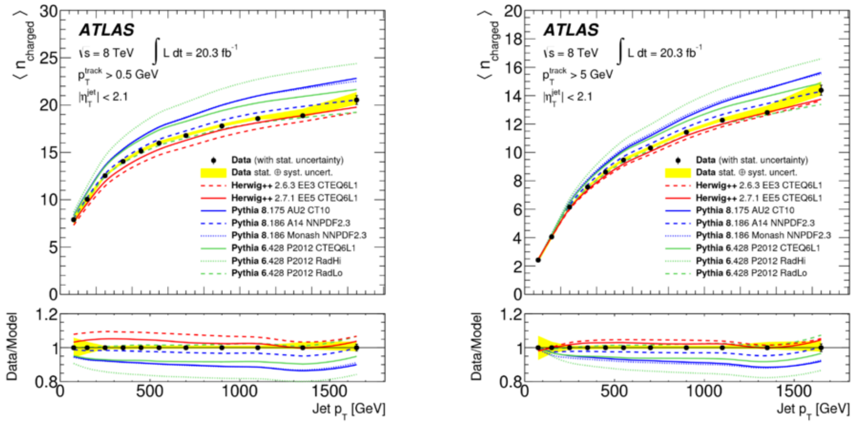

Figure 4: The measured average charged-particle multiplicity as a function of the jet p_T for (left) $p_{T,min}^{track}$>0.5 GeV; and (right) $p_{T,min}^{track}$>5 GeV [4]. The band around the data is the sum in quadrature of the statistical and systematic uncertainties. Error bars on the data points represent the statistical uncertainty (which are smaller than the markers for most bins).

jet is very sensitive to the difference between quark and gluon jets. That difference is larger than the sensitivity of the observable to the QCD modeling of final state radiation, matrix element calculation, and fragmentation and hadronization models.

In conclusion, the average and standard deviation of jet charge, and the average charged-particle multiplicity inside jets, obtained as a function of the p_T of the jet, are observables sensitive to various QCD effects. The ATLAS Collaboration performed a comprehensive set of measurements of these observables on the bulk of its 8 TeV dataset, and compared the unfolded results to various modeling of QCD effects such as parton shower, parton distribution

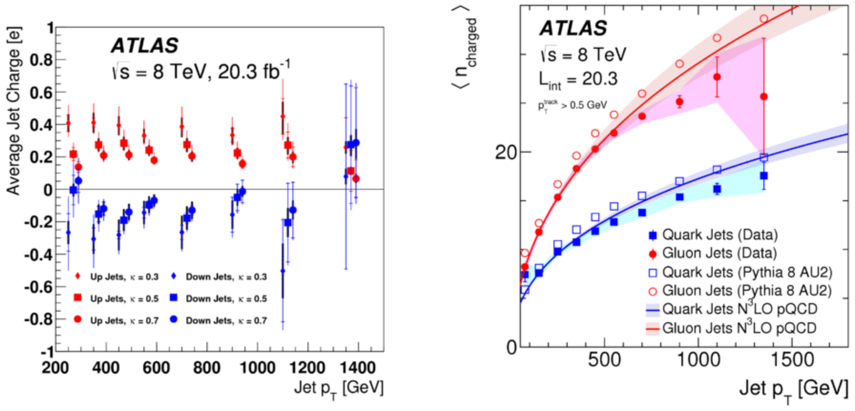

Figure 5: Left: The extracted value of up- and down-quark jet charges in units of the positron charge in bins of jet p_T for κ=0.3, 0.5, and 0.7 [5]. Right: The jet p_T dependence of the average charged-particle multiplicity ($p_{T,min}^{track}$>0.5 GeV) for quark- and gluon-initiated jets, extracted with the gluon fractions from PYTHIA 8.175 with the CT10 PDF [4]. In addition to the experimental uncertainties, the error bands include uncertainties in the gluon fractions from both the PDF and ME uncertainties.

functions, fragmentation and hadronization. Observed discrepancies between data an predictions cannot be explained by PDF variations, but are sensitive to the amount of final-state parton radiation generated by the parton shower and to the fragmentation and hadronization models used to describe the parton-to-jet transition. A robust strategy to improve the accuracy of the modeling of these QCD effects would consist in using the standard deviation of the jet charge with a low κ value to tune the fragamentation, hadronization and parton shower models, and then to use the same observable at a high κ value to tune the parameters controlling the amount of final-state parton radiation yielded by the parton shower. These tunings can then be tested and even adjusted using the average jet charge distribution with both low and high κ values. Such procedure would allow for a better description of observables measured in event topologies more sensitive to soft partonic activity. Finally, these observables, as well as the average charged-particle multiplicity inside jets, can be used to determine the flavor (up, down, gluon) of the parton initiating a jet. This information can be used to separate signal from background in new physics searches.

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