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# Gluon/quark jet substructure

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Jet substructure plays an important role in understanding the dynamics of a jet, measurements of the standard model physics, and searches for the physics beyond the standard model. This presentation summarizes the recent measurements of quark and gluon jet substructure performed by the ATLAS and CMS Collaborations.

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## 1. Introduction

Quarks and gluons, generally known as partons, produced during a collision in particle colliders are observed as a cluster of stable particles. These particles are kinematically combined using dedicated clustering algorithms to reconstruct the initial parton. Distributions, spatial as well as momentum, of these stable particles provide a handle to identify the nature of the original parton. This correlation led to rising interest in theoretical understanding and experimental studies to investigate the jet substructure. Partons originating from the decays of the heavy, Lorentz-boosted particles e.g., top quarks or W, Z, or Higgs bosons, have characteristic distributions of the jet constituent particles. Therefore, the jet substructure can also be used in the measurements of heavy and boosted objects. The jet substructure is also used in experimental measurements for mitigating the pileup contribution. There is a range of measurements by LHC experiments related to the studies of jet substructure and their usage as an important handle for different analyses [1–7]. In this talk, we discuss recent measurements by the ATLAS [8] and CMS [9] experiments to investigate the substructure of quark and gluon jets.

## 2. Measurements of soft-drop jet observables at 13 TeV

The ATLAS Collaboration measured soft-drop jet observables using proton-proton collision data at 13 TeV corresponding to an integrated luminosity of 32.8 $\mathrm{fb}^{-1}$ [10]. Here, substructure observables are measured with soft-drop grooming which suppresses the contributions of soft and wide angle radiations. In this measurement, jets are clustered using the anti-$k_\mathrm{T}$ algorithm with a radius parameter of 0.8 and required to have $p_\mathrm{T} > 300$ GeV and $|\eta| < 1.5$. The subjets are identified by reclustering the selected jet with the Cambridge-Aachen algorithm. Soft drop condition for the last two subjets reads as:

$$\frac{min(p_{T,j1}, p_{T,j2})}{p_{T,j1} + p_{T,j2}} > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta} \quad (1)$$

This measurement is performed with $z_{cut} = 0.1$ and $\beta \geq 0$. With these conditions, relative jet mass ($\rho = log\frac{m^2}{p_T^2}$, where ‘m‘ is the groomed mass and ‘$p_T$‘ is ungroomed), $p_\mathrm{T}$-balance ($z_g$), and opening angle between two subjets ($r_g$) are measured. Measurements are found to be in good agreement with the Monte Carlo predictions and the analytical calculations. The importance of nonperturbative calculations is obvious in the small values of $\rho$ and $r_g$, as shown in Figure 1 (left). The observables are also measured using only charged particles which led to a significant reduction in the correction factors and systematic uncertainties. The observables, with only charged particles, have better sensitivity in discriminating between quark-initiated and gluon-initiated jets. Subsequently, these observables are used to extract the distributions for quark-initiated and gluon-initiated jets using a template fit method. Extracted distributions for the $\rho$ variable are shown in Figure 1 (right). Separation power increases with $\beta$ parameters. It was observed that relative mass for the gluons-initiated jet is on the higher side due to the large associated color factor. There are many interesting observations from this measurement that can be found in Ref. [10].

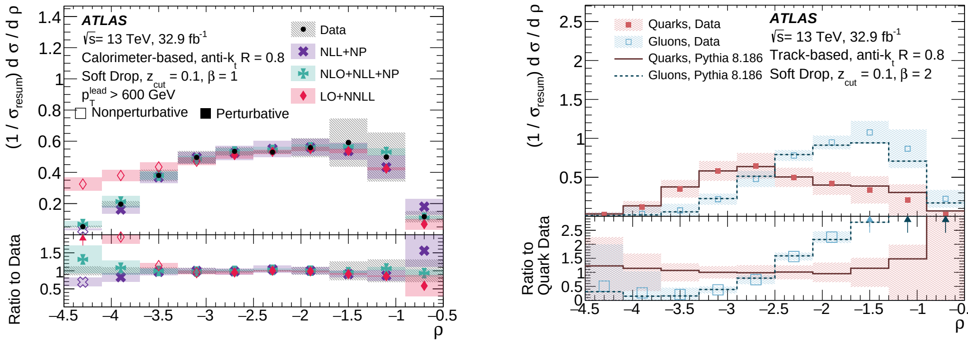


**Figure 1:** Left: Comparison of the unfolded $\rho$ distribution with the theoretical predictions. The theory error bands include perturbative scale variations as well as nonperturbative model variations (NLO+NLL only). Right: Comparison of the quark and gluon unfolded $\rho$ distributions for the track-based measurement [10].

## 3. Study of quark and gluon jet substructure in Z+jet and dijet events from pp collisions

The CMS Collaboration performed a measurement of the generalized angularities in dijet and Z + jet processes using proton-proton collision data corresponding to an integrated luminosity of 35.9 fb$^{-1}$ [11]. This analysis measured jet constituent multiplicity, thrust, width, $(p_{\mathrm{T}}^{\mathrm{D}})^2$, and LHA observables for different configurations i.e., 0.4 vs 0.8 jet radius parameters, observables with charged particles only vs all particles, central vs forward rapidity, $p_{\mathrm{T}}$ dependence and effect of grooming. The measured distributions, for Z + jet events, are better described by Madgraph + Pythia8. Herwig++ predicts smaller values than Pythia 8 except for $(p_{\mathrm{T}}^{\mathrm{D}})^2$. In dijet events, Monte Carlo predictions provide a worse description than for Z + jet events. Analytical calculations provide a good description of the measured observables, except for the LHA. The mean of the different angularities decreases with jet $p_{\mathrm{T}}$, described qualitatively by predictions, which is expected due to increasing Lorentz-boost. The Monte Carlo predictions underestimate the mean values except for Madgraph + Pythia8, which describes well at low $p_{\mathrm{T}}$ but overestimates at higher $p_{\mathrm{T}}$. Madgraph + Pythia8 provides a better description of the observables in a quark enriched region where Herwig++ fails. Sherpa's predictions do a good job of describing the observables in a gluon-enriched region. A larger value of $\alpha_s$ predicts larger values of measured angularities, except that of $(p_{\mathrm{T}}^{\mathrm{D}})^2$. Gluon jets have larger values for measured angularities except for $(p_{\mathrm{T}}^{\mathrm{D}})^2$. Discrimination, between a quark and gluon jet, the ability of the measured observables decreases with the jet $p_{\mathrm{T}}$. Overall, the Sherpa prediction provides a better description of the differences between a quark and a gluon jet, whereas other predictions overestimate the differences. One of the comparison plots for different configurations is shown in Figure 2. There are many other interesting features that can be explored in Ref. [11].

## 4. Summary

The jet substructure is gaining importance in many experimental measurements from the standard model to searches for new phenomena. This talk summarized the recent measurements

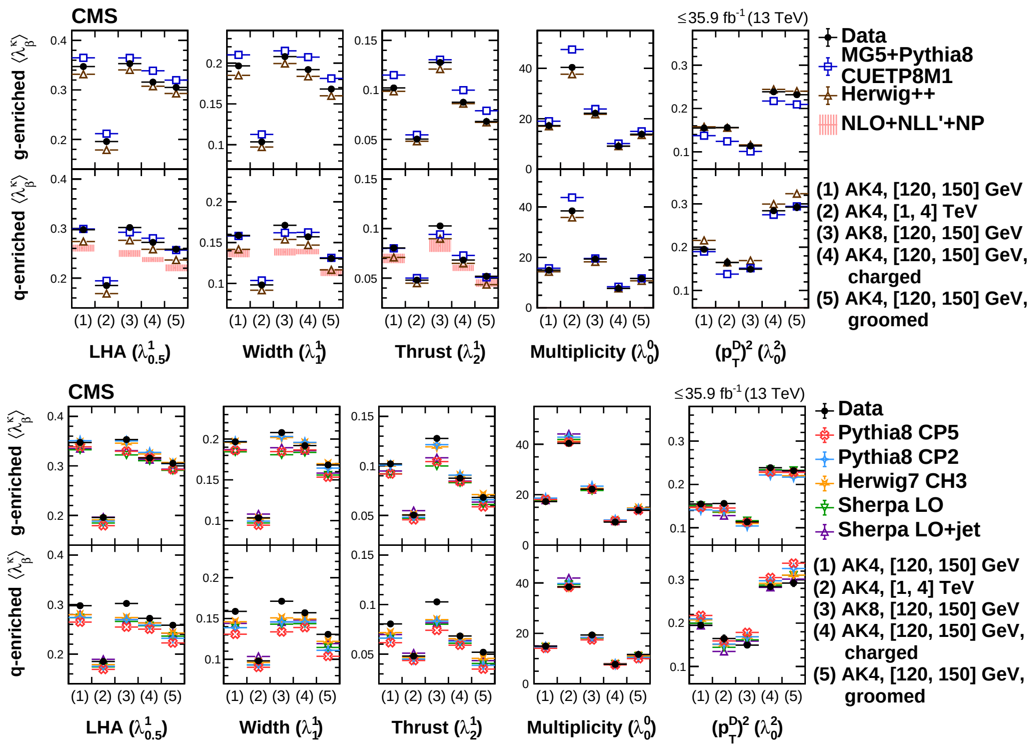


**Figure 2:** Mean value of substructure observables in regions with gluon-enriched and quark-enriched jets, for the different configurations. The upper and lower plots show the same data distribution compared with different generator predictions. The error bars on the data correspond to the total uncertainties. The error bars on the simulation correspond to the statistical uncertainties [11].

by the ATLAS and CMS experiments using proton-proton collision data at $\sqrt{s}$ = 13 TeV. These measurements investigate jet substructure with different event topologies and phase-space. The Monte Carlo predictions are doing a good job in describing the measurements, but there is a scope for further improvements in constraining the associated uncertainties.

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