Quark-gluon Jet Discrimination At CMS

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ABSTRACT

Many physics analyses at the LHC are looking into processes where the signal jets are originating from quarks, while jets in the background are more gluon enriched. Based on observables sensitive to fundamental differences in the fragmentation properties of gluons and quarks, a likelihood discriminant is constructed to distinguish between jets originating from quarks and gluons. The performance of the tagger is evaluated using Z+jets and dijet events produced in proton-proton collisions at a centre-of-mass energy of 8 TeV, recorded by the CMS experiment at the LHC.

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1 Construction of a quark-gluon likelihood discriminant

Because of different colour interaction and hadronization, gluon jets are wider, with higher multiplicities and have a more uniform energy fragmentation, while quark jets are more likely to produce narrow jets with hard constituents that carry a significant fraction of the energy. The CMS quark-gluon likelihood discriminant makes use of these jet properties through variables provided by the CMS particle-flow reconstruction. The individual discrimination performances of such variables can be described using receiver operating characteristic (ROC) curves (Figure 1). These curves, derived from simulation, show the efficiency to select a quark jet for possible selection cuts used to reject different fractions of gluon jets.

![ROC curves for quark-gluon jet discrimination](image)

Figure 1: Single variable performance comparisons for quark-gluon jet discrimination using ROC curves for central jets with $80 < p_T < 100$ GeV (left) and forward jets with $50 < p_T < 65$ GeV (right). The rationale and detailed definition of the chosen variables can be found in Ref. [1].

Based on their performance and robustness with respect to track reconstruction, particle identification and pile-up, three variables are chosen to build a likelihood discriminator:

- the **multiplicity**, i.e. the total number of particle flow candidates reconstructed within the jet
- the jet **energy sharing** variable
  \[ p_T D = \sqrt{\sum_i p_{T,i}^2} / \sum_i p_{T,i} \]
  which has $p_T D \to 1$ for jets made of only one particle that carries all of its momentum and $p_T D \to 0$ for a jet made of an infinite number of particles
- the **angular spread** is measured by minor axis $\sigma_2$ of the jet in the $\eta - \phi$ plane

A better discrimination power and stability to pile-up effects is found by restricting the charged particle flow candidates to those linked to tracks compatible with the primary interaction vertex, and restricting the neutral particle flow candidates to those who have a transverse momentum larger than 1 GeV. The likelihood discriminant is binned in $p_T$ and pile-up ($\rho$) in order to account for the strong dependence of the means and shapes of the variables. The discriminant is constructed for jets in both the central (with pseudorapidity $|\eta| < 2.4$) and forward region (with $2.4 < |\eta| < 4.7$).

2 Validation on data

The performance of the discriminator has been validated on 8 TeV data by identifying two control samples, each aimed at enriching one of both parton flavours. A Z+jets control sample, with the leading jet being back-to-back with the Z in the transverse plane by requiring their azimuthal difference to be greater than 2.5 radians, is expected to offer a relatively pure sample of quark jets. A dijet sample, where the back-to-back requirement is applied on the azimuthal angle between the two leading jets, provides us a gluon-enriched sample. Validations for both data samples, compared with simulation, are shown in Figure [3].
A smearing function is chosen to vary the discriminator shape in simulation to match the shape in data:

\[ g(x, a, b) = \frac{1}{2} \tanh(a \arctanh(2x - 1) + b) + \frac{1}{2} \]

The two parameters \((a, b)\) allow the population to shift through the center and towards the center or the extremes, while still keeping the distribution between 0 and 1. The values of these parameters are obtained by a minimisation of the \(\chi^2\) obtained from a comparison between data and simulation. The same smearing functional form is applied independently on the quark and gluon distributions. The application of the smearing to the likelihood discriminant is shown in Figure 4.

Because a different hadronization model will result in slightly different input variables, and therefore a different discriminator output, the optimisation of the smearing parameters is performed independently for both PYTHIA 6 and HERWIG++ simulations. As shown in Figure 5, the smearings correct for the worse discriminating performance in data compared to the PYTHIA 6 simulation, and for the better performance compared to the HERWIG++ simulation. After applying the smearing functions, PYTHIA 6 and HERWIG++ simulations are in agreement with data, and predict the same discriminator performances.

Figure 2: Comparison of data with MADGRAPH + PYTHIA 6 simulation, for jets with \(80 < p_T < 100\) GeV and \(|\eta| < 2\) in Z+jet events, for the three input variables used in the likelihood discriminator.

Figure 3: Data validation of the likelihood discriminant for jets with \(40 < p_T < 50\) GeV and \(|\eta| < 2\), comparing Z+jet data with MADGRAPH + PYTHIA 6 simulation (left), dijet data with PYTHIA 6 simulation (middle) and dijet data with HERWIG++ simulation (right).

### 3 Shape uncertainty on the likelihood discriminant

A general applicable recipe is developed to estimate the uncertainty on the likelihood discriminant output. A smearing function is chosen to vary the discriminator shape in simulation to match the shape in data:

\[ g(x, a, b) = \frac{1}{2} \tanh(a \arctanh(2x - 1) + b) + \frac{1}{2} \]
Figure 4: Validation of the smearing function method for jets with $50 < p_T < 65$ GeV and $|\eta| < 2$ in dijet events. The data is compared to the simulation before and after the application of the smearing. The smearing function was derived in the $Z+$jets case (left), good closure is observed when applied to the dijet case (right).

Figure 5: Change in discriminating performance by comparing the fraction of quarks and gluons with a quark-gluon likelihood discriminant greater than 0.5 as a function of the jet transverse momentum, before and after smearing. Different smearings were retrieved for PYTHIA 6 (left) and HERWIG++ (middle), and are in agreement with each other (right).

4 Conclusions

A likelihood discriminant has been developed to separate jets originating from gluons or light-quarks. The discriminator input variables and output distributions have been validated using $Z+$jets and dijet events. A smearing function is applied to distort the shape of the output distributions in simulation, in order to reproduce better the observed data outputs.

References

[1] CMS Collaboration, CMS-PAS-JME-13-002.
[2] CMS Collaboration, https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME13002