Hadronic results from CMS experiment at the LHC

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Abstract. The Compact Muon Solenoid (CMS) is one of the two large multipurpose experiments at the LHC. We present the CMS results related to tests of QCD predictions for jet, dijet, and multijet production in pp collisions at center-of-mass energies of 7 TeV and 8 TeV. The results also include recent hadronic event shape measurements, $\alpha_s$ extraction, charged hadron measurements, dijet azimuthal decorrelations, searches for BFKL effects in the azimuthal correlations of forward-backward and forward-central jets at 7 TeV, and studies of the transition from the perturbative to the non-perturbative regime using minijets at 8 TeV.

1. Introduction
Events with collimated streams of particles, called jets, are abundantly produced in high energetic proton-proton collisions at the LHC. Such events can be described by Quantum Chromodynamics (QCD) in terms of parton-parton scattering where the outgoing scattered partons manifest themselves as hadronic jets. The benchmarks of the Standard Model are jet and multijet production cross sections which confront the perturbative QCD (pQCD) predictions at the smallest distance scales ever probed. CMS provides unexplored kinematic regimes to test the QCD predictions. A detailed description of the CMS experiment can be found in Ref. [1]. The hadronization and parton shower models can be optimized by using the jet observables. The parton density functions (PDF) can also be constrained with the measurement of jet cross sections which are sensitive to the strong coupling constant $\alpha_s$. The observables sensitive to multijet production, such as the hadronic event shapes, the dijet azimuthal decorrelations, and the ratio of the 3–jet to 2–jet production cross section, are used to compare data to the predictions of various QCD Monte Carlo (MC) generators.

2. Measurements
Inclusive jet and dijet production cross section measurements are the tools to investigate the structure of the proton. Such a measurement [2] is performed by using the data corresponding to 5 fb$^{-1}$ of integrated luminosity. Jets are reconstructed with the anti-$k_T$ clustering algorithm with distance parameter $R = 0.7$. The measured cross sections are compared to pQCD predictions at NLO, using five sets of PDFs. The charged particle production, multi-particle production (MPI) and underlying event (UE) activity measurements are important topics to test the soft QCD and used to tune the MC generator parameters. The characteristic features and relative importance of different mechanisms of MPI are studied in pp collisions at $\sqrt{s} = 7$ TeV [3]. In this study the UE and jets are analyzed for the first time with the observables such as jet $p_T$ spectra, rates and...
shapes. The results are compared to MC predictions which fail to fully describe the intrajet spectra. In low-multiplicity events, jets are narrower than the MC models, whereas in high-multiplicity events their widths are as predicted by the MC event generators. Most of the MC models reproduce well the UE features in all the multiplicity bins considered.

The inclusive forward jet production cross sections as well as the dijets events with at least one jet emitted at central and the other in forward region are measured at $\sqrt{s} = 7$ TeV in pp collisions [4]. The differential cross sections binned in $p_T$ and $\eta$ are compared to NLO predictions, MC event generators and models. Within the theoretical and experimental uncertainties, all the predictions are in agreement with the measurement.

In the inclusive jet cross section measurement at $\sqrt{s} = 8$ TeV [5], the data are compared to various pQCD predictions at NLO and found to have good agreement in the entire phase space. Figure 1 shows the comparison of differential inclusive jet cross sections measured at low and high transverse momenta to NLO predictions using the NNPDF2.1 PDF set times the NP correction factor (left) and the ratio of data to the theoretical prediction of NNPDF2.1 (right). The recent inclusive jet cross section measurements at $\sqrt{s} = 8$ TeV are also performed by CMS [6, 7].

![Figure 1](image.png)

Figure 1. Differential inclusive jet cross sections in comparison to NLO predictions (left). Ratio of data to the prediction of the NNPDF2.1 PDF set (right).

The ratios of 3–jet to 2–jet cross section measurements are done using jets within the central region at $|y| < 2.5$ [8, 9]. In the most recent measurement [10], the value of $\alpha_s(M_Z)$ at the scale of the Z boson mass is measured for the first time at high momentum scales. The result is found as $\alpha_s(M_Z) = 0.1185 \pm 0.0019$ (exp.) $\pm 0.0028$ (PDF) $\pm 0.0004$ (NP) $\pm 0.0022$ (scale) which is in agreement with the world average value. The running of $\alpha_s(Q)$ and its total uncertainty as a function of the momentum transfer $Q = p_T$ are shown in Figure 2 (left). An overview of the gluon, sea, u valence ($u_V$), and d valence ($d_V$) PDFs at starting scale $Q^2 = 1.9$ GeV$^2$ is shown in Figure 2 (right). A significant improvement of precision is observed in the high-$x$ region by including the CMS data with DIS data at HERA. The CMS jet data have a larger gluon PDF at high-$x$ compared to the DIS data.

The azimuthal angular decorrelations of jets most forward and backward in rapidity are measured with the CMS detector at 7 TeV [11]. The most forward and the most backward jet pairs in a dijet event are called Muller-Navelet (MN) jet. Due to the highest rapidity separation between MN jets which can be populated with soft emissions, correlation between the jets is an observable which is sensitive to the details of the QCD evolution. BFKL effects can be disentangled from the standard DGLAP approach.

Azimuthal correlations between forward-central jet pairs are also studied with a large separation in pseudorapidity, $\Delta \eta = |\eta_{jet1} - \eta_{jet2}|$ [12]. The DGLAP based generators are found
Figure 2. The running of the strong coupling $\alpha_s(Q)$ and its total uncertainty (left). Overview of the gluon, sea, $u_V$ and $d_V$ PDFs at starting scale $Q^2 = 1.9$ GeV$^2$ (right).

to be describing the complex observables well. But, no conclusion about the presence of BFKL like parton dynamics can be drawn from the present measurements.

Hadron production in pp collisions at $\sqrt{s} = 8$ TeV is measured by the CMS and TOTEM experiments [13]. An inclusive sample which events were triggered by forward activity in either side of the detector and a non-single-diffractive enhanced sample which events were triggered by both TOTEM T2 telescopes are used for the measurement. The production yields of leading charged-particle jets and charged particles [14] provide information on the underlying parton-parton cross section mechanism. A large sensitivity to the underlying physics is seen in the comparisons of data to various MC event generators. The measurement indicates the saturation of parton-parton cross sections can be seen already in a few GeV of $p_T$ range at LHC energies.

3. Summary

An extensive list of QCD studies is presented from the CMS experiment. The large pp collision dataset has been collected during the Run I Phase and the CMS collaboration has explored measurements that shed light on a new era. Additionally the $\alpha_s$ has been extracted from jet measurements up to the TeV scale for the first time.

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