Abstract

The collisions of hadrons at very high centre-of-mass energies provide a direct probe to the nature of the underlying parton-parton scattering physics. The scattering of the elementary quark and gluon constituents of the incoming hadron beams produces a high momentum partons which then fragment to spray of particles clustered in the form of jets. These jets are the final structures observed in the detector and they preserve the energy and direction of the initial partons. Hence jets can serve as a direct test of theory of strong interactions called Quantum Chromodynamics. The inclusive multijet production cross-section is an important observable which provides the details of parton distribution functions (PDF) of the colliding hadrons and the precise measurement of the strong coupling constant α_S. Instead of individual cross-sections, the cross-section ratio is a better tool to determine the value of α_S as many theoretical and experimental uncertainties cancel in the ratio.

A measurement of inclusive multijet event cross-sections and the cross-section ratio is presented using data from proton-proton collisions collected with the CMS detector at a centre-of-mass energy of 8 TeV corresponding to an integrated luminosity of 19.7 fb^{-1}. Jets are reconstructed with the anti-k_t clustering algorithm for a jet size parameter R = 0.7. The inclusive 2-jet and 3-jet event cross-sections as well as the ratio of the 3-jet over 2-jet event cross-section R_{32} are measured as a function of the average transverse momenta p_{T} of the two leading jets in a phase space region ranging up to jet p_{T} of 2.0 TeV and an absolute rapidity of $|y| = 2.5$. The measurements after correcting for detector effects are well described by predictions at next-to-leading order in perturbative quantum chromodynamics and additionally are compared to several Monte Carlo event generators. The strong coupling constant at the scale of the Z boson mass is extracted from a fit of the measured R_{32} which gives $\alpha_s(M_Z) = 0.1150 \pm 0.0010\,(\text{exp}) \pm 0.0013\,(\text{PDF}) \pm 0.0015\,(\text{NP})\,^{+0.0050}_{-0.0000}\,(\text{scale})$ using MSTW2008 PDF set. The current measurement agrees well with the world average value of $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ as well as previous measurements.

Chapter 1

Introduction

Particle physics deals with the study of the basic constituents of matter and the forces governing the interactions among them. The Standard Model (SM) is the most accepted theory which describes the nature and properties of the fundamental particles and their interactions. The elementary particles leptons and quarks, known as fermions, interact through the exchange of gauge bosons and acquire mass through a scalar boson called the Higgs. The four fundamental forces of interaction existing in nature are : the electromagnetic force, the strong force, the weak force and the gravitational force. Quantum Choromodynamics (QCD) is the theory of the strong interactions between the quarks mediated by the massless gluons. The partons (quarks and gluons) have a peculiar property of "color" charge. The quarks strongly binds into colorless particles called hadrons such as protons and neutrons together known as nucleons, pions etc. The structure and the properties of sub-atomic particles can be explored by first accelerating them using particle accelerators and then colliding at very high energies. The end products of these collisions get detected in the particle detectors constituting the real data. The data sets analyzed in details to reveal the structure and characteristic properties of the fundamental particles.

To investigate the very rare particles or to search for physics beyond SM, the particle accelerators have become ever bigger and more complex. The Large Hadron Collider (LHC) is one of the today's biggest and most powerful collider where the protons are accelerated and collided at extremely high center-of-mass energies to probe their internal structure described by parton distribution functions (PDFs). The PDF sets give the probability for finding a parton at an energy scale Q with a fractional momentum x of the proton. Since the proton is not elementary and is made up of partons, the proton-proton (pp) collisions are viewed as interactions between their constituent partons. The final products of the scattering are observed by Compact Muon Solenoid (CMS), one of the detectors located around the interaction points. The scattering cross-section can be defined as a sum of terms with increasing powers of the strong coupling constant α_S convoluted with PDFs. The lowest-order α_S^2 term represents the production of two partons in final states whereas terms of higher-order α_S^3, α_S^4 etc. signify the existence of multi partons in final states. The final state partons give a parton shower (PS) due to decrease in energy through emission of other quarks and gluons. The colored products of parton shower hadronize to a spray of colorless hadrons known as jets. The jets are the final structures observed in the detector. So they carry the significant information about the energy and direction of the initial partons and hence are important to study. The final partons have the probability to radiate more gluons resulting in multijets in the final state. Such events are produced in large number and are an important source for testing the predictions given by QCD. They also serve as an important background in the searches for new particles and physics beyond SM.

The inclusive multijet event cross section σ_{i-jet} given by pp $\rightarrow i\ jets + X$, where every jet counts, is proportional to α_s^i. The inclusive jet cross-section studied in terms of jet p_{T} and rapidity y is one of the important observables as it provides the essential information about the PDFs and the precise measurement of α_S. Also the ratio of cross-sections given by Eq. 1.1 is proportional to the QCD coupling α_S

and hence can be used to determine the value of α_S.

$$R_{mn} = \frac{\sigma_{m-jet}}{\sigma_{n-jet}} \propto \alpha_S^{m-n} \tag{1.1}$$

Instead of studying inclusive cross-sections, the cross-section ratio is more useful because of the partial or complete cancellation of many theoretical and experimental uncertainties between numerator and denominator. The CMS Collaboration has previously measured the ratio of the inclusive 3-jet cross-section to the inclusive 2-jet cross-section as a function of the average transverse momentum, $< p_{T1,2} >$, of the two leading jets in the event at 7 TeV [1] and lead to an extraction of $\alpha_s(M_Z)$ $= 0.1148 \pm 0.0055$, where the dominant uncertainty stems from the estimation of higher-order corrections to the NLO prediction. In this analysis, a measurement of inclusive 2-jet and 3-jet event cross-sections as well as ratio of 3-jet event cross-section over 2-jet R_{32}, is presented using an event sample collected by the CMS experiment during 2012 at the LHC and corresponding to an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$ of pp collisions at a centre-of-mass energy of 8 TeV. The event scale is chosen as before to be the average transverse momentum of the two leading jets, but will be referred to as $H_{\mathrm{T},2}/2$ in this thesis. The measurements are used to determine the value of the strong coupling constant at the scale of the Z boson mass $\alpha_s(M_Z)$ and the running of α_S with energy scale Q is studied.

This thesis is organized as :

Chapter 2 gives a brief overview of the Standard Model of particle physics and the theory of strong interactions QCD with main emphasis on the jets and jet algorithms.

Chapter 3 deals with experimental apparatus which covers the details of the CMS detector and its various sub-detectors.

Chapter 4 presents the measurement of inclusive differential multijet cross-sections and the cross-section ratio. The measurements are corrected for detector effects by unfolding procedure which is discussed in details in this chapter. The sources of the experimental uncertainties are studied in details.

Chapter 5 contains a detailed description of the NLO pQCD theory predictions compared to data and the extraction of α_S. The NLO calculations are corrected with the non-perturbative and electroweak corrections. The theoretical uncertainties are calculated from various sources. The unfolded measurements are compared to the predictions at NLO in pQCD and additionally as well as to predictions from several Monte Carlo event generators.

Chapter 6 describes the method to extract $\alpha_s(M_Z)$ from the current measurement and the running of α_S with energy scale Q is presented along with the previous measurements from different experiments.

Chapter 7 summarizes the results and conclusions of the work done in this thesis.

Chapter 7

Summary

Inclusive multijet production cross-section measured precisely in terms of jet transverse momentum is one of the important observables in understanding physics at hadron colliders. It provides the essential information about the structure of parton through parton distribution functions (PDFs) and the precise measurement of the strong coupling constant α_S. The value of the strong coupling constant at the scale of the Z boson mass $\alpha_s(M_Z)$ can be determined using cross-section ratio instead of individual cross-sections because many uncertainties of theoretical and experimental origin cancel between numerator and denominator which reduces the dependence on PDFs, renormalization and factorization scales, luminosity etc.

In this thesis, a measurement of the inclusive 2-jet and 3-jet event cross-sections as well as the cross-section ratio R_{32} has been presented. The data sample has been collected from proton-proton collisions recorded with the CMS detector at a centre-of-mass energy of 8 TeV and corresponds to an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$. The jets are reconstructed with the anti-k$_t$ clustering algorithm for a jet size parameter R = 0.7. The inclusive 2-jet and 3-jet event cross-sections are measured differentially as a function of the average transverse momentum of the two leading jets, referred as $H_{\mathrm{T},2}/2$. The ratio R_{32} is obtained by dividing the differential cross-sections of inclusive 3-jet events to that of inclusive 2-jet one in each bin of $H_{\mathrm{T},2}/2$. An appropriate selection criteria has been designed for choosing the best events for analysis. The measurements are performed at a central rapidity of $|y| < 2.5$ in a range of $0.3 < H_{\mathrm{T},2}/2 < 2.0\,\mathrm{TeV}$ for inclusive 2-jet event cross-sections and $0.3 < H_{\mathrm{T},2}/2 < 1.68\,\mathrm{TeV}$ for inclusive 3-jet event cross-sections and ratio R_{32}.

The measured cross-sections after correcting for detector effects by using an iterative unfolding procedure are compared to the perturbative QCD predictions computed, using NLOJet++ program, at next-to-leading order (NLO) accuracy and complemented with non-perturbative (NP) corrections that are important at low $H_{\mathrm{T},2}/2$. The data are found to be well described by NLO calculations. The upwards trend observed in the inclusive 2-jet and 3-jet data at high $H_{\mathrm{T},2}/2$ in comparison to the prediction at NLO QCD, is explained by the onset of electroweak (EW) corrections in the 2-jet case. For the 3-jet event cross-sections these corrections have not yet been computed yet. In the 3-jet to 2-jet cross-section ratio R_{32}, the EW corrections are assumed to cancel. In fact, NLO QCD provides an adequate description of R_{32} in the accessible range of $H_{\mathrm{T},2}/2$. In contrast, leading order (LO) tree-level Monte Carlo (MC) predictions obtained using MadGraph5 event generator interfaced to pythia6 exhibit significant deviations. The sources of experimental and theoretical uncertainties are studied in details. The experimental uncertainty ranges from 4 to 32% for inclusive 2-jet event cross-sections, from 4 to 28% for 3-jet event cross-sections and from 1 to 28% for cross-section ratio R_{32}. It is dominated by the uncertainty due to the jet energy corrections (JEC) at lower $H_{\mathrm{T},2}/2$ values and by statistical uncertainty at higher $H_{\mathrm{T},2}/2$ values. The theoretical uncertainty ranges from 3 to 30% and 5 to 34% for inclusive 2-jet and 3-jet event cross-sections respectively and from 3 to 11% for ratio R_{32}. The PDF uncertainty derived with the CT10-NLO PDF set is the dominant source of theoretical uncertainty.

The inclusive multijet cross-sections being proportional to the powers of the strong coupling constant α_S ($\sigma_{\text{n-jet}} \propto \alpha_S^{\text{n}}$) are used to extract the value of the strong coupling constant at the scale of the Z boson mass $\alpha_s(M_Z)$. In cross-section ratio R_{32} which proportional to α_S, many uncertainties and PDF dependencies largely cancel and hence becomes the better tool to extract the value of $\alpha_s(M_Z)$. In this thesis, a fit of the ratio of the inclusive 3-jet event cross section to that of 2-jet, R_{32} in the range $0.3 < H_{\text{T},2}/2 < 1.68\,\text{TeV}$ using the MSTW2008 PDF set gives :

$$\begin{aligned}\alpha_s(M_Z) &= 0.1150\,\pm 0.0010\,(\text{exp})\,\pm 0.0013\,(\text{PDF})\,\pm 0.0015\,(\text{NP})\,^{+0.0050}_{-0.0000}\,(\text{scale})\\ &= 0.1150\,\pm 0.0023\,(\text{all except scale})\,^{+0.0050}_{-0.0000}\,(\text{scale})\end{aligned}$$

Very similar results are obtained using the MMHT2014 PDF set which gives :

$$\begin{aligned}\alpha_s(M_Z) &= 0.1142\,\pm 0.0010\,(\text{exp})\,\pm 0.0013\,(\text{PDF})\,\pm 0.0014\,(\text{NP})\,^{+0.0049}_{-0.0006}\,(\text{scale})\\ &= 0.1142\,\pm 0.0022\,(\text{all except scale})\,^{+0.0049}_{-0.0006}\,(\text{scale})\end{aligned}$$

The equally compatible values of $\alpha_s(M_Z)$ are determined with separate fits to the inclusive 2-jet and 3-jet event cross-sections provided the range in $H_{\text{T},2}/2$ is restricted to $0.3 < H_{\text{T},2}/2 < 1.0\,\text{TeV}$. The extracted $\alpha_s(M_Z)$ values in sub-ranges of $H_{\text{T},2}/2$ are evolved to corresponding $\alpha_S(Q)$ along with the error bars at different scales Q. The current measurement of $\alpha_s(M_Z)$ and the running of $\alpha_S(Q)$ as a function of Q is in well agreement within uncertainties with the world average value of $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ [66] and already existing determinations performed by the CMS and other experiments.

The inclusion of the EW corrections in inclusive 2-jet event cross-sections become relevant at $H_{\text{T},2}/2$ beyond 1 TeV. Their availability for 3-jet one and hence cross-section ratio R_{32} can improve the precision of the measurement of $\alpha_s(M_Z)$. Also as the theoretical calculations will be available for inclusive 4-jet event cross-sections, the various cross-section ratios such as $R_{43} \propto \alpha_S^1$ and $R_{42} \propto \alpha_S^2$ can be measured to extract the value of the strong coupling constant more precisely. Currently LHC is running at high center-of-mass energy of 13 TeV delivering a higher instantaneous luminosity and this makes possible to access the extended phase space and perform the measurements with more accuracy.