Exploring Jet Quenching Phenomena in Proton-Proton Collisions through Monte Carlo Simulation and Data Analysis

Yize Mo[1,3,†], Kerao Zhang[2,4,*,†]

[1]Department of Physics, Jilin University, Jilin, 130012, China
[2]School of Nuclear Science and Engineering, North China Electric Power University, Beijing, 10096, China

[3]moyz1120@mails.jlu.edu.cn
[4]120211110425@ncepu.edu.cn
*corresponding author
†These authors contributed equally and should be considered co-first authors.

Abstract. Jet quenching is a significant phenomenon for studying the properties of the Quark-Gluon Plasma (QGP), typically observed in heavy-ion collisions. This phenomenon refers to the substantial energy loss experienced by high-energy jets as they traverse the QGP. This study explores whether a similar effect occurs in proton-proton (pp) collisions. We simulated 10,000 proton-proton collision events using the PYTHIA event generator, with a center-of-mass energy set to 5360 GeV and a minimum transverse momentum threshold (pthatmin) of 500 GeV. Neutrino events were excluded from the simulation to focus on high-energy jets. The jet reconstruction was carried out using FastJet software and the inverse kT algorithm (R = 0.4), followed by fitting the four-momentum of the reconstructed jet using the ATLAS jet energy resolution curve, which helps to approximate the actual detector response more accurately. This study focuses on the correlation between the missing transverse momentum (MET) and the secondary jet volume ratio (pT2/pT1). It is found that the MET value falls below 40 GeV when pT2/pT1 is smaller than 0.4 and, due to the coverage of the detector, when the contribution of W bosons or neutrinos is extremely small. In addition, we study the distributions of the leading and secondary jets in terms of pseudo-combination (η) and polar angle (θ) in this case. This study provides a background for observing jet quenching in heavy-ion collisions and helps to analyse emerging physical phenomena in heavy-ion collisions.

Keywords: component, Jet quenching, pp collision, missing transverse momentum, QGP.

1 Introduction

Jet quenching is one of the main tools for studying quark-gluon plasma (QGP). It is defined as the suppression of hadron yields at high transverse momentum (pT) due to the loss of energy due to hard scattering of particles as they traverse the medium[1].

Quark-Gluon Plasma (QGP) is a state of matter that is characterised by an extremely high temperature and density. In this state, quarks and gluons are no longer confined within protons and neutrons, but exist in a free, deconfined state. The formation of QGPs necessitates the

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attainment of exceedingly high energy densities, a feat typically accomplished through heavy-ion collisions in the context of nuclear physics experiments[2].

In the quark-gluon plasma (QGP) state, where the strong interaction between quarks and gluons plays a major role, it is possible to investigate the fundamental properties of the strong interaction described by quantum chromodynamics (QCD) by studying the QGP[3]. Study of jet quenching phenomenon helps to obtain the properties of QGP[4].

These phenomena are explored primarily in heavy-ion collision experiments (e.g., experiments at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC))[5]. By studying changes in jet structure and jet quenching, researchers can learn something about the physical properties of the QGP, and this information will advance the development of our studies of early universe conditions and fundamental interactions.

The principal aim of this study is to investigate, through Monte Carlo simulations and data analysis, whether the phenomenon of jet quenching observed in heavy-ion collisions also occurs in proton-proton (pp) collisions. This study focuses on the reconstruction and selection processes of jets, in particular the behaviour of high-momentum jets. We study similar energy loss effects in pp collisions by than observing the momentum distribution and energy loss patterns of the jet.

2 Experimental Method

In this study, we use the PYTHIA simulator and FastJet jet reconstruction to investigate jet quenching in proton-proton (pp) collisions. The methodology is described below.

2.1 Basic Definitions and CMS Coordinate System

We used the coordinate system of the CMS detector. In this coordinate system, the z-axis is aligned with the direction of the beam, the x-axis points to the centre of the LHC ring, and the y-axis is perpendicular to the plane of the LHC ring and points upwards. The transverse momentum, pT, is defined as follows:

$$p_T = |\vec{p}| \sin\theta$$

The θ is the polar angle relative to the z-axis. The pseudorapidity η is defined as:

$$\eta = -\ln[\tan(\theta/2)]$$

The pseudorapidity is used to describe the distribution of particles along the z axis.

2.2 Simulation of Event Generation

To simulate proton-proton (pp) collisions, we use the PYTHIA 8.3.12 [6] event generator. PYTHIA 8.3.12 is a powerful Monte Carlo simulation tool which can simulate a variety of complex physical processes in high-energy particle collisions in detail, including the strong interaction mechanism, the formation of jets, scattering between quarks and gluons, and secondary particle production. The advantage of PYTHIA 8.3.12 is that it can provide researchers with accurate simulations of collision events that occur in real experiments, thus supporting data analysis and theoretical predictions.

We used PYTHIA to generate 10,000 proton-proton collision events. The collision centre energy (eCMS) was set to 5360 GeV. In order to generate jet events with the highest possible energy, we set the minimum transverse momentum threshold (pthatmin) of the generation process to 500 GeV.

In the event generation process, we excluded neutrinos in the final particle part. This choice is based on the detection properties of neutrinos: as electrically neutral elementary particles, neutrinos interact very weakly with matter and are therefore difficult to detect directly by experimental detectors.[7] Their exclusion helps to focus clearly on the jet quenching phenomenon.[8]

2.3 Event Collection and Jet Reconstruction

After simulating proton-proton (pp) collision events, we used FastJet[9] software to perform a detailed jet reconstruction analysis of the generated particle data. FastJet can handle a large number of particle events and reconstruct the four-dimensional momentum of the jet from the particle data.

In this investigation, the esteemed anti-kT algorithm[10] was employed for jet reconstruction, with a discerning selection of a jet radius parameter (R = 0.4). This algorithm, widely recognized for its resilience and immunity to soft radiation, stands as a prominent choice in contemporary high-energy physics experiments. The method of this algorithm is to gradually merge particles with similar positions to construct the jet, and its main advantage lies in the suppression of soft radiation, which effectively circumvents the reconstruction errors caused by low-momentum particles or background noise, thus providing a more accurate jet structure.

In the field of high-energy physics experiments, the choice of jet radius directly affects the accuracy and effectiveness of jet reconstruction. Reducing the jet radius (R) facilitates an enhanced delineation of neighbouring jets, thus reducing soft radiation and potential events. In addition, this method also improves the sensitivity to high-momentum jets. Therefore, we deliberately chose (R = 0.4) in our study with the aim of obtaining more reliable experimental data by striking a balance between reconstruction accuracy and reduction of background interference.[11, 12]

2.4 Jet Energy Fitting and Selection

In order to enhance the realism of the simulated data, a Gaussian fit was performed on the reconstructed jet tetra-momentum using the jet energy resolution curve from the ATLAS detector. The aforementioned fitting procedure enables the simulation of the response characteristics of a genuine detector, thereby guaranteeing that the reconstructed jet energy is in close alignment with the measurements observed under experimental conditions.

Following the fitting process, a further selection of jet events was performed to guarantee that the jets included in the subsequent analysis were within the physical coverage of the detector and to observe high-momentum jets. We set the selection criteria: transverse momentum (pT) of the forward jet greater than 600 GeV and pseudo-amplitude (|eta|) less than 1. These criteria are qualitatively based on the physical coverage of the actual detector, and are intended to ensure that we only analyse high-momentum jet events that can be efficiently detected experimentally[13].

This selection process filters out jets that are difficult to measure accurately because they are located near the edge of the detector or have low momentum, and focuses on jets with higher momentum that are more likely to exhibit significant physical effects. By applying these selection criteria, we ended up with a high-quality data set of jet events.

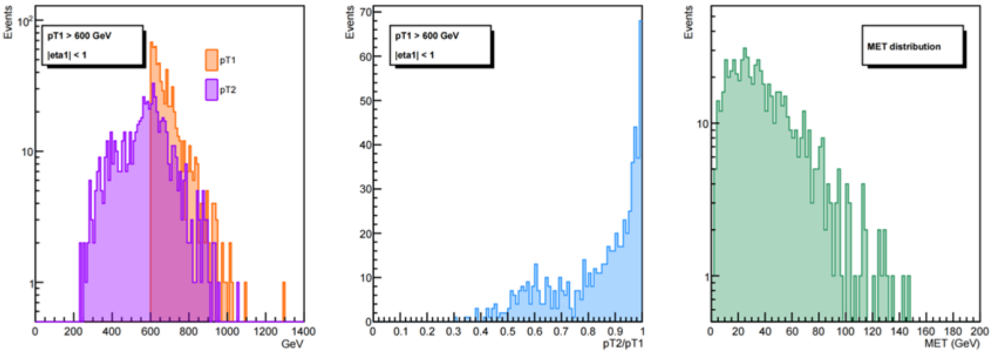
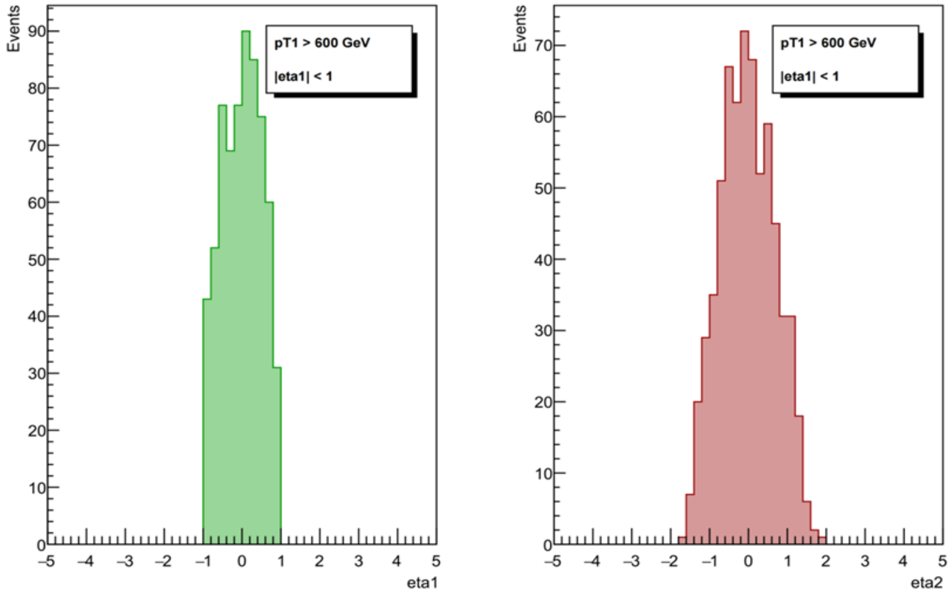


Fig. 1. This figure displays the distributions after applying event selection and resolution fitting. It includes the following distributions: the transverse momentum of the leading jet (pT1), the transverse momentum of the subleading jet (pT2), the ratio of the transverse momentum of the subleading jet to the leading jet (pT2/pT1), and the distribution of missing transverse energy (MET).



(a) (b)

Fig. 2. This figure displays the distributions after applying event selection and resolution fitting, including: (a) the pseudorapidity of the leading jet (eta1) and (b) the pseudorapidity of the subleading jet (eta_2).

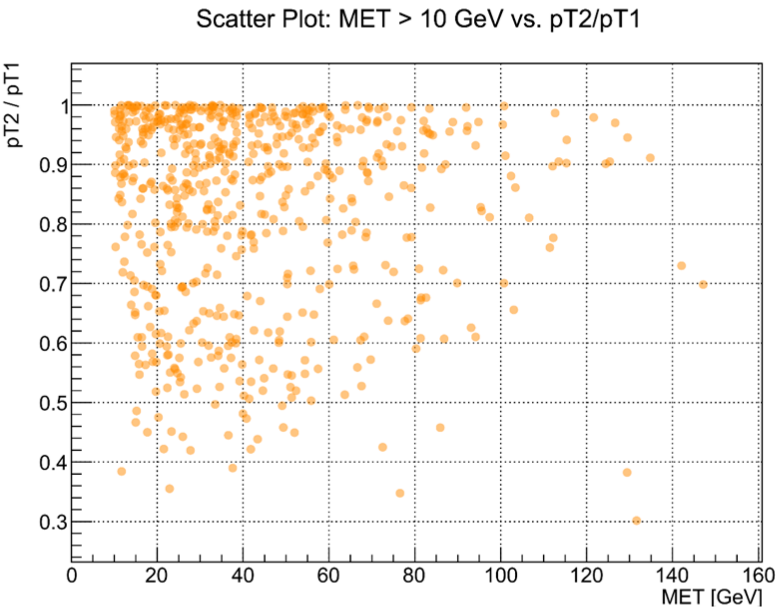
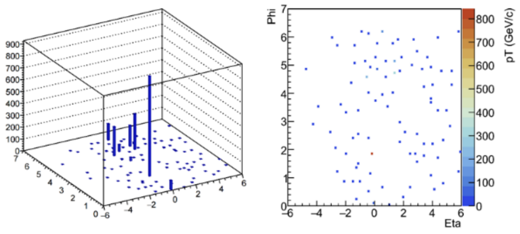


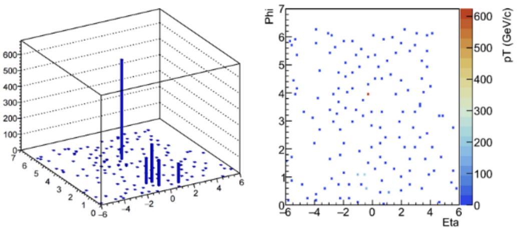
Fig. 3. This figure illustrates the relationship between the missing transverse energy (MET) and the ratio of the transverse momentum of the subleading jet (pT2) to the leading jet (pT1) for each event, under the condition that MET > 10 GeV.

3 Results

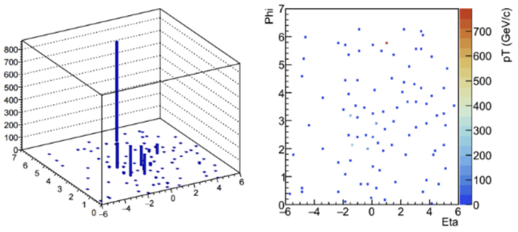
In cases where the subleading jet momentum ratio (pT2/pT1) is relatively small (pT2/pT1 < 0.4), we observe that MET values are often lower (MET < 40 GeV). Smaller MET values might indicate a reduced contribution from W bosons or relatively minor contributions from neutrinos. Typically, larger MET values are associated with W boson decays producing leptons and neutrinos, with neutrinos leaving a significant missing energy signal because they are not directly detectable by the detector. Thus, we specifically focus on events with MET < 40 GeV and (pT2/pT1 < 0.4), analyzing the distribution of the leading jet and subleading jet in pseudorapidity (eta) and polar angle (theta). This analysis aims to further reveal jet characteristics and their relationship with MET, providing additional insights into jet behavior in high-energy collisions.



(a)pt2/pt1=0.36, MET=14.51GeV



(b) pt2/pt1=0.39, MET=34.52GeV



(c) pt2/pt1=0.30, MET=14.85GeV

Fig. 4. This figure shows the distribution of the transverse momentum (pT) with respect to the pseudorapidity (eta) and the polar angle (theta) for each event, under the conditions (pT2/pT1 < 0.4) and (10 GeV < MET < 40 GeV).

Upon examining Figure 4, we find that even in the absence of W boson decays, phenomena resembling jet quenching still occur. Further analysis indicates that both leading and subleading jets are predominantly distributed near pseudorapidity (eta) close to 0. This observation might be influenced by the detector's angular coverage limitations. In this study, we assumed a detector coverage of (|eta| < 1), which might lead to incomplete detection of jets in some events, thereby creating a pseudo jet quenching signal. In other words, these detector angle limitations could generate a false signal resembling jet quenching, rather than actual jet energy loss. So when a jet quenching-like phenomenon occurs in heavy ion collisions it is not necessarily energy loss, but could also be due to false signals caused by the detection range. This finding provides a useful background for studying QGP produced in heavy-ion collisions.

4 Conclusion

In this paper, we mainly simulate the PP collision under high energy, and discuss whether the PP collision produces a phenomenon similar to the Jet Quenching phenomenon in the heavy ion collision, and the conclusion is that the PP collision can produce a phenomenon similar to Jet Quenching due to the limited detection range of the detector. We can conclude from this that the judgment of the phenomenon of jet quenching cannot be judged only by leading jet and subleading jet, but we can try to determine whether jet quenching occurs based on the comparison of leading jet with other jets. This study provides an important background for the study of jet quenching phenomenon in heavy ion collisions.

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Yize Mo and Kerao Zhang contributed equally to this work and should be considered co-first authors.

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