LIP-STUDENTS-19-03

Heavy flavour jets production in Pb+Pb collisions with the ATLAS detector

Inês Rebanda[1,a] and Rodrigo Gazola[1,b]

[1] *Faculdade de Ciências da Universidade de Lisboa, Portugal*

Project supervisor: H. Santos

October 2019

Abstract. Just after the Big Bang the matter was in a unique state of high density and temperature, resulting in a deconfined state called Quark Gluon Plasma (QGP). This state of matter is reproduced in laboratory but it has a very short lifetime becoming impossible to measure it directly; it is possible to infer its properties, though. A well-known way to study this state of matter is the jet quenching produced in Heavy Ion (Pb+Pb) collisions at the ATLAS/LHC. Jets originating in the bottom quark constitute a golden probe of the QGP because its energy loss, either collisional or radiative, is expected to be different from the one suffered by lighter jets. The main goal of this internship was to reproduce the jet quenching results from a previous published analysis, then to compare it to the results obtained regular B-tagging algorithms (mv2c10) and (DL1).

Keywords: LHC, ATLAS, Quark-Gluon Plasma, Heavy-Ions

1 Introduction

1.1 The ATLAS detector

The ATLAS detector (A Toroidal LHC ApparatuS) is one of the detectors from LHC, at CERN [2]. It is a multilayer cylinder. The collisions occur at the center which is surrounded by the track detector (Inner Detector - ID). The second layer is the electromagnetic calorimeter followed by the hadronic calorimeter. These are the most important parts of the detector for reconstructing jets, the object of the present study. The particles reach the calorimeters and deposit their energy in the form of clusters. The calorimeters are surrounded by a muon spectrometer.

1.2 The Quark Gluon Plasma

The Quark Gluon Plasma is a state of matter predicted by Lattice Quantum Chromodynamics (QCD) that occurs in unique conditions of temperature and density, and whose properties cannot actually be measured directly. By QCD theory, and so far confirmed by experimental research, it is not possible to find isolated quarks and gluons in nature, due to color confinement. In fact, separating quarks from each other spends more energy than the creation of a new quark-antiquark pair. On the other hand, the strong force is negatively correlated to the energy of center of mass $\sqrt{s}$ and positively by the length scale. So, there is evidence for an asymptotical free strong interacting state, instead. The QGP shows up for a tiny period of time: An almost perfect fluid that allows quarks and gluons to experience non-confined interactions.

1.3 Jet Quenching

A jet is a narrow cone of particles that are produced in the process of fragmentation of a quark or a gluon. In ultra-relativistic hadron collisions at LHC, the formation of dijets balanced in p_{T} and back-to-back oriented, due to momentum conservation, is expected. Such behavior is observed in pp interactions and peripheral Pb+Pb collisions. However, in head-on (central) Pb+Pb collisions, the emerging quarks and gluons evolve as parton showers that propagate through a hot and dense medium. Constituents of the parton showers interact and emit medium-induced gluon radiation and, as a consequence, the resulting jet loses energy, a phenomenon denominated jet quenching.

1.4 Heavy-Flavour Jets

In collisions it is expected the formation of all kind of jets, namely gluon-jets, tau-jets, light-jets, c-jets, b-jets. The last ones are the rarest, with a rate of around 5%. b-jets are a particular good probe to study the nature of the energy loss suffered by the quarks while travessing the QGP. Due to its large mass, the bottom quark is produced in hard parton scatterings at the early stages of the collisions, perceiving thus the entire evolution of the plasma. On the other hand, because the heavy quark mass inhibits the medium-induced gluon radiation, it is expected that the energy loss of b-jets passing through QGP is smaller than for other jets [3].

1.5 Flavour Tagging

The process of identifying jets originating in a given kind of particle is called Flavour Tagging. The inputs to recognize b-jets, the so-called b-tagging algorithms, are the trajectories of charged particles (tracks) reconstructed in the ID. mv2c10 is a Boosted Decisions Tree (BDT) algorithm, implemented in the ROOT Toolkit for Multivariate Data Analysis (TMVA) [4]. It combines the output of the basic taggers based on the impact parameter relatively to the primary vertex and the properties of the secondary vertex. Regarding the former, a new class of high-level algorithms called DL1, which stands for Deep Learning, is being used in addition to the MV2 family in order to improve b-tagging and c-tagging tasks. Differently than the

[a] e-mail: inesrebanda@gmail.com
[b] e-mail: rodrigo@gazola.org

previous BDT, which nodes makes binary decisions in a vertical hierarchy, a Neural Network presents layers with fully connected nodes, which propagates individual values in between. Usually a Neural Network is characterized by an input layer, a number of hidden layers (which define it's depth) and an output layer. A Deep Neural Network is a NN with a high number of hidden layers. The use of this algorithm has shown to improve results for b-tagging and c-tagging [5] in comparison to the previous BDT.

1.6 Relevant Variables

The important jet kinematic and jet quenching related variables used in this study are the following:

- θ : Polar angle;
- $\eta = -\ln(\tan\theta/2)$: Pseudorapidity;
- ϕ : Azimuthal angle;
- p_{T} : Transverse momentum;
- $A_J = (p_{\mathrm{T}}^1 - p_{\mathrm{T}}^2)/(p_{\mathrm{T}}^1 + p_{\mathrm{T}}^2)$: Dijet asysmmetry in transverse momentum;
- $\sqrt{s_{NN}}$: Center of mass energy of the nucleon-nucleon pair.

2 Experimental procedure

Data have been analyzed using the Framework ROOT in the language C++. ROOT is a tool to process and develop statistical analysis from CERN data. Cuts were made in the variable p_{T} for leading (jet with highest reconstructed p_{T} out of the two - see Figure 1) and subleading (lowest p_{T}) jets, denominated p_{T}^1 and p_{T}^2, with the goal of reproducing the results of [1] and focusing in the enhance of the asymmetry distribution. On the other hand, this kinematic window increased the probability that the remaining data were less contaminated by jets originating in the underlying event (fake jets) and pile-up[1]. The results are not corrected for detector and underlying event effects. Control studies in order to check that the selected jets have the expected basic kinematic distributions have been performed. The distribution of jets as a function of the variable ϕ should be uniform after accounting for the necessary corrections for the non-uniformities in the cells of the calorimeter (Figure 2). The distribution of jets as a function of the variable η should present a shape of a bell because partons originating in these jets tend to emerge at 90 degrees relatively to the beam axis (Figure 3).

[1]Pile-up stands for multiple collisions within the same or adjacent LHC bunch crossings.

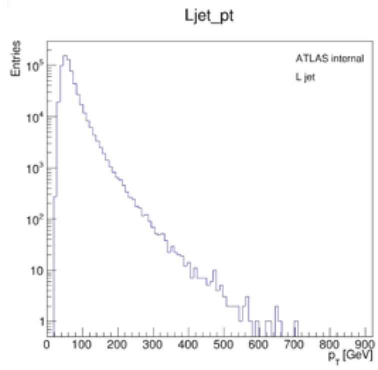

Figure 1. Distribution of the transverse momentum (p_{T}) for the leading jets. Data taken from fall 2018 at LHC ATLAS Experiment, $\sqrt{s_{NN}}$ = 5.02 TeV.

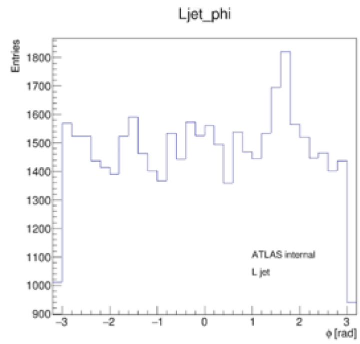

Figure 2. Azimuthal angle distribution (ϕ) for leading jets. Data taken from fall 2018 at LHC ATLAS Experiment, $\sqrt{s_{NN}}$ = 5.02 TeV.

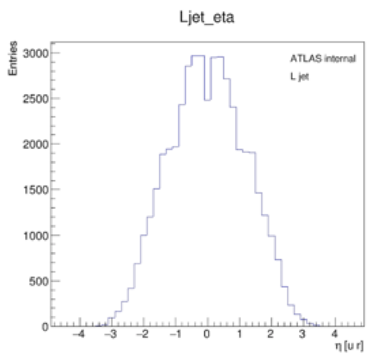

Figure 3. Distribution of pseudorapidity (η) for leading jets. Data taken from fall 2018 at LHC ATLAS Experiment, $\sqrt{s_{NN}}$ = 5.02 TeV.

To ensure that the distributions were matching with what had been observed in previous analysis, results from a paper published in 2010 [1] were reproduced using data from ATLAS experiment $\sqrt{s_{NN}}$ = 5.02 TeV taken in the fall of 2018. A similar kinematic phase space has been used: leading jet $p_{\mathrm{T}}^1 > 100$ GeV, subleading jet $p_{\mathrm{T}}^2 > 25$ GeV, leading jet $|\eta| < 2.8$ and subleading jet $|\eta| < 2.8$. The first variable to be compared was the $\Delta\phi$ which stands for the angle between the two jets. The distribution is expected to peak at π to preserve the transverse momentum. The broad distribution is attributed to more than one jet recoiling against the leading jet. A cut in the $\Delta\phi > \pi/2$ has been applied to reduce contributions from multi-jet final states. After establishing this kinematic window the dijet asymmetry, A_J, has been measured. The results obtained at this stage of the analysis were in good agreement with the reference publication [1]. The second part was the identification of flavour jets with the goal of obtaining two independent dijet asymmetry distributions: one from b-jets and the other from light-jets. For such, the two b-tagging algorithms, DL1 and mv2c10, were used.

3 Results

The data analyzed has shown slightly different results between b-jets and light jets in central collisions. The distributions for peripheral interactions have shown to be equivalent for both kind of jets, within statistical uncertainties. On the contrary, in central collisions the comparison has shown a higher number of symmetrical b-jets than light jets. This seems to confirm the expectations that the b-jets are less affected by the QGP while passing through it [3]. Results need to be corrected for detector effects before drawing a definite conclusion.

4 Skills acquired

This internship allowed us to expand our knowledge in certain subjects of Physics that we were not very familiar with or hadn't even heard about. We were taught how to use ROOT which we then used to analyze the data and also learned a new programming language (C++) which was the language used to work with ROOT. Besides that we also improved our English (both written and spoken) and our communication/presentation skills.

5 Conclusions

In this project the first goal was to reproduce the results from [1] and then to differentiate b-jets and light jets in Pb+Pb collisions. That was accomplished using both the algorithm DL1 and mv2c10. Although it wasn't possible to compare properly the two algorithms efficiency, as correction for detector effects would be indispensable, it was noticed singularly that b-jets and light jets in central collisions (0-20%) behave differently, which may indicate different physical behavior against QGP.

References

[1] G. Aad et al. (The ATLAS Collaboration), "Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the ATLAS Detector at the LHC", (2010). doi:10.1103/PhysRevLett.105.252303.

[2] The ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, (2008). doi:10.1088/1748-0221/3/08/S08003.

[3] Dokshitzer, Yuri L. and Kharzeev, D.E, "Heavy quark colorimetry of QCD matter", (2001). doi:10.1016/S0370-2693(01)01130-3

[4] A. Höcker et al, "TMVA - Toolkit for Multivariate Data Analysis", (2009). CERN-OPEN-2007-007

[5] The ATLAS Collaboration, "Optimisation and performance studies of the ATLAS b-tagging algorithms for the 2017-18 LHC run", (2017). ATL-PHYS-PUB-2017-013

[6] The ATLAS Collaboration, "Future of the ATLAS heavy ion program", (2012). ATL-PHYS-PUB-2012-002

[7] The ATLAS Collaboration, "Measurements of b-jet tagging eciency with the ATLAS detector using t t events at $\sqrt{s_{NN}}$ = 13TeV", (2018). ArXiv ePrint: 1805.01845

[8] Helena Santos, "Overview of Heavy Ions from the ATLAS Experiment", (2019). ATL-PHYS-PROC-2019-026

[9] The CMS Collaboration, "Jet properties in PbPb and pp collisions at $\sqrt{s_{NN}}$ = 5.02TeV", (2018). doi:10.1007/JHEP05(2018)006

[10] The ATLAS Collaboration, "Measurement of the pseudorapidity and transverse momentum dependence of the elliptic ow of charged particles in lead-lead collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the ATLAS detector", (2012). arXiv:1108.6018v3 [hep-ex]

[11] Michela Paganini, "Machine Learning Algorithms for b-Jet Tagging at the ATLAS Experiment", (2017). ATL-PHYS-PROC-2017-211

[12] Lanfermann, Marie, "Identification of b-jets and c-jets using Deep Neural Networks with the ATLAS Detector - The Development and Performance of a Family of DL1 High-level Flavour Tagging Algorithms", (2019). CERN-THESIS-2019-073